Yarn texturing technology

Yarn texturing technology

J W S Hearle, L Hollick and D K Wilson

The Textile Institute

CRC Press
Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED
Cambridge England

Published by Woodhead Publishing Limited in association with The Textile Institute
Woodhead Publishing Ltd
Abington Hall, Abington
Cambridge CB1 6AH, England
www.woodhead-publishing.com

Published in North and South America by CRC Press LLC
2000 Corporate Blvd, NW
Boca Raton FL 33431, USA

First published 2001, Woodhead Publishing Ltd and CRC Press LLC
© 2001, Woodhead Publishing Ltd
The authors have asserted their moral rights.

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. Reasonable efforts have been made to publish reliable data and information, but the authors and the publishers cannot assume responsibility for the validity of all materials. Neither the authors nor the publishers, nor anyone else associated with this publication, shall be liable for any loss, damage or liability directly or indirectly caused or alleged to be caused by this book.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming and recording, or by any information storage or retrieval system, without permission in writing from the publishers.

The consent of Woodhead Publishing and CRC Press does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from Woodhead Publishing or CRC Press for such copying.

Trademark notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation, without intent to infringe.

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data
A catalog record for this book is available from the Library of Congress.

Woodhead Publishing ISBN 1 85573 575 X
CRC Press ISBN 0-8493-1310-4
CRC Press order number: WP1310

Cover design by The ColourStudio
Typeset by Best-set Typesetter Ltd., Hong Kong
Printed by T J International, Cornwall, England

Contents

Preface

In 1946, when I started my career in textiles, nylon, which had come to the market less than ten years before, was virtually synonymous with parachute fabrics and 'nylons', the ladies' stockings first brought to Europe by American servicemen. Polyester was being explored in laboratories for competitive uses. Both were flat, continuous yarns, densely packed in fabrics. Over the next few years, nylon and polyester appeared in other markets. Wash-and-wear was an attraction and so, when I went on a Fellowship to South Carolina in 1953, I bought nylon and polyester shirts, socks and underwear – all made of fabrics that would be unacceptable today, because of their poor comfort and appearance.

It was in South Carolina that I first came across texturing. Hugh Brown, a highly inventive physicist, who had become Dean of Textiles at Clemson, was exploring texturing by running nylon yarn over a hot wire. A few miles away Deering-Milliken researchers were developing edge-crimping, and from Switzerland we heard of the long process for twist texturing. When I returned to Manchester, I introduced textured yarns into my lectures, and, with Malcolm Burnip and Gordon Wray started research into the relation between process conditions and yarn structure and performance in false-twist texturing. This research continued in various ways until I retired from UMIST in 1985.

Like many of the major advances in textile manufacturing, starting with Arkwright and cotton spinning 200 years ago, texturing has led to fierce patent litigation. I learnt a great deal from tests and studies in my role as an expert witness. I wrote thousands of pages of affidavits, but never went on the witness stand in person. Apart from opposition proceedings on a variety of patents, I was active in three phases of law-suits. First, on a Stoddart and Seem patent, which applied to single-heater false texturing for stretch yarns. This started with a threats action against Fluflon Ltd and continued with infringement actions until it petered out. Second, on another Stoddart and Seem patent, which covered double-heater, false-twist texturing for set polyester yarns. This led to a re-examination of the patent by the US Patent office, almost 20 years after its priority date, and eventually to two trials in Florida. Third on the DuPont Petrille patent for POY yarns, the feed-stock for draw-texturing: a case in India died for want of prosecution after running for a few months, first with oral evidence and then with affidavits, and DuPont versus ICI was settled just before it was due to open in the High Court in London. There were other cases, with which I was not involved, notably a trial in Canada in the1950s on stretch yarns and one in USA in the 1970s on set yarns with Milliken and Burlington as the main opposing protagonists.

My co-author, Keith Wilson, as a student in the Faculty of Technology of the University of Manchester, was introduced to textured yarn technology by my lectures. He then went on to a career in the fibre and textile machinery industries, which progressively took him closer first to false-twist texturing and then to air-jet texturing. Our other co-author, Les Hollick, has a great depth of experience in the manufacture of textured yarns.

For physicists, like myself, working in an academic environment, there is a great temptation to concentrate research on problems that are interesting – and amenable to mathematical theorising or neat experiments – but in industrially related departments, it is important that even basic research should add useful insights to commercial operations, either current or with future potential. Les Hollick makes a similar comment about the place of technologists in business in the following words:

> The aim of any manufacturing organisation, no matter what business they are engaged in, is to secure a positive return on investment. A healthy balance sheet benefits the owners, the shareholders or, in the case of a co-operative, the workers themselves. If any organisation is to have sufficient funds to secure full employment and to provide for future investment in plant and equipment, concentration on running a viable business is required. It is very tempting for the technologist to pursue work purely because it is exciting or interesting. If time permits this is fine, but first and foremost continual concentration on product and process improvement is required. This does not mean that such work cannot be fun; far from it, if the work itself becomes mundane and tedious then it is time to find alternative employment.
>
> It is the function of the technologist to examine every detail of the process, the design of the machine itself, the quality and suitability of machine components and ancillaries that are employed, as well as obviously, the quality of the feedstock and the process conditions employed. These must be carefully evaluated to ensure that they are the best available at economic cost. The elimination of sub-standard product and the maximisation of yield of first quality product, which can be sold at a competitive price and still be viable, is of paramount importance.

> Communication between the technologist and those directly involved with the manufacture of the product, at all levels, must be simple and clear. The temptation to escape into jargon must be avoided. It used to be sufficient to 'speed up the traverse system to cure some overthrows'; now unfortunately it's all to easy to 'realise an increase in the angle of wind in order to secure optimum packaging conditions'. These statements may be impressive, but no one else in the room will have any idea what you are talking about. Clear and concise communication and the ability to motivate others to strive towards a common goal is a skill every bit as important as technical prowess.
>
> Finally, it must never be forgotten that the contribution by well trained and well motivated operatives, who understand the importance of correct yarn handling and operating procedures, is one of the greatest assets that any company involved in the manufacture of yarn can have. Constantly keeping the workforce up to date with the current situation and what improvements are to be implemented is one aspect of the technologist's work that cannot be ignored.

In this book, we hope that the combination of authors, who range from the detached academic to the involved technologist, has enabled us to provide for students, teachers and the yarn texturing industry, both an explanation of relevant scientific and engineering principles and a wealth of information on industrial practice.

John Hearle

About the authors

J W S Hearle
John Hearle graduated in physics from the University of Cambridge. His course was interrupted for three years from 1945 to 1948, during which he became a research officer at the Shirley Institute – British Cotton Industry Research Association. In 1949, he joined the Manchester College of Technology (now UMIST) as an Assistant Lecturer. He remained on the Faculty until he retired in 1985, having been Professor of Textile Technology and Head of the Department of Textiles since 1974. Professor Hearle is still active in consulting, writing and lecturing, with the occasional contribution to original research. He has been a Smith-Mundt Fellow at Clemson, South Carolina, a Visiting Associate Professor at MIT, and a Distinguished Visiting Professor of Mechanical Engineering at the University of Delaware. John Hearle is an Honorary Fellow and Honorary Life Member of the Textile Institute, and a former Chairman of Council, and a Fellow of the Institute of Physics.

L Hollick
The only justification that is held for contributing to this book is experience; Les Hollick has worked in several different aspects of the textile industry. He started work in Courtauld's Synthetic Fibres Laboratory in 1969 and worked there for a period of ten years. Several different aspects of the textile trade including spin finish development, wet spun modacrylic fibres, draw twisting, stuffer-box texturing and false-twist texturing of nylon and polyester fibres for both carpet and apparel end uses were covered. After leaving Courtaulds Les Hollick worked for a brief period of time with Snia Viscosa, now Nylstar, in the spinning, draw twisting and beaming of nylon 6. Since leaving Snia, he has been employed with Unifi on the development of yarn products and machinery for nylon and polyester draw-texturing, air-jet textured yarns and two-for-one twisting.

D K Wilson

After graduating from UMIST in textile technology, Keith Wilson worked initially for ICI Fibres both in the UK and USA. During this time he was employed variously as a maintenance, project and services engineer in plants producing nylon, polyester and polypropylene filament yarns, and as an R & D Engineer engaged in the development of polyester tyrecord. A transition to yarn texturing with Viyella International was followed by a move to the textile machine industry, at first with with Platt Saco Lowell. He then moved to Switzerland and a position as Head of Sales with Heberlein. Here the Management Team, of which he was a member, took the decision to diversify the company's product range by adding air-jet texturing to the existing and well established false-twist texturing technology. In 1979 Keith Wilson returned to the UK to start his own business which was (and still is) engaged with the sale, service and development of key modules for the fibre and yarn processing industries. More recently test instruments for yarns; fibres and polymers were added to the product range.

1
The origins of texturing

1.1 Introduction

In the 1950s, a new branch of the textile industry – the texturing of continuous-filament yarns – became established as a commercial success, although, at that time, it was more common to talk of '*bulked yarns*', '*stretch yarns*' and '*crimped yarns*'.

The words '*textile*' and '*texture*' have the same root, and the development of the meaning of *texture* is interesting, as shown by the following extracts from *The Shorter Oxford English Dictionary*.

> Texture [noun] . . . 1. The process or art of weaving –1726. 2. The produce of the weaver's art; a woven fabric; a web. *arch*[aic], *1656*. **b** *transf* [erred] Any natural structure having an appearance or consistence as if woven; a tissue; a web e.g. of a spider 1578. 3. The character of a textile fabric, as to its being fine, close, coarse, ribbed, twilled, etc., resulting from the way in which it is woven 1685. 4. The constitution, structure, or substance of anything with regards to its constituents, formative elements, or physical character 1660. 5. *fig*[uratively] Of immaterial things; Constitution; nature or quality, as resulting from composition. Of the mind; Disposition as 'woven' of various qualities; temperament, character 1611. 6. In the fine arts; The representation of the structure and minute moulding of a surface (*esp*[ecially] of the skin), as dist[inct] from its colour 1859. . . . [verb] to construct by or as by weaving; to give a t[exture] to.

The '*minute moulding of a surface*' and the consequent verb *to* '*texture*' is the closest to the meaning of yarn texturing, as now applied to a '*useful art*' of the textile industry. There is also a semantic paradox: '*an absence of texture*' is itself '*a form of texture*'. A yarn composed of long, parallel filaments, which is lightly twisted or interlaced to give coherence, will form dense, smooth fabrics with a minimum of textural features. The first woven nylon was excellent for parachute fabrics, but unsatisfactory for shirts, though, for a short time, it was sold for this use.

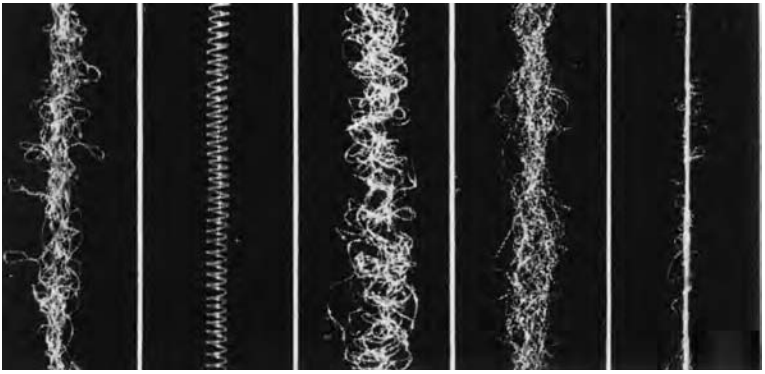
For the natural filament, silk, which is the most expensive and luxurious of the traditional fibres, the triangular shape of the filaments, the variability in cross-section and the physical properties of the material do give a subtle texture and an attractive feel and hand. When rayon and acetate yarns were produced in the early years of the 20th century, they were marketed as '*artificial silk*', by exploitation of the basic continuous-filament form, even though they lacked the special features of the natural fibre. The market was limited: another factor dictated the need for change, in order to create a larger market for manufactured fibres. Just as we would not want to live on a diet of caviar, so do we prefer the texture of fabrics made from cotton, wool, flax and other natural fibres for much apparel. Yarns spun from short, staple fibres have more softness, bulk, warmth and extensibility than fabrics from flat (i.e. untextured), continuous-filament yarns, and a different surface texture.

The first response was to cut filaments into short lengths and spin yarns on cotton or wool machinery. It also proved possible to cause the uncoagulated, liquid core of viscose rayon to burst out of the skin and give bicomponent fibres, which simulated the crimp of wool. Nevertheless, there was a challenge to inventors to find ways to avoid the route of cutting and disorganising the filaments and then reorganising the staple fibres in spun yarns. Could continuous-filament yarns be modified to compete with spun, staple-fibre yarns? A stimulus came from highly twisted, crepe yarns, whose torque forces caused woven fabrics to be crinkled and puckered. The invention of the false-twist process of twisting, setting and untwisting by Finlayson at *Celanese* led to textured acetate yarns for hand-knitting, and by *Heberlein* to the use of textured viscose rayon during the 1939–45 war. However, the set of cellulosic yarns is easily lost; the crimp can be pulled out. The market for these forms of textured rayon and acetate did not survive.

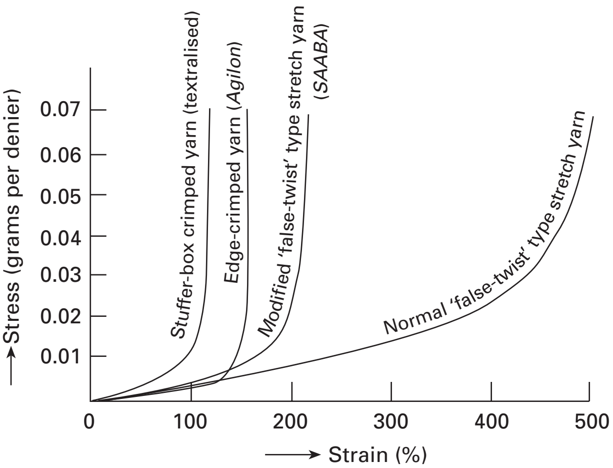
It was the '*permanent set*' of nylon that led to the commercial success of yarn texturing. At first, it was thought necessary to set nylon in steam, so the continuous false-twist process was not used. *Heberlein* developed a long, multistage process with setting in an autoclave. Despite the high cost, their *Helanca* yarns were a great success because the elastic extensibility up to around 400% made them excellent for stretch stockings, men's socks, swimwear and other form-fitting garments. The next invention was by Stoddart and Seem, who found that nylon could be set by continuous processing in a dry heater, provided the temperature was closely controlled. They modified uptwisters by adding heaters and twist-tubes, and licensed the production of *Fluflon* yarns, which took over the market and led on to the production of custom-built, false-twist texturing machines.

The next driving force for invention was the need to make yarns with high bulk and softness, but only a small degree of stretch. Such yarns were needed for firmer woven and knitted fabrics. One method was to stabilise a stretch yarn in a slightly contracted state: the bulk is there, but the high stretch is eliminated. In the late 1950s, a stabilised nylon yarn called *SAABA* ('soft as a baby's arse') was marketed, but did not last. The big surge came from set polyester yarns. *ICI* developed *Crimplene* yarns, which, until the fashion bubble burst, were extraordinarily successful in double-jersey knit fabrics. At first the setting was a separate process in an autoclave, but then double-heater machines, which had been invented by Stoddart and Seem in the 1950s, came into use. The market in the USA for textured polyester yarns increased from six million pounds in 1966 to 845 million pounds in 1973, and 17 companies were listed as making false-twist texturing machines. Since then, the industry has been rationalised. There are fewer yarn producers and two companies, *Barmag* and *Murata*, dominate the supply of machinery.

Twist-texturing was not the only method to be invented in the 1950s. A book based on a 1959 symposium (Wray, 1960) contained chapters on four different methods of making bulked yarns: *the* ***false-twist*** *method*; *a* ***stuffer-box*** *method* [*Ban-Lon*]; ***edge crimping*** [*Agilon*]; ***air-texturing*** [*Taslan*]. Pictures of these yarns are shown in Fig. 1.1 and their stretch characteristics are shown in Fig. 1.2. All of these methods seemed important at the time, but only the false-twist methods and, to a smaller extent, air-texturing, which depends on mechanical interlacing, are now important for the apparel market. Jet-screen texturing is used for coarse, BCF (bulked continuous-filament) carpet yarns. The remainder of this chapter will provide an overview of these three methods, with additional comment on their historical development. Some scientific approaches to fibre properties, process mechanics and yarn structural mechanics will be covered in Chapters 2 and 3, and then the three will be described in detail in Chapters


(a) (b) (c) (d) (e)

1.1 Bulked nylon filament yarns from the 1950s. (a) Stretch yarn by false-twist technique. (b) *Agilon* (edge-crimped) monofilament. (c) *Agilon* multifilament yarn. (d) *Ban-Lon* (stuffer-box) yarn. (e) *Taslan* (air-textured) yarn. Reproduced from Wray (1960).



1.2 Stretch characteristics of 1950s yarns, up to about 1% of fibre break load. *Taslan* (air-textured) yarns have no geometric stretch – only fibre extension, which is negligible at the stresses in this diagram. Set polyester yarns, developed in the 1960s, have stretch in the 10–20% range. Reproduced from Piller (1973). Courtesy of World Textiles Publications, Bradford.

4–7, with the common features of quality control and logistics in Chapters 8 and 9. A fuller list of texturing techniques, including later inventions, is given in Table 1.1. This book is concerned with the texturing of continuous-filament yarns as a separate part of textile processing. Other technologies with similar purposes, such as the production of crimpable, bicomponent yarns by fibre producers or the use of differential shrinkage to produce high-bulk, staple-fibre yarns, are not appropriate for detailed coverage. However, the last chapter, as well as describing the minor methods, will review the whole field, since old methods could be revived in new guises in the future and some recent academic research may eventually lead to industrial use.

1.2 Twist-texturing

1.2.1 The basic principles

The basis of twist-texturing is to twist a yarn as highly as possible, set it by heating and cooling, and then untwist it. This gives '*a twist-free bundle of twist-lively filaments*' (Arthur, 1960). In order to relieve the torque, the filaments snarl into 'pig-tails', which cause a large yarn contraction. The yarn can be stretched to over five times its fully contracted length before

Table 1.1 Texturing methods

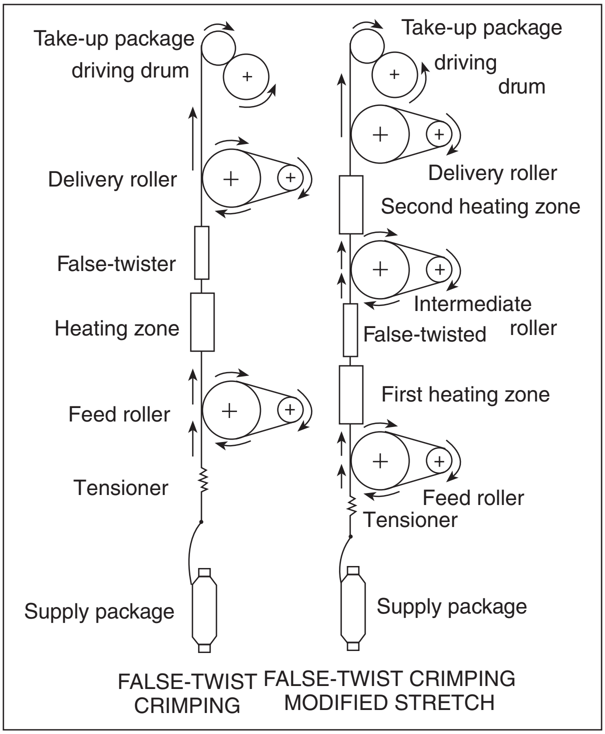
Method	Yarn character	Current status
Dependent on heat-setting		
Single-heater, false-twist	High-stretch	Major use of nylon
Modified false-twist	High bulk, medium stretch	Obsolete for nylon
Set, double-heater, false-twist	High-bulk, low stretch	Major use of polyester
Trapped twist texturing	Variant twist textured	Obsolete
Stuffer-box	High-bulk, medium stretch	Obsolete (*Ban-Lon*)
Edge-crimped	High-bulk, medium stretch	Obsolete (*Agilon*)
Knit-de-knit	Yarn crimp	Minor use
Hot-fluid jet (BCF)	High bulk, low stretch	Major use in carpet yarns
Impact texturing and moving cavity texturing	High bulk, low stretch	Variants of BCF, little used
Jet-tube (*Fibre M*)	High bulk, low-stretch	No longer made
Mechanical method		
Air-jet	Projecting loops	Significant production
Other methods		
Bicomponent filaments	Fibre crimp	Revived interest
Differential shrinkage	High-bulk, low-stretch	Only staple fibre yarns
Gear-crimping	Fibre crimp	Staple fibres, obsolete

the filaments are straightened out. The recovery power is strong. Fabrics can be highly stretched, but come back when released.

However, it is not only the fibre twist setting that is important. The filaments are in a helical configuration in the twisted yarn, and, after setting, they want to return to the crimped form. This dictates the initial form of fibre buckling. When a fully extended stretch yarn is allowed to contract by 10 to 20%, the filaments follow helical paths, which alternate from right-handed to left-handed. When a yarn is set in this form, it has high bulk and low stretch. The basic form of the machines for both stretch and set yarns was established in the 1950s, as shown by Fig. 1.3.

1.2.2 Reducing the steps

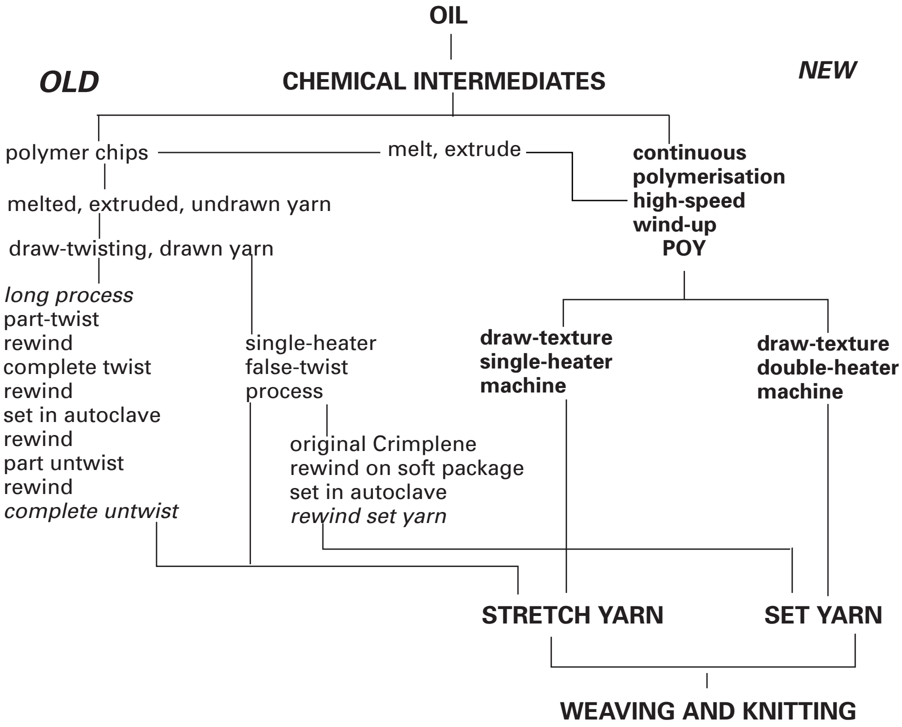
The production of synthetic fibres, such as nylon, polyester and polypropylene, involves extraction and preparation of chemical intermediates by oil-refining companies, followed by polymerisation and extrusion by



1.3 Layout of single-heater machine for stretch yarns and double-heater machines for set yarns. Reproduced from Wray (1960).

fibre producers. Polypropylene, which is easier to convert into fibres, is more commonly produced on a smaller scale by user-companies from polymer chips. '*Throwsters*', to use a term derived from the silk industry meaning to twist silk filaments into yarns, carry out the texturing operations and supply textured yarns to the weaving and knitting industries. Since the 1950s, as shown in Fig. 1.4, the number of steps necessary to make textured nylon and polyester yarns has been reduced from over ten to two.

Three developments made it possible to reduce fibre production from three steps to one. These are continuous polymerisation, high-speed wind-ups and interlacing by an air-jet, instead of a low level of twisting to give coherence to the yarns. In a coupled process, the draw rolls below the spinneret collect solid undrawn yarn at about 800 m/min and then the wind-up at about 3000 m/min draws the yarn. Much greater productivity is possible if coarser, undrawn yarn can be wound up and the drawing is combined with texturing. From the spinneret, the yarn goes directly to high-speed

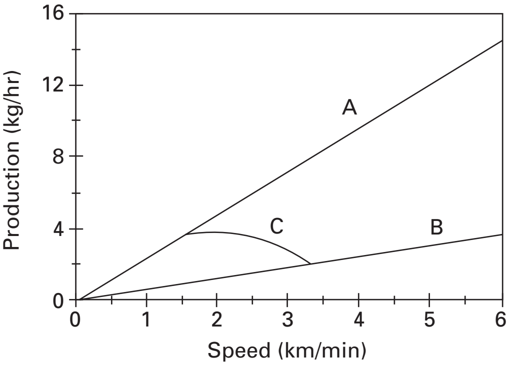


1.4 The contrast between the current two-step processing and the many steps of earlier operations.

rollers and wind-up. However, there is an economic and, for polyester, a technical problem.

As the withdrawal speed is increased, the time-scale for orientation induced by elongation and attenuation in the molten thread-line becomes less than the time-scale for disorientation by molecular relaxation. Consequently the yarn becomes partially oriented and its residual draw ratio is reduced. In order to give the required linear density (tex) in the final drawn yarn, the yarn that is wound up must be finer than would be required if the full draw ratio was to be imposed. Figure 1.5 is a schematic indication of the change in productivity as speed is increased. The optimum depends on how orientation increases with wind-up speed, but would be a wind-up of about 2000 m/min.

The technical objection to draw-texturing polyester yarns is that undrawn polyester is an unstable, amorphous material. Its properties change with time, which, in turn, affects the properties of the textured yarn, and eventually it becomes impossible to process. The only way to use undrawn



1.5 Schematic illustration of change in productivity with wind-up speed for textured yarn of 100 dtex. (A) Undrawn yarn with draw ratio of 4. (B) Drawn yarn with draw ratio of 1. (C) POY changing from draw ratio of 4 at 1.5 km/min to 1 at 3.5 km.

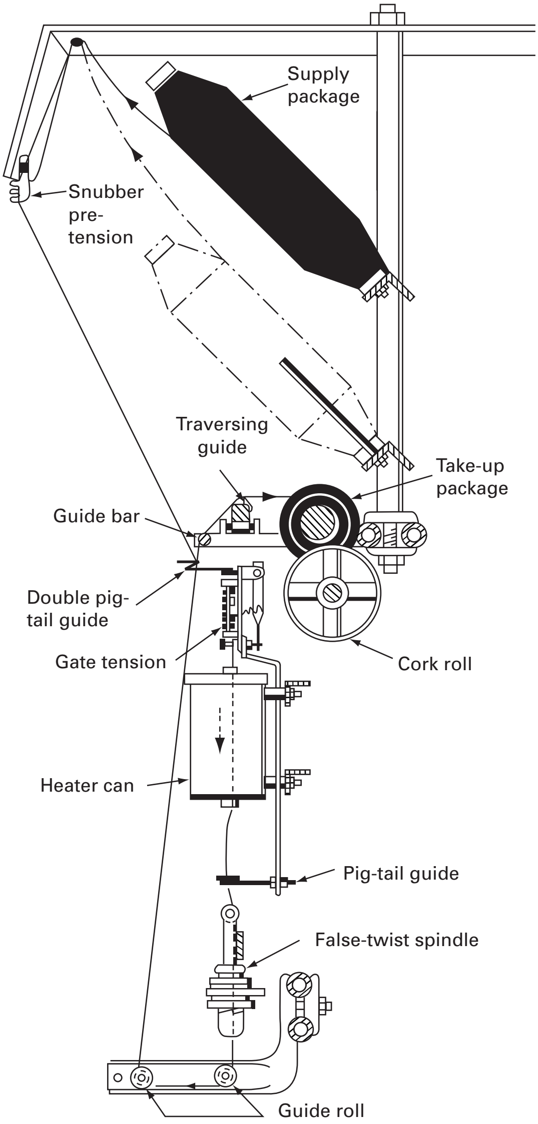
polyester as the supply yarn is to process at a controlled short time after fibre production. However, the partial orientation induced by withdrawal above a critical speed at about 3000 m/min produces an incipient crystallisation, which stabilises the yarn. Such partially oriented yarn (POY), with a residual draw ratio of around 1.5, is what is supplied for draw-texturing.

The long *Helanca* process, which in 1963 was still described as 'conventional' (Chemstrand, 1963), involved three basic steps, twist–set–untwist, but many more actual steps because of the need for rewinding onto suitable packages and because all the twist could not be inserted or removed in single operations. The major advance was the change to the continuous false-twist process in the late 1950s. A similar advance occurred a decade later, when the batch process for producing *Crimplene*, the set-textured polyester yarn, was replaced by continuous double-heater machines.

Until the 1970s, when a fully drawn yarn was supplied to a single-heater texturing machine, it was usually run at a small overfeed. The yarn contraction generated the necessary tension. With undrawn yarn or POY, two methods of draw-texturing were tried. In sequential draw-texturing, another set of rolls is added at the entry to the machine. The next set of rolls runs at a higher speed, so that a drawn yarn is overfed into the false-twist zone. In simultaneous draw-texturing, which proved to be the better method, the draw is accomplished by feeding in POY through the entry rolls and running the output rolls from the false-twist zone at a higher speed, in order to draw the yarn at the same time as it is being twisted. This has consequences for the yarn form, which are described in Chapter 2.

1.2.3 Increasing the speed

The *Fluflon* machine, shown in Fig. 1.6, which was the first to be used to false-twist texture nylon, has a number of interesting features, which differ from practice today. These are worth noting as examples of the technical options and as the starting point for a period of rapid technical advance.



1.6 The *Fluflon* adaptation: the first machine for false-twist texturing of nylon. Reproduced from Chemstrand (1963).

The machine was a modification of existing uptwisters. Supply packages of fully drawn nylon yarn, with about 1 turn/cm of twist, were about 0.5 kg. Tension in the texturing zone was controlled by a pig-tail tensioner, which consisted of interleaved teeth under spring control: it was thus a ***constant-tension*** and not a ***constant-extension*** process (strictly contraction, if there is overfeed). The heaters, which were about 15 cm long, were ceramic tubes wound with electric heater coils and contained in a cocoa-tin filled with insulation: it was thus a ***non-contact*** and not a ***contact*** *heater*. The false-twist spindle consisted of a pulley that was mounted on the end of a tube. What would normally be the rotation drive for the take-up package of the uptwister drove the rotation of the tube. The rationale for this design was that the rotation of the pulley about its bearing allowed forward motion of the yarn to be unimpeded, while the grip of the yarn on the pulley meant that the yarn on the heater was twisted by the rotation of the tube. The whole spindle was comparatively massive: the tube was over 5 cm long and about 1 cm in diameter. At about 30 000 rpm, the production speed was about 10 m/min. Nevertheless, as shown by Table 1.2, this was a major increase in productivity compared to the *Helanca* long process.

By 1960, machines specifically designed for false-twist texturing were on the market. Contact heaters became the norm and their lengths increased by over ten times to around 2 m. The cooling zone also had to be increased in length for higher speeds. For spindles, it was soon realised that a pulley was unnecessary. The yarn could be dragged forward over a rotating pin:

Table 1.2 Production speeds for false-twist texturing. All figures approximate; partly based on Wray (1960) and Chemstrand (1963) for 77 tex (70 denier) nylon

Date	Technique	Spindle speed (rpm)	Linear speed (m/min)	Production (kg per spindle per week) (168 hr)
	Twist–set–untwist			
1950	*Helanca* long process			effectively 0.1
	False-twist process			
1955	*Fluflon*	30 000	10	0.8
1970	Magnetic pin	300 000	100	8
1990	Friction twist	3 000 000	1000	80
	Others			
1960	*Agilon* (edge-crimp)		60	5
1960	*Ban-Lon* (stuffer-box)		250	20
1960	*Taslan* (air-jet)		100	8
1990	Air-jet*		500	80 (two-ply)

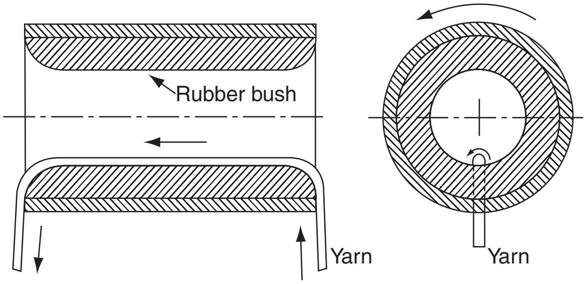
* Normally used on heavier yarns.

the normal force exerted on the yarn by the pin generated the twisting torque, but the axial friction increased yarn tension. The spindles could be reduced tenfold in size to about 2 mm by 1 cm and were held by magnetic action against rotating rolls. Spindle speeds increased by an order of magnitude to around 300 000 rpm.

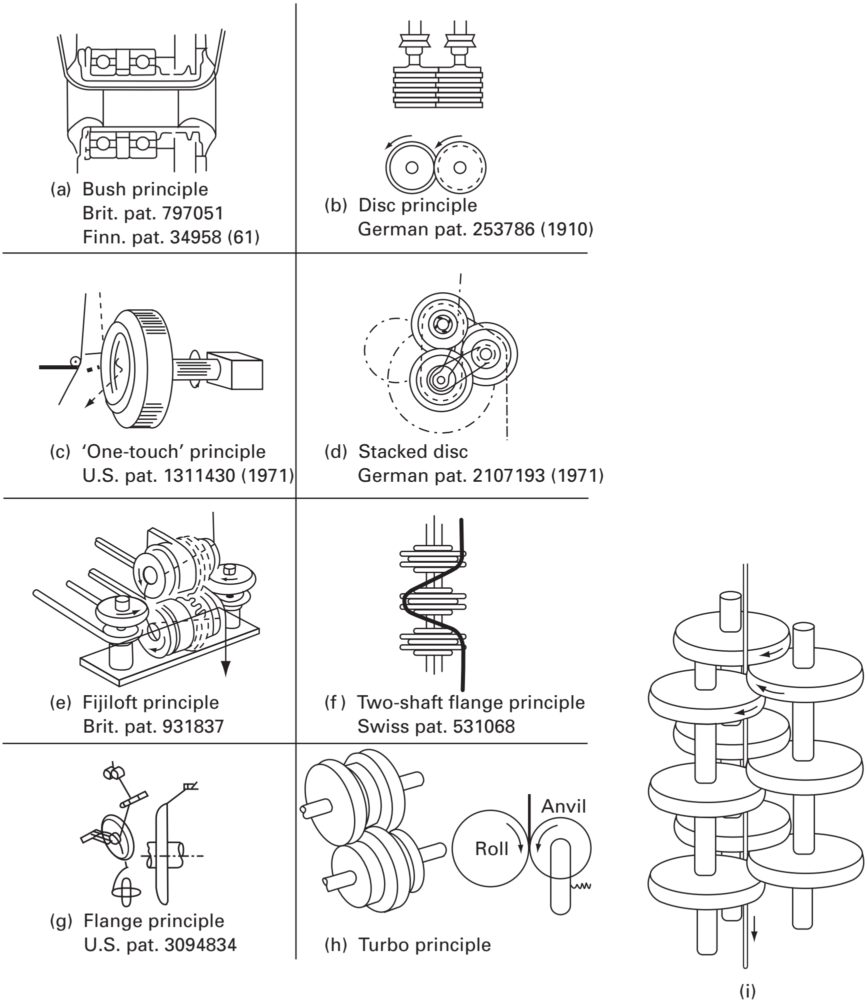
In the mid-1950s, at the time when commercial false-twist texturing was just starting with *Fluflon* machines, friction twisting was invented by Arthur and Weller at *British Nylon Spinners* (which later became part of *ICI Fibres*, and, in turn, of *DuPont*). They realised that there was a terrific gearing advantage, if, instead of using a rotating pulley or pin, the yarn was directly rotated by contact with a moving surface. As will be discussed in Chapter 2, there are complications in the mechanics, but the order of magnitude of the advance is given by the equation:

$$\text{yarn rpm} = \text{spindle rpm} \times (\text{spindle diameter}/\text{yarn diameter}) \quad [1.1]$$

The *British Nylon Spinners (BNS)* friction twister was a hollow tube lined with rubber, through which the yarn passed as shown in Fig. 1.7. About ten machines were produced and used commercially, but then became obsolete. The industry used magnetic pin-spindles, and a decade passed before *Spinner Osakeyhtiö* from Finland introduced a new friction-twisting machine and set the scene for modern false-twist texturing. Many companies experimented with designs for friction-twisting heads, some internal and others external, as shown in Fig. 1.8. The final solution, which is the current design, was a hybrid. The yarn is driven against the outer edge of discs, but is constrained in a three-dimensional, zig-zag path within three sets of overlapping discs. Another method of twisting was invented by *Murata* from Japan and is used on their machines. The yarn is held between two belts moving in opposite directions, which both forward and twist the yarn, as shown in Fig. 1.9. Twisting by an air-jet was also tried, but the machine did not achieve commercial success.



1.7 Friction twisting as invented by Arthur and Weller. Reproduced from Wray (1960).



(a) Bush principle
Brit. pat. 797051
Finn. pat. 34958 (61)

(b) Disc principle
German pat. 253786 (1910)

(c) 'One-touch' principle
U.S. pat. 1311430 (1971)

(d) Stacked disc
German pat. 2107193 (1971)

(e) Fijiloft principle
Brit. pat. 931837

(f) Two-shaft flange principle
Swiss pat. 531068

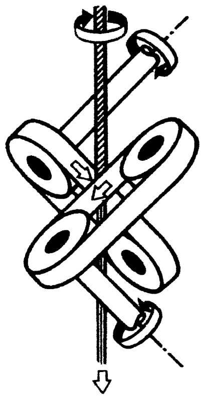
(g) Flange principle
U.S. pat. 3094834

(h) Turbo principle

(i)

1.8 (a)–(h) Various forms of friction twisting. (i) Another view of (d), stacked discs, which became the common form. Reproduced from Goswami *et al* (1977), *Textile yarns: technology, structure and applications*. Reprinted by permission Wiley-Interscience, New York, USA.

Table 1.2 shows the increases in speeds and productivity which came between 1950 and 1990 as a result of these advances. Coupled with the integration of processes through draw-texturing, this shows how a new textile operation, which started with crude adaptations of old machines, can be transformed by the talent of inventors and the skill of machinery makers. When synthetic fibre production started, the maximum available wind-up



1.9 Belt twister. Reproduced from *Murata* technical literature.

speed was about 1000 m/min; now it is around 10 000 m/min. There is no mechanical reason why a false-twist texturing machine should not operate at such a speed, although unless improvements were made to reduce the length of heating and cooling zones, the machines would be too high to fit in most factories. The limitation is the interaction between the yarn and the machine. At around 1000 m/min surging in yarn tension starts and the yarn ceases to be properly twisted.

1.3 Jet-screen texturing: BCF yarns

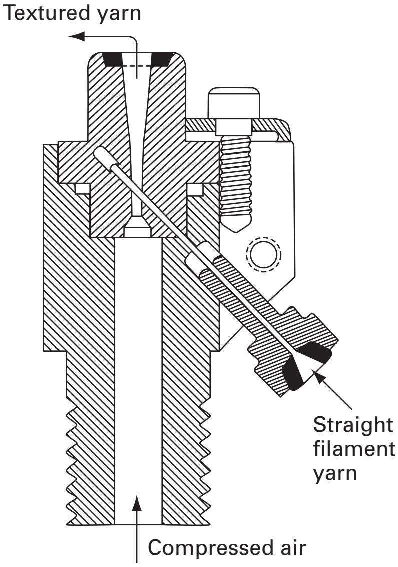
False-twist texturing depends on setting fibres in one geometry and then changing to another, which generates stress that can be relieved by buckling. Another principle is to set fibres in the required crimped form. This was the basis for stuffer-box and some other methods listed in Table 1.1, but, except for some limited use of knit-de-knit, these methods are no longer used for apparel textiles. Another approach is adopted to produce BCF yarns, which are used as coarse carpet and upholstery yarns. Its origins lie in *DuPont* research on jets. Turbulent hot fluid produces an asymmetric shrinkage, which causes filaments to buckle.

False-twist texturing is extensively described in the public domain, because the advances made by fibre producers and machinery makers had to be 'sold' to the many throwster companies, and this spawned considerable academic research. In contrast to this, BCF production methods are less well documented. Fibre companies produce and sell the yarn. They developed their own processes and machines, and had no incentive, except for patent protection, to disclose the technology. Only the yarn properties and performance are important in the market. The situation is changing to some extent as machinery makers have moved into the supply of fibre production equipment, but is still subject to proprietary secrecy. In the production of BCF yarn, the yarn is fed through a hot-fluid jet and then collected on a drum round which the yarn passes, like a caterpillar, as it cools to stabilise the set, before being taken to the wind-up.

1.4 Air-jet texturing

The third significant texturing process in current use, air-jet texturing, operates by mechanical interlocking and not by heat-setting. It can therefore be applied to any continuous-filament yarn, including rayon, glass and the new high-performance fibres, as well as nylon, polyester and polypropylene. The method was invented by *DuPont* in the 1950s and an early jet design is shown in Fig. 1.10. The basis of the method is that yarn is overfed into the compressed air jet-stream, so that loops are forced out of the yarn. The loops need to be locked into the yarn, and this can be achieved by twisting the yarn at the take-up. The alternative, which is the current practice, is to design the jets and the yarn path so that there is sufficient entanglement in the core of the yarn to stabilise the loops.

Over the years, a variety of jet designs have been produced. The major supplier to the industry is *Heberlein*. In addition to air-jet textured yarns as such, the addition of an air-jet to false-twist texturing enables yarns with a different character to be produced.



1.10 An early *Taslan* jet from DuPont. Reproduced from Wray (1960).

1.5 The future

The methods described in this chapter, single- and double-heater false-twist texturing, jet-screen BCF and air-jet texturing, are now mature technologies. Production is economical and a variety of yarns can be produced to meet the needs of apparel, household and technical textiles. Quality control is highly developed and the logistics is efficient. After a commentary on scientific principles, these are the subjects of the main chapters of this book.

What changes can be expected in future? There is always the opportunity to produce yarns with a different character to provide a new fashion market. This might be done by new variants of obsolescent processes or by new inventions. The other major challenge is to increase speeds beyond the false-twist texturing limit of about 1000 m/min. Linked to this is the possibility of reducing two steps to one by adding a texturing operation to fibre production. Economically, a texturing stage at the end of fibre production would need to lead to high-speed wind-ups at around 5000 m/min or more. It must also be remembered that the more stages there are in a process, the greater the chance of breakdown. The efficiency of each stage must be well matched.

The *FibreM* process, which is a jet-to-stuffer-box technique invented by the *Heathcoat* company, was used to a limited extent in the 1970s. Although commercially operated at around 1000 m/min, it was demonstrated at ITMA in 1975 with a high-speed wind-up running at 4000 m/min. The yarn character differed from conventional, set-textured polyester yarns. The market did not develop and manufacture by *Heathcoat* ceased, although the principles may have been adopted in some producer-texturing by *ICI* and formed the basis of a machine produced by the *Mackie* company for texturing coarse, polypropylene yarns. An important aspect of jet-screen and *FibreM* texturing is that the setting of the yarn by heating and cooling occurs in a large reservoir of piled-up yarn, and not, as in false-twist texturing, in the extended length of single yarns. The yarn takes time to pass through the reservoir and this means that the process can be run at high speeds without an excessive length for the setting zones.

It remains to be seen whether the reservoir principle will be adopted in some new form. In the meantime, some lessons from the steam-setting technology used in the *FibreM* process have been applied to false-twist texturing in research by Foster at *UMIST*. Together with more rapid cooling, this reduces the length of the texturing zone and enables speed to be increased without surging. This and other ideas suggested here are described in the last chapter of this book.

2

Scientific and engineering principles in twist-texturing

2.1 Introduction

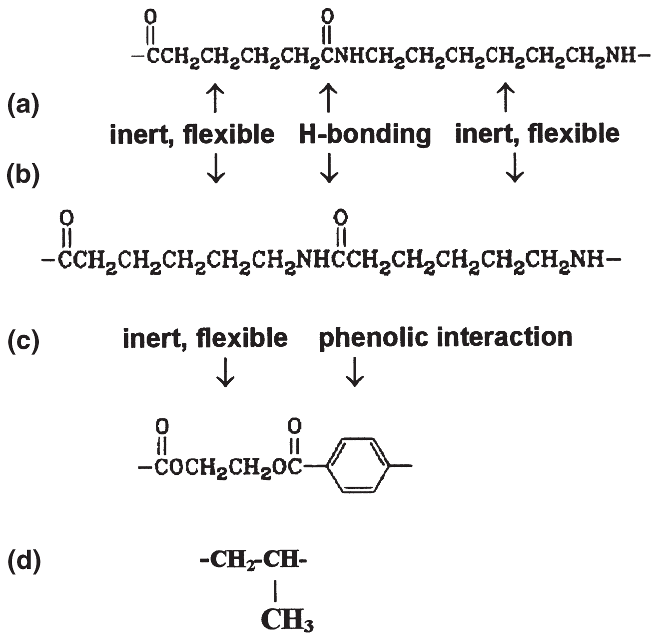
Like most developments on the mechanical side of the textile industry, the inventions and developments in yarn texturing have not come as a rational sequence from basic science, through engineering calculations to practical implementation. Empirical advance based on intuitive understanding has been the norm. This is not to say that the academic research has been wasted. As the science of any aspect of the subject is clarified, this feeds into the qualitative understanding of those concerned with practical operations. The mathematics may be ignored, but the ideas enter the technical consciousness.

Coverage on texturing is patchy and this is shown by the gaps in this chapter. Some topics have been subject to detailed experiment and analysis, but others have been neglected – or been too difficult to deal with. This chapter aims to provide a background of fundamental studies, where these help in understanding the more practical chapters that follow. Since it is rarely possible to make explicit design calculations, the emphasis will be on principles, and not on mathematical detail, which can be found in the original publications.

2.2 Fibre science: Heat-setting

2.2.1 Fibre structure

The action of air-jet texturing does not change the internal structure of fibres, so it is not necessary to discuss the structures of the whole range of fibres which may be air-jet textured. All the other methods depend on heat-setting, which involves effects at the molecular and fine structure level. Figure 2.1 shows the chemical formulae of four fibre types. Nylon 6 and nylon 66 differ only in a slight rearrangement of the order of chemical groups. This has two consequences: the repeat in nylon 6 is half that in nylon

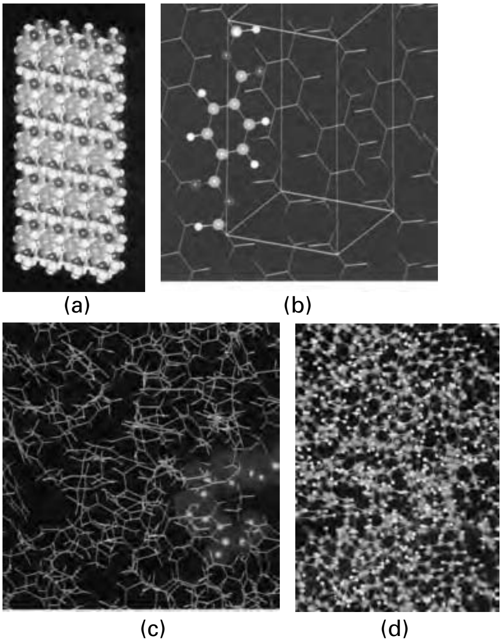


2.1 Features of the chemical formulae of (a) polyamide – nylon 66, (b) polyamide – nylon 6, two repeats, (c) polyester – polyethylene terephthalate (PET), (d) polypropylene.

66, and the nylon 6 molecule is directional. It is probably the latter, which affects the way in which molecules can pack into a crystal lattice, that causes the melting point of nylon 6 to be about 50°C less than that of nylon 66. In order to avoid unnecessary duplication, the word '*nylon*' in what follows covers both 6 and 66. Most of the results quoted will be for nylon 66, so that the above difference must be kept in mind in application to nylon 6. The polyester shown is polyethylene terephthalate (PET or 2GT), which is the common type for fibres. Other nylons, such as nylon 4, and polyesters, such as 3GT (polypropylene terephthalate) and PEN (polyethylene naphthalate), which have appeared on the market, will not be explicitly discussed, but have only detailed differences in structure and properties. The third type is polypropylene.

Nylon and polyester molecules have features in common. Both contain sequences of about six aliphatic groups, which link to other molecules only through weak van der Waals forces. In nylon, these are ($—CH_2—$) groups; in PET they are ($—CO—O—CH_2—CH_2—O—CO—$). These sequences alternate with ($—CO—NH—$) groups in nylon, which form stronger hydrogen bonds with neighbouring molecules, and with benzene rings in PET, which both stiffen the chain and have a strong electronic interaction with one another. It is this alternation of flexible, inert groups and interacting groups that makes these fibres particularly suitable in textiles. The long repeat gives a strong tendency to form perfect crystalline register, since a distribution of small, local defects, such as occur with the simple (—CH_2—) repeat of polyethylene, is not a possible form. Polypropylene contains only inert hydrocarbon groups and so is more like polyethylene. The molecules take up a regular three-fold helix in the crystal lattice and irregular variants of this form in amorphous regions.

Drawn nylon and polyester fibres are about 50% crystalline, in the sense that their density is half-way between that of a perfect crystal (Fig. 2.2(a,b)) and that of an amorphous network (Fig. 2.2(c,d)). This is confirmed by other techniques. However, such partial order covers many possible fine structures, and current representations are certainly over-simplified and may miss significant features. The simplest view is a composite of crystallites in an amorphous matrix, but this leaves open many possibilities in size, shape and distribution of crystallites and in linkages between them. In order to get up to 50% crystallinity, it is necessary to pack crystallites in a regular pattern. An example of a '*common working model*', which appears in similar


(a) (b)

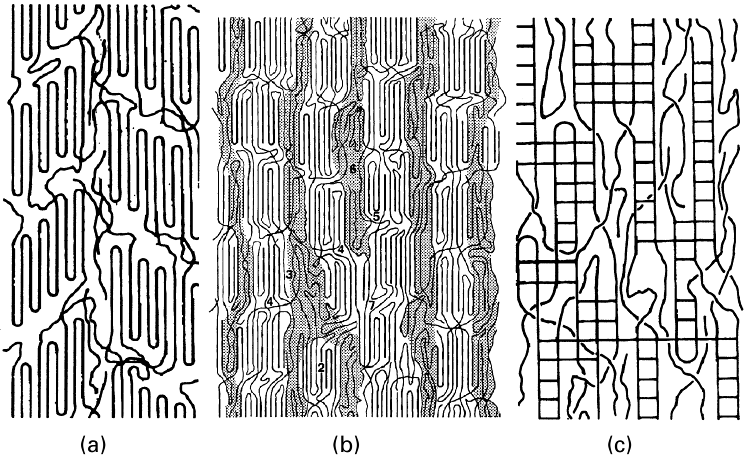
(c) (d)

2.2 Computer-generated models of molecular packing in PET. (a),(b) Crystalline. (c),(d) Amorphous. Produced for *Polyester: 50 years of achievement*, Brunnschweiler and Hearle (1993) by Dr Andrew Tiller of BIOSYM Technologies Inc.

forms in drawings by different people, is shown in Fig. 2.3(a). The crystallites are brick-shaped and are packed in pseudo-fibrils. At the ends of the crystallites, some chains turn back in folds and others fringe off to form tie-molecules, which lead through the amorphous regions to neighbouring crystallites. Some distinction may be made between amorphous regions between crystallites within a fibril and amorphous regions between fibrils. Another picture, which is based on X-ray diffraction studies and aims to be more realistic, is shown in Fig. 2.3(b). An alternative view is a more uniform structure, with segments locally in crystallographic register. A schematic illustration of a possible form is shown in Fig. 2.3(c).

Fibres are oriented preferentially along their axial direction, to an extent that depends on the severity of the drawing process. The evidence is that crystallite orientation tends to be high, though this may be in localised zones, which vary slightly in off-axis orientation. Orientation of segments in amorphous regions is weaker.

It is necessary to consider how this picture, which is based on studies of axially drawn fibres, changes for false-twist texturing. If fully drawn yarns are used as the feedstock, the fine structure will have been stabilised and only minor changes due to heat-setting will occur. The situation is different for draw-texturing of undrawn or partially oriented yarns. Undrawn nylon is semi-crystalline, but the draw, which is combined with twisting, will lead to major disruption and reformation of the fine structure. For polyester, the effects are even stronger, because undrawn polyester is amorphous;



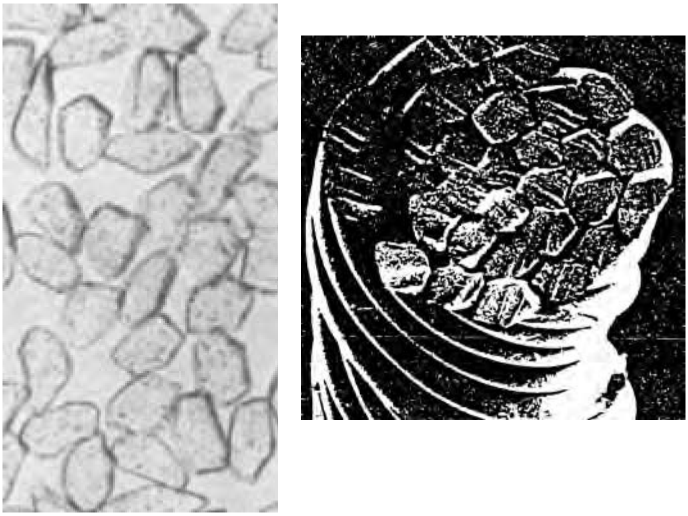
2.3 Fine structure of nylon and polyester fibres. (a) A view of the common working model by Hearle and Greer (1970b), drawn in order to show angled ends, related to the crystal lattice, as a cause of a feature of the small-angle, X-ray diffraction pattern of nylon 66. (b) A view by Murthy *et al* (1990), based on X-ray diffraction studies of nylon 6. (c) A more uniform view of the structure, Hearle (1978).

crystallisation occurs during drawing. Polyester POY, produced at around at 3000 m/min, has an incipient crystallinity, which stabilises the structure to a degree that eliminates changes between production and texturing, but the full development of crystallisation occurs during drawing. Above 3500 m/min, the density begins to rise rapidly, and, at 6000 m/min, is comparable to a drawn yarn. The consequence of the combination of drawing and twisting in simultaneous draw-texturing is that the oriented fine structures, which are imperfectly represented in Fig. 2.3, must be regarded as following helical lines within the fibres, at helical angles increasing from zero along the axis to a maximum at the fibre surface. The fine structure will also fit into the bent form of the helical paths of the fibres themselves within the yarn.

A larger-scale consequence of the coincidence of drawing and twisting is that, during the process of major deformation, the fibres are subject to the large transverse forces in twisted yarns under tension. This distorts the cross-sectional shape of the fibres, so that they pack into an almost solid assembly, as shown in Fig. 2.4. At the centre of the yarn, the form approximates to a regular hexagon, but towards the outside the shape differs.

2.2.2 Thermal transitions

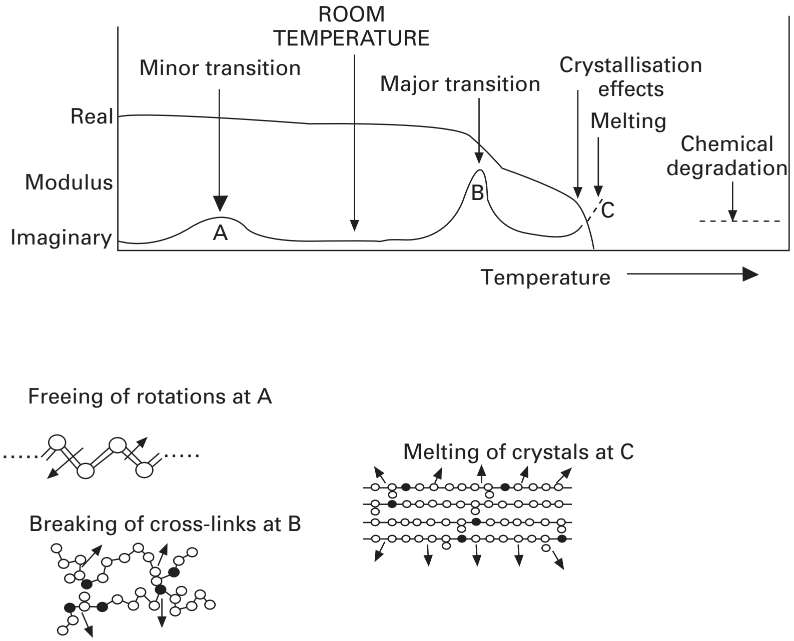
Nylon 66 and polyester (PET) fibres have five important regions of thermal transitions: at around –100°C, 100°C, 200°C, 260°C and 300°C. The


(a) (b)

2.4 Cross-sections of filaments from simultaneous draw-textured polyester. (a) From Monsanto (1974). (b) SEM picture.

temperatures are approximate, because the transitions are broad and the position of the peak of the transition depends on the rate of change and other factors. Four of these changes are shown in the schematic diagram, Fig. 2.5. The two lower temperature transitions are best studied by dynamic mechanical tests, which are explained below and give parameters listed in Table 2.1. The lowest would only have direct relevance to textured yarns if these were to be used at very low temperatures, for example in space. The one at around 100°C has considerable practical importance in the behaviour of yarns after texturing. Melting at around 260°C (lower in nylon 6), is an obvious change from solid to liquid, which can be studied in more detail by thermal analysis. The highest temperature transition is chemical degradation, which limits the time at high temperature in melt spinning and, unless precautions are taken, can cause faults in yarn due to the formation of cross-linked gel particles.

The effects at around 200°C (lower for nylon 6), which will be covered in Section 2.5, are critical factors in the production of textured yarns by heat-setting, but, surprisingly, have largely been ignored in scientific studies of the molecular level. Dynamic mechanical analysis results commonly stop at around 180°C, before the effects are apparent. We know more about the



2.5 Schematic view of thermal transitions in an 'ideal fibre'. From Hearle (1967).

Table 2.1 Characterisation of dynamic mechanical properties at frequency $\omega = 2\pi f$, with f in Hz

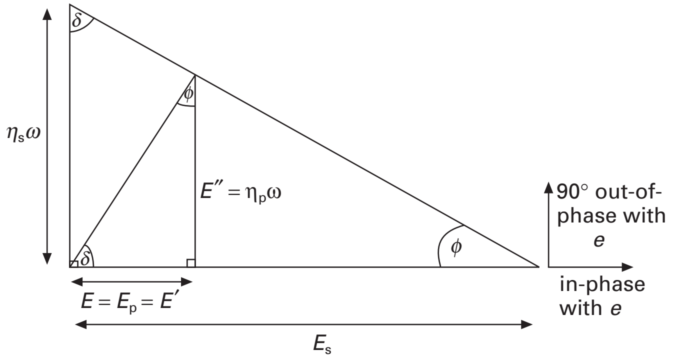
Representation	Elastic part (in-phase)	Viscous part (out-of-phase)
Simple related forms		
Spring and dashpot in parallel	Spring constant = E_p	Viscosity = η_p
Modulus and loss factor	$E = E_p$ = in-phase stress amplitude ÷ strain amplitude	$\tan\delta = \eta_p\omega/E_p$
Complex number	Real part = $E' = E = E_p$	Imaginary part = $E'' = \eta_p\omega$
Energy loss per cycle at strain amplitude e_m		$\frac{1}{2}(2\pi)\eta_p\omega e_m^2 = \pi E e_m^2 \tan\delta$
Creep time constant		η_p/E_p
Other forms		
Spring and dashpot in series	Spring constant = E_s $= E_p \sec^2\delta$	$\eta_s = E_s/\omega\tan\delta$
Stress relaxation time constant		η_s/E_s

phenomena from responses in industrial operations than from fundamental research, which accounts for the fact that they were not included when Fig. 2.5 was drawn.

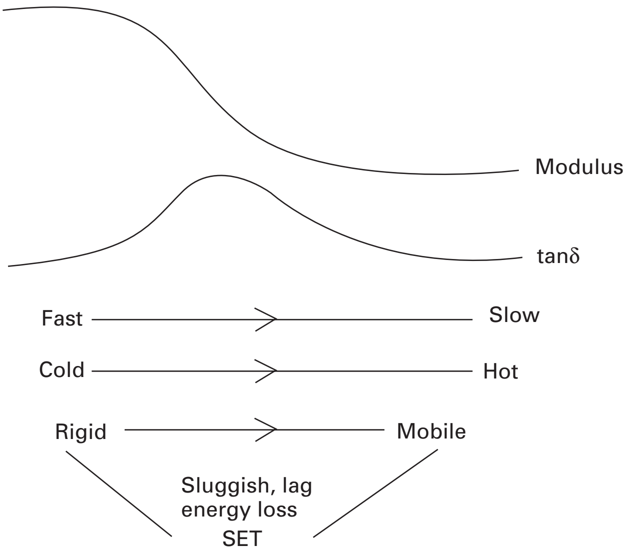
2.2.3 Dynamic mechanical analysis: temporary set

Thermo-mechanical analysis (TMA) consists of applying an oscillating deformation (normalised as strain), in extension, bending or twisting, and measuring the oscillations in the resulting force (normalised as stress). If the material is perfectly elastic, stress and strain will be in phase; their ratio will be the elastic modulus; and there will be no energy dissipation – energy stored on extension will be released on contraction. If the material is a perfect, viscous liquid, stress and strain will be 90° out-of-phase and the work done by the applied force will be dissipated as heat in both extension and contraction. Polymers are visco-elastic and so lie between these two extremes. The elastic part is given by the ratio of the in-phase components of stress and strain; the viscous part by the out-of-phase components. A variety of ways of reporting these properties are used, as summarised in Table 2.1, with the relations between the various quantities shown in Fig. 2.6.

A thermo-mechanical transition in the solid state, often referred to as a '*second-order transition*' in contrast to a '*first-order transition*' such as



2.6 Summary vector diagram showing relations between quantities used to express dynamic mechanical properties. From Morton and Hearle (1993).

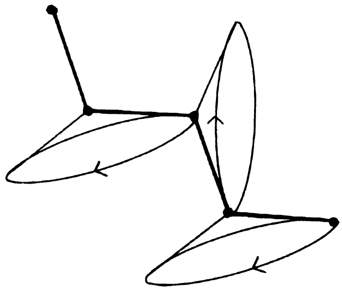


2.7 Features of a second-order transition.

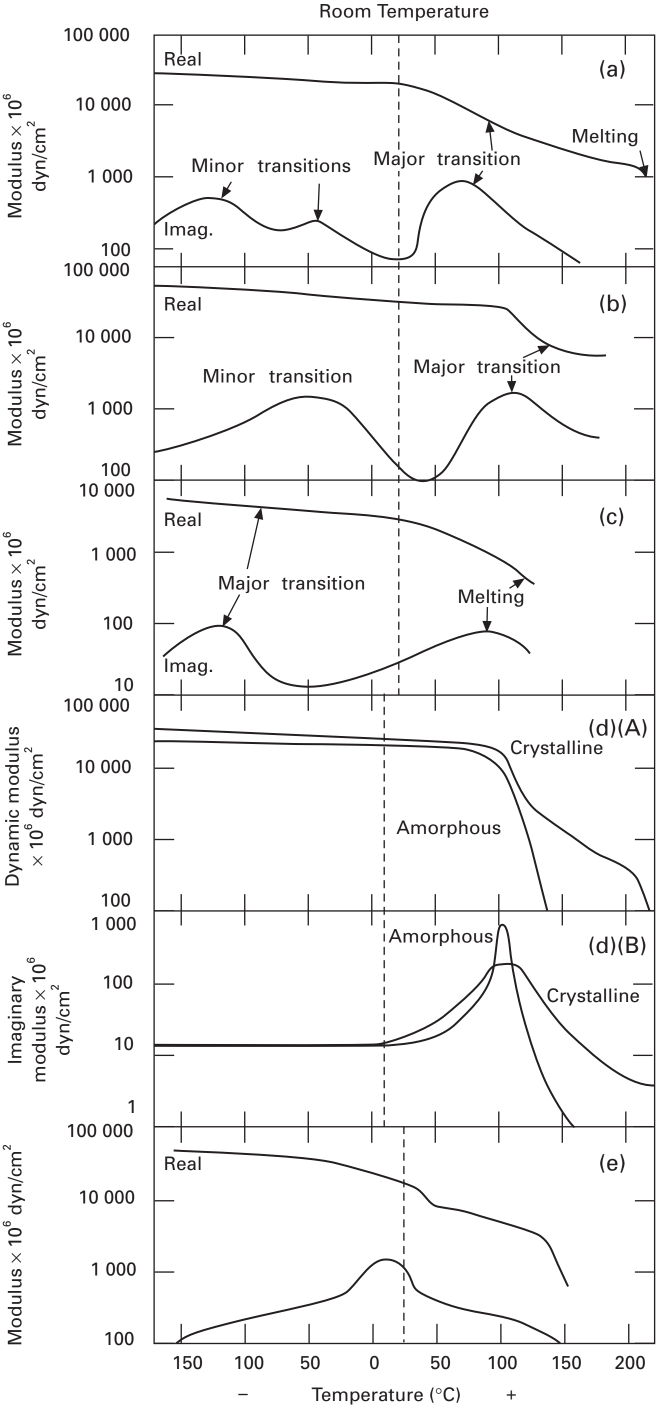
melting, is due to some element within the structure changing from a rigid form to a mobile state. The features of such a transition are shown in Fig. 2.7. The elastic modulus drops because the material is more easily deformed. The viscous part peaks because there is a sluggish response in going through the transition. This is what is shown by the experimental results, but the practical effect for the performance of textured yarns is that the material will be set in going down in temperature through the transition. The presence of a peak in tan δ or E'' is indicative of a temperature range in which setting will occur. If there is no change in structure, the effect is reversible, and so this is a temporary set, which can be released by heating above the transition temperature in a stress-free state – though, in practice, this may be prevented by interference between neighbouring fibres.

In simple polymers, there is one major transition, the '*glass transition*', from the rigid, glassy state to the flexible, rubbery state. In natural or synthetic rubbers, this can be demonstrated by cooling the material in liquid air; in glassy plastics, such as polystyrene or PVC, it can be shown by heating. In either case cooling will set a bent piece of material in a rigid, deformed state, which will be lost on reheating. If there is cross-linking or if the molecules are entangled and deformation is rapid, the material will show rubber elasticity above the transition temperature, but if the molecules can move as a whole, viscous flow will occur over longer periods of time. The simplest polymers consist of a chain of carbon atoms, which are linked together by tetrahedral bonds, as shown in Fig. 2.8. Above the glass transition temperature, there is freedom of rotation around the bonds, so that the chain acts like a sequence of freely pin-jointed rods, as indicated in Fig. 2.5(a). Below the transition, the thermal vibrations are too weak to overcome the energy barriers to rotation, which will be higher when there are side-groups such as benzene rings, and so the chain acts as a rigid, zig-zag rod. The consequences are clearly shown for amorphous polystyrene in Fig. 2.9(d). Crystallisation complicates the picture, but for polyethylene (Fig. 2.9(c)), which has no large side-groups, the glass transition is at −120°C.

For nylon and polyester, the transition at around 100°C is often referred to as the glass transition, but really the glass-to-rubber transition is split into two parts. For nylon (Fig. 2.9(a)) with its (—CH_2—) sequences, the same transition occurs as in polyethylene at low temperature, though it splits into two because of the presence of other groups in the chain. In polyester (Fig. 2.9(b)) the comparable sequences cause a similar low-temperature transition. The importance of these transitions is that they give some limited



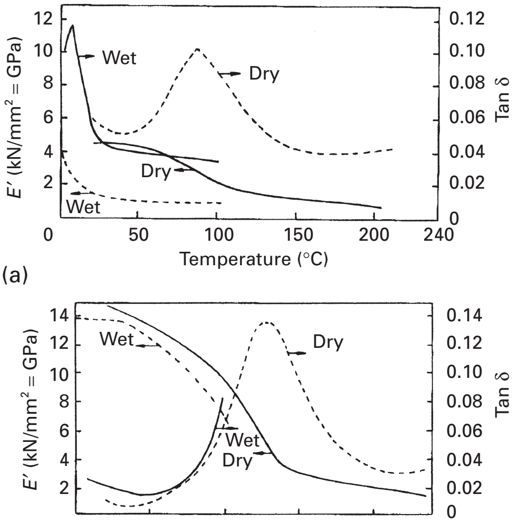
2.8 Rotation at tetrahedral carbon–carbon bonds.



2.9 Dynamic mechanical properties of polymers. (a) Nylon 6. (b) Polyester (PET). (c) Polyethylene. (d) Polystyrene. (e) Polypropylene. From Hearle and Miles (1971), after Takayanagi (1963).

freedom to the molecular structure, but which, at room temperature, is still constrained by the hydrogen bonding in nylon and the phenolic interactions in polyester. The material is neither too hard like polystyrene, nor too soft like polyethylene. The extensional properties are right for textile use. Polypropylene (Fig. 2.9(e)) has a single transition which spans room temperature. This gives a suitable intermediate stiffness, but at the expense of some sluggishness in response and poor recovery.

The transition above room temperature is due to the onset of mobility at the cross-links, as indicated in Fig. 2.5B. In nylon, below the transition, all the hydrogen bonds are permanently in place, causing the amorphous material to act like a highly cross-linked rubber with a maximum extension of around 50%. Above the transition, the hydrogen bonds are in a state of dynamic equilibrium, as they are in liquid water. At any instant, most of them are in place, but they are continually breaking and reforming. A similar effect occurs due to electronic interactions between the benzene rings in polyester. More details of the transitions are shown in Fig. 2.10 (nylon 66 behaves similarly to nylon 6). The transition in dry nylon is a little below 100°C, whereas in polyester it is above 100°C. A more important effect is that, due to the absorption of water, the transition temperature drops to near 0°C when nylon is wet. Consequently there is a temporary set when nylon is dried. Temporary set can be avoided in wash-and-dry cycles of polyester, but not for nylon.

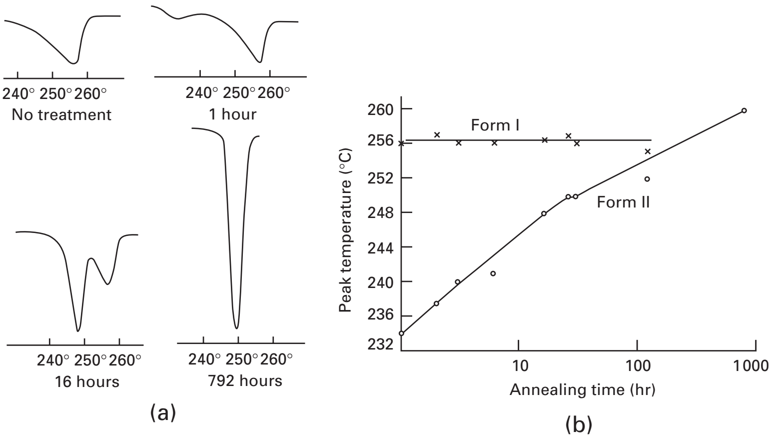


2.10 Dynamic modulus *E′* and loss factor tan δ, wet and dry, for (a) nylon 6 and (b) polyester (PET), from Van der Meer (1970).

2.2.4 Crystallisation, annealing and melting

The uncertainty, which results from different measurement techniques, in the temperatures at which changes take place is shown by the fact that different books quote temperatures between 250 and 265°C for the melting points of nylon 66 and polyester (PET) fibres and higher still for perfect crystals. At about 240°C, the fibres stick together. This sets a maximum for the temperature at which texturing can be carried out; at higher temperatures, the result is a solid rod (Hearle *et al*, 1961). Although melting is not directly involved in texturing, the annealing effects associated with crystallisation are relevant to heat-setting. The phenomena can be studied by measuring the input of latent heat needed for melting (the endotherm) or its evolution (the exotherm) on crystallisation. There are two techniques, differential scanning calorimetry (DSC) and differential thermal analysis (DTA): the former, which is now preferred, increases or decreases temperature at a constant rate and measures the difference in the necessary heat input or output in the sample and a control; the latter measures temperature difference at constant heat input.

An important set of studies of multiple melting effects in nylon and polyester was reviewed by Hearle and Greer (1970a). Figure 2.11(a) shows DSC traces for undrawn nylon 66, which had been annealed at 220°C for increasing times, and Fig. 2.11(b) shows the change in the melting temperature. The sample initially shows a broad melting endotherm with a peak at 256°C, but on annealing, a second endotherm appears at a lower temperature. With increasing time, this lower endotherm grows and increases in temperature,



2.11 DSC response of undrawn nylon 66. (a) Change in form in DSC traces with annealing time. (b) Change in melting temperature. From Bell *et al* (1968), 'Multiple melting in nylon 6' *J Polymer Sci* **A2 6**. Reprinted by permission John Wiley and Sons Inc.

eventually passing the first peak, which has shrunk while maintaining a constant temperature. The first endotherm is referred to as form I and the second as form II. The change from form I to form II also occurs on cold drawing.

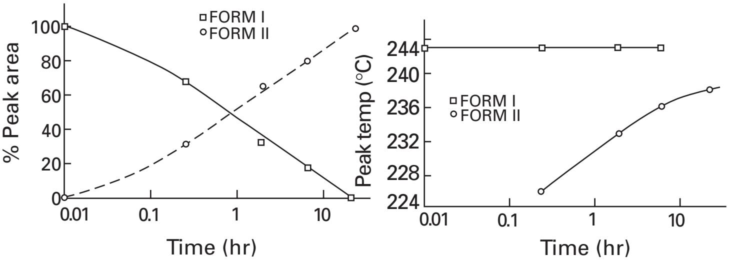
The situation is slightly different in polyester, because undrawn material is amorphous. This means that when a sample is heated in DSC, an exotherm appears at a temperature, typically around 120°C, at which crystallisation takes place. However, the melting behaviour is similar to nylon, as shown by Fig. 2.12.

The change from form I to form II runs counter to what would be expected from thermodynamics. Usually, annealing leads to a more stable form, with larger and more perfect crystals which will melt at a higher temperature. Another striking feature is the constancy of the melting temperature of form I, which suggests that it is a well-defined and unchanging form. However, the paradox can be resolved and a thermodynamic and structural interpretation, which may be relevant to what happens in texturing, can be given (Hearle, 1978).

The classical argument on melting is expressed in terms of the thermodynamic free energy F of the system given by:

$$F = U - TS \qquad [2.1]$$

where U = internal energy, T = temperature and S = entropy. In a crystal, where molecules are bonded together in a regular lattice, the internal energy, which drops as atoms are attracted to one another, and the entropy, which relates to disorder, are both low. In a liquid, they are both higher. Liquid and solid are in equilibrium when the free energies are equal. The



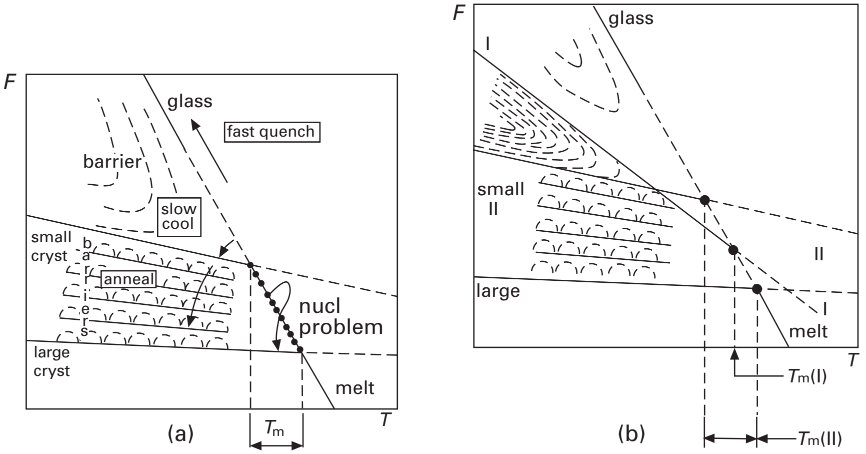
(a) (b)

2.12 Change from form I to form II by annealing polyester (PET) film. (a) Change in DTA peak area. (b) Change in melting temperature. From Bell and Murayama (1969), 'Relations between dynamic mechanical properties and melting behavior of nylon 66 and poly(ethylene terephthalate)' *J Polymer Sci* **A2 7**. Reprinted by permission John Wiley and Sons Inc.

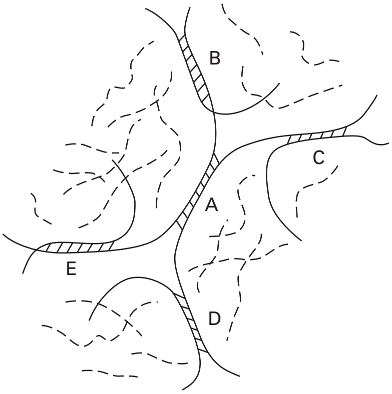
conventional picture is shown in Fig. 2.13(a). The line for the melt, which becomes a glass at low temperature, starts high but falls rapidly, because of the large values of U and S. The lowest line for a large, perfect crystal has a lower slope and cuts the melt line at the equilibrium melting point. However, it is not easy to overcome the energy barriers to form large crystals and this leads to the initial formation of small crystals, which have higher U and S and therefore melt at a lower temperature. Annealing progressively improves crystal size and perfection and increases the melting point.

The classical argument can be modified to include forms I and II, by postulating that form I is a new state with values of U and S which lie between those for a conventional crystal and a melt. As shown in Fig. 2.13(b), the line for form I will cut the line for the melt at its melting point. However, at the lower annealing temperature, the form I line will lie above the form II line for small crystals, and so the change from form I to form II is thermodynamically favoured. The initial melting point of form II is less than that of form I, which explains the paradox. Further annealing follows the conventional pattern of increasing crystal size and perfection and eventually takes the melting point of form I above that of form II.

What are the structures of forms I and II? Various suggestions have been made, but the following explanation is plausible, even if not explicitly proven or even exactly described. Form II is assumed to be a conventional assembly of crystallites in an amorphous matrix, as schematically shown in Figs 2.3(a) and (b). Form I is assumed to be a more uniform structure, such as the suggestion in Fig. 2.3(c). Another schematic view is shown in Fig. 2.14,



2.13 Variation of free energy F with temperature T. (a) Conventional picture. (b) With forms I and II. From Hearle (1978).



2.14 Schematic view of form I with separate segments in crystallographic register. From Hearle (1978).

and the structure has been called a '*dynamic crystalline gel*'. It is a gel, because it is a solid, cross-linked structure; it is crystalline because the cross-links are segments in crystallographic register; it is dynamic because the cross-links will be continually breaking and reforming – but when, for example, **A** is open, **BCDE** will hold the structure together, and so on, as **A** joins up again and others open. Such a form would have internal energy U and entropy S between that of regular crystal and an amorphous melt and so is compatible with the thermodynamic argument.

2.2.5 Heat-setting

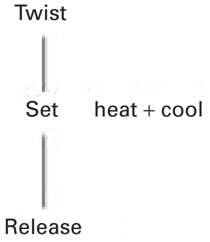
At last, we come to what is directly relevant to texturing. What happens at texturing temperatures between about 180 and 220°C? As already mentioned, there has been a lack of fundamental research on what happens in this temperature range, particularly in regard to the mechanisms involved and the structural changes. It was recognised by Miles (ca 1937) in the early days of nylon research that nylon 66 could be 'permanently' heat-set. By this it was meant that the set, which was applied to pleats and creases in garments, was stable to the ordinary actions of stress, temperature and moisture in use, in contrast to the temporary set described in Section 2.3. There was a rule-of-thumb that the set could be overcome and a new form set by treatment at a higher temperature. This is important, because it means that textured yarns can be reset, as needed in fabric form in apparel or in plied BCF yarns for carpets.

When semi-crystalline, drawn yarns were the feedstock in false-twist texturing, the yarns were heat-set in their helical forms, in which the filaments were twisted and bent. With draw-texturing, the structural changes are different. For polyester, the incoming POY yarn is essentially amorphous, with only incipient crystallinity and the semi-crystalline structure forms during the first stage of texturing. For nylon, the yarn will have crystallised, but the structure will be massively disrupted by the drawing and twisting, and a new stable structure will be formed. Some twist runs back to the feed-rolls in the incoming cold zone, but the draw and additional twisting will take place as the yarn warms up and softens on entering the heater.

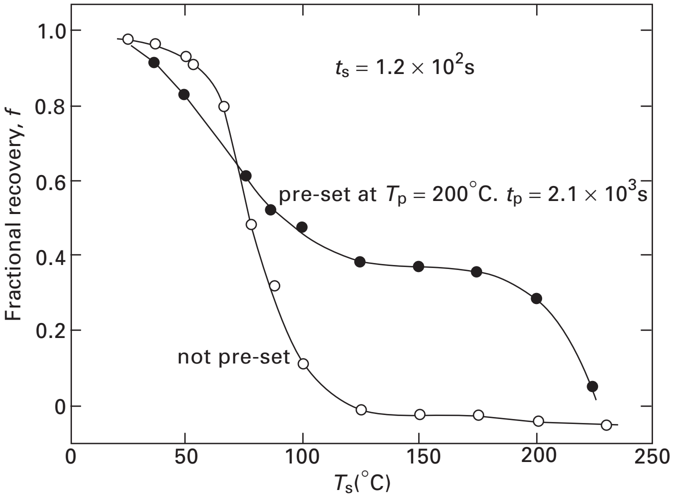
There is an interesting question in terms of the meaning of the word '*setting*'. A thermo-setting resin, such as the adhesive *Araldite*, is set by the action of heat, which cross-links the molecules; but, for thermoplastics such as nylon and polyester, setting requires heating and cooling. Heat puts the structure into a more mobile state and allows a rearrangement of the molecules, but it is really the cooling which sets the form. Consequently an adequate cooling zone is needed between the heater and the false-twist spindle, where the yarn is untwisted. Beyond the spindle, the yarn is straight and fully extended under tension. When it is wound on a package, it will still be warm and it then remains on the package for a long time. Stress relaxation, which is a form of temporary set, will take place. Consequently, when the yarn is removed carefully from the package, it does not appear to be textured. The stretch and bulk needs to be developed. This can be done by 'milking' the yarn, increasing and decreasing tension, or by the action of heat or moisture, as is done in relaxing the yarn for tests of stretch and bulk.

In a sense, as discussed above, heat-setting does not occur in draw-texturing on single-heater machines, which produce stretch yarns, though it needs to be understood in terms of subsequent yarn, fabric and garment processing. Heat-setting does become directly relevant for double-heater machines producing set yarns. For nylon, the rule-of-thumb seems to be reasonably valid, though the necessary, increased severity of treatment must take account of stresses and moisture as well as temperature. In producing modified nylon yarns with less stretch, the second heater was at a higher temperature than the first. For polyester, the effects are different. The second heater is run at a lower temperature than the first. This gives the clearest evidence that it is not necessary to increase the severity to process polyester, which seems to be able to reset repeatedly at the same or lower temperatures. It is possible that only a partial relaxation of stress, or a partial setting, occurs on the second heater.

Heat-setting was a subject of research at UMIST, but this still left many unanswered questions, especially in terms of multiple setting sequences. One set of painstaking experiments on heat setting was carried out on a 28 dtex polyester (PET) monofilament yarn (Salem, 1982). The sequence is shown Fig. 2.15. After twisting, which gives the strain γ_0, the sample is put into a hot oil bath at a temperature T_s for a time t_s, then cooled and finally



2.15 Heat-setting sequence used by Salem (1982).



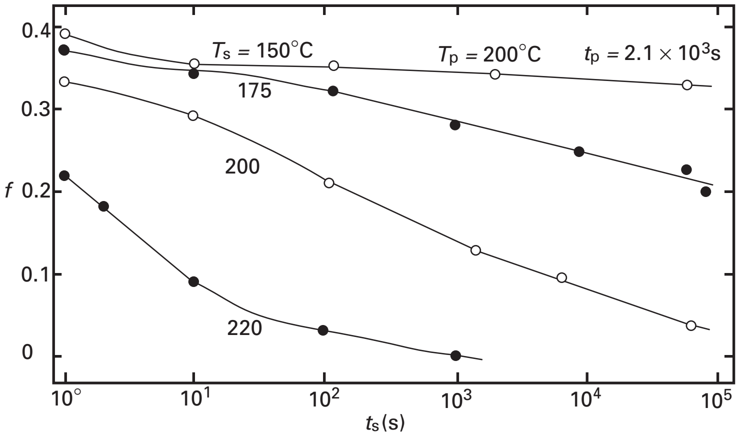
2.16 Fractional recovery after setting of polyester monofilament. From Salem (1982).

released, when the strain drops to γ_r. The fractional recovery f is given by (γ_r/γ_0): complete set is given by $f = 0$ and no set by $f = 1$. In some tests, the yarn was pre-set by heating at temperature T_p for a time t_p and cooling without deformation. Some experiments followed the same procedure in bending.

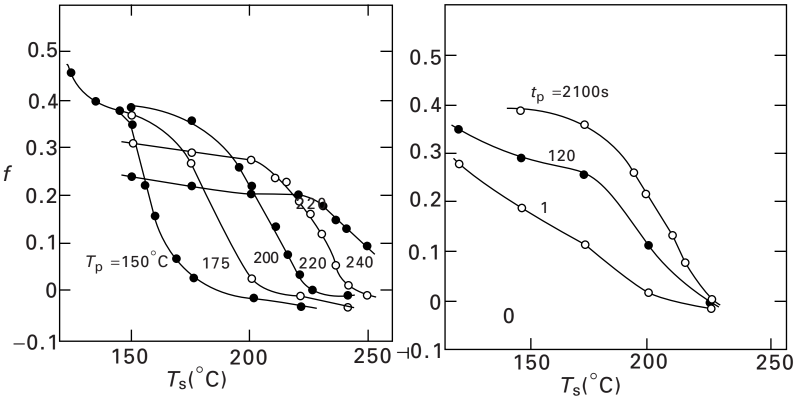
Figure 2.16 shows the change in recovery with setting temperature for both conditions. Effects in bending and twisting are similar. If the yarn had not been pre-set, the 100°C transition gives a sigmoidal plot from $f = 1$ to $f = 0$ between 50 and 125°C. There is full relaxation of the torsional stress and set is apparently complete – but this is a temporary set which would easily be lost. The 'permanent' set, which occurs at a higher temperature, is not shown up in the plot. If the yarn has been pre-set at a higher temperature, 200°C in Fig. 2.16, the lower-temperature transition is only partly effective in relaxing the stress: set is incomplete at 125°C and there is a plateau in the value of *f* until the higher-temperature setting action takes place between 180 and 220°C. Figure 2.17 shows that the setting action in polyester is highly time-dependent. The rate of setting increases rapidly with increase of temperature. After pre-setting at 200°C, there is little setting at 150°C for setting times up to one day; but after one minute, setting has started at 175°C and is complete at 220°C. These effects are relevant to twist-setting of fully drawn yarns, although the maximum shear strains of 0.6% in the tests are much lower than the severe conditions of twist-texturing. But, as already mentioned, draw-texturing creates a new semicrystalline morphology, not the modification of an existing structure.

The effect of the pre-setting conditions is relevant to what happens on the second heater in the production of set polyester yarns. It also relates to what happens in subsequent textile processing, such as the setting of polyester knitwear or BCF nylon carpet yarns. In Fig. 2.18(a), the setting action takes place only above the pre-setting temperature. However, this is for tests in which pre-setting lasted for 35 minutes, almost 2000 times longer than the setting time of 1.2 seconds. Figure 2.18(b) shows that, when the pre-setting time is reduced, set occurs at lower temperatures. When temperatures and times are equal, at 200°C and two minutes, the second set is only 10% short of being complete.

A limited set of experiments on nylon showed a similar effect of presetting and setting temperatures, but almost no effect of time. This confirms the view that there is a difference between the setting responses of nylon and polyester. Setting in nylon appears to establish a structure that is more difficult to change than that of polyester.



2.17 Effect of time on setting of polyester. From Salem (1982).



(a) (b)

2.18 Effect of pre-set conditions on setting of polyester at 200°C. (a) Change of pre-set temperature with pre-set time of 2100 s and set time of 1.2 s. (b) Change of pre-set time with pre-set temperature of 200°C, equal to set temperature, and set time of 120 s. From Salem (1982).

2.2.6 Steam-setting

If nylon 66 fibres are placed in a capsule filled with water and heated, melting is observed at a temperature that is 80°C lower than for dry fibres. Similarly heat-setting actions take place at lower temperatures. Since fabric processing was mostly done in steam, this led to the definition of an '*equivalent steam-set temperature*' to characterise the response to dry heat. For nylon 66, the range of 180–220°C, in which 'permanent' setting is effective, corresponds to 100–140°C in steam. Super-heated steam is therefore necessary to set nylon. In polyester the reduction in melting temperature is much less, so that higher steam temperatures are needed.

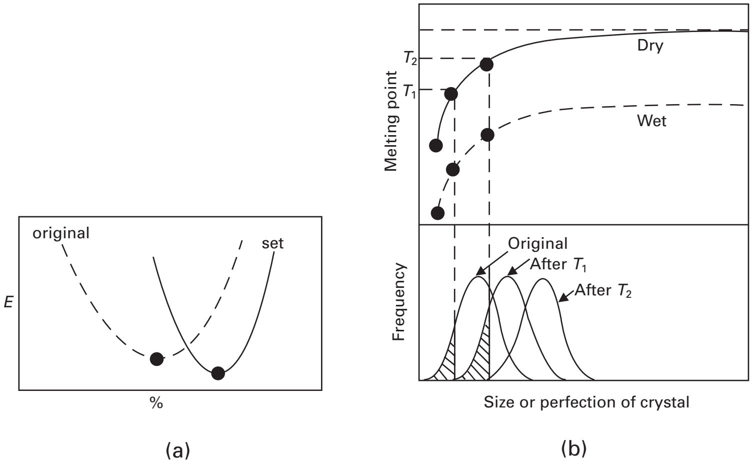
The use of steam does have advantages in efficiency of heating and, as described in Chapter 10, research has shown that it enables shorter heaters to be used. However, the practical difficulties of containing the steam have prevented its use in commercial false-twist texturing.

2.2.7 Mechanisms of setting

The limited and sometimes contradictory experimental information on heat-setting of nylon and polyester is mirrored in its structural interpretation. The problem is compounded by the uncertainty about the fine structure of these fibres, as discussed in Section 2.2.1; the reasons for the observed differences between nylon and polyester are not understood. For the practical operations of texturing, it is not necessary to know what molecular mechanisms are involved, and so only a brief discussion of the subject will be given here.

The temporary set at around 100°C (lower in nylon with absorbed water) is clearly due to the upper part of the glass-to-rubber transition, which is attributed to the onset of mobility in the hydrogen bonding of nylon and the benzene ring interactions of polyester. The change is in the amorphous regions of the fibres.

The 'permanent' set at around 200°C is usually associated with changes in the crystalline regions, but there are several variant explanations. There is a simplistic argument. Thermodynamically, as illustrated in Fig. 2.19(a), there is a driving force to a lower energy state, which will be more stable. The change is opposed by the energy barriers of intervening states, which may be overcome in time by thermal vibrations, and is complicated by the fact that there will be multiple energy minima with different structures. In structural terms (Fig. 2.19(b)) the explanation would be that smaller, less perfect crystals have a lower melting point than large, perfect crystals, which have a lower free energy. Values as high as 300°C have been quoted for the melting point of perfect polyester (PET) crystals and as low as 250°C for the observable melting of semi-crystalline fibres. Setting would be achieved by the melting of the smallest, least perfect crystals in the distribution of size and perfection and the formation of larger, more perfect crystals. This picture fits in with the rule-of-thumb that it is necessary to go to higher temperatures to achieve a new set; with each increase of temperature, the distribution of crystal size and perfection will shift to higher values. The effects take place at a lower temperature wet than dry.

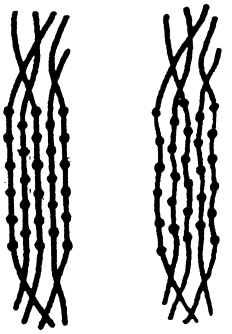


2.19 Simplistic view of setting. (a) Change to a lower minimum energy state; (b) due to formation of larger and more perfect crystals.

For nylon, where the rule-of-thumb on severity of setting seems to be reasonable, provided some account is taken of stress, time and moisture, there are two problems with the simple explanation. First, it is not clear that the crystal-melting effects would go down to the 180–220°C range where setting occurs. The peak in the polyethylene loss modulus below 100°C, shown in Fig. 2.9(c), suggests that there is a separate mechanism, which is clear of melting, but comparable data are not available for nylon and polyester. Second, it is difficult to see how structures such as those in Fig. 2.3(a) and (b) could change to a similar form on a larger scale without a complete melting and recrystallisation of the fibre.

There are other possibilities associated with the crystalline parts of the fine structure. In metals, the movement of defects in crystals is a mechanism of annealing, and this will occur in polyethylene and probably in polypropylene. However, defect models are not easy to formulate for the large repeats in nylon and polyester molecules. A more reasonable suggestion is that the thermal vibrations might be strong enough to allow molecules under stress to be pulled through the crystallites, thus changing the arrangement of tie-molecules and stabilising a new form.

Another possibility is that the multiple melting effects, described in Section 2.2.4, with the change from form I, the dynamic crystalline gel, to form II, the micellar structure, may be relevant. A variant of this, which can be supported on the basis of the greater density of energy levels in the melt than in the crystal (Hearle, 1994), is that, over the relevant temperature range, micelles will be flipping between a rigid crystalline form and a mobile liquid form, which is held in position by molecular entanglements, as shown in Fig. 2.20. As with the dynamic crystalline gel, enough units would be in the rigid state at any given time to hold the fibre together, but their identity would be continually changing. If the molecules were under stress, some limited rearrangement would be possible when a micelle is in the molten state.



2.20 Flipping of micelles between crystal and melt.

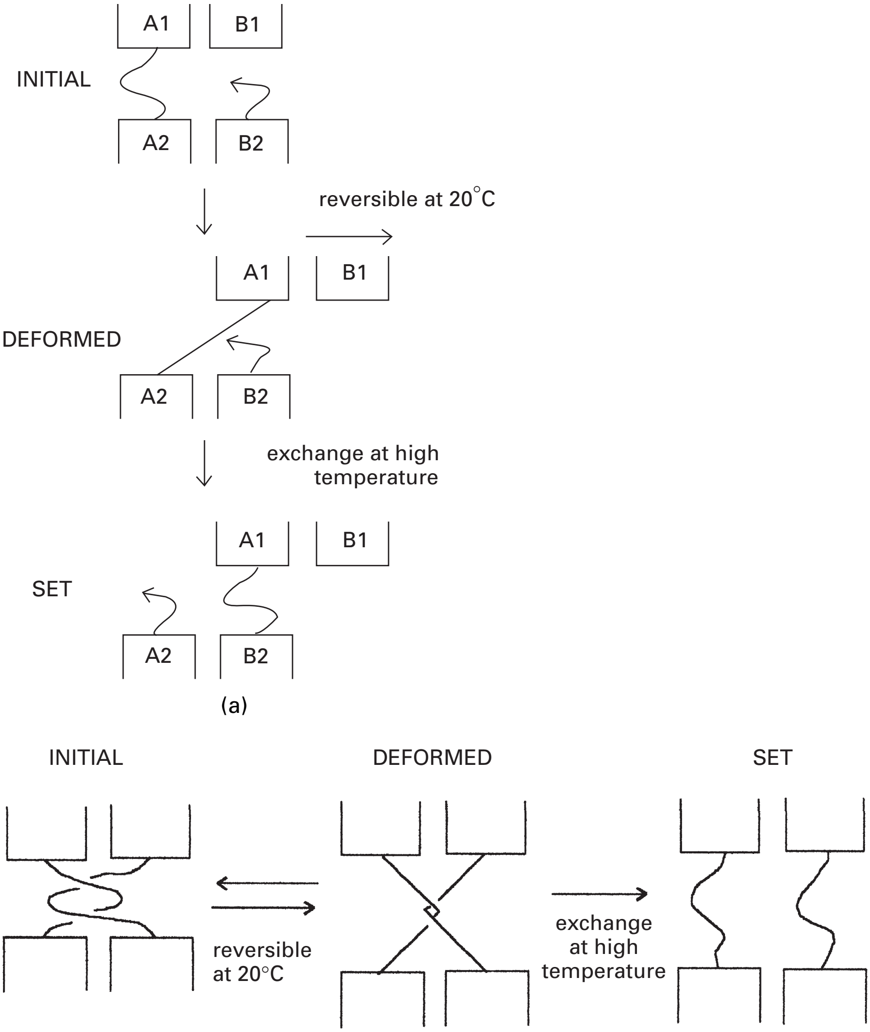
A more unusual suggestion (Hearle, 1994) is that polymer crystallisation involves quantum effects and is not a purely classical phenomenon. The quantum theory explanation of diffraction experiments with two slits through which an electron or a photon can pass, is that both possibilities exist until measurement detects which has happened. The states are superposed until the quantum state-function collapses to a single classical form. Penrose (1989) states that this occurs on a larger scale when a system has many energy levels close together and that the collapse may be time-dependent. One would also expect it to be temperature-dependent because of the influence on energy levels. For some quasi-periodic, alloy crystals, which need to be defined over larger scales, he suggests that many forms will coexist until one becomes large enough to be the single, classical form. There are certainly many forms with different energy levels associated with a semi-crystalline polymer structure. It is therefore conceivable that during melt-spun fibre formation, and then again when fibres are heated to a critical temperature range for heat-setting, there is a superposition of states, which collapse on cooling to the single, stable state. An attraction of this view is that it shows how annealing to give larger and better crystals, which does occur, could be achieved without a complete melting of the fibres.

Finally, it is possible that heat-setting is not related to the crystalline regions, but is due to a breaking and re-forming of tie-molecules in amorphous regions, as illustrated schematically in Fig. 2.21. Molecules under stress would break and then re-form in new preferred positions, thus stabilising the structure. This is more likely in polyester than in nylon, and would explain the ability to re-set at the same or lower temperatures, since the mechanism would operate whenever the temperature was raised. It is known that trans-esterification, the rupture and re-formation of the ester linkages in polyester molecules, occurs at a high rate owing to thermal vibrations in the melt (Kugler *et al*, 1987), and extrapolation from the 250–280°C range of measurements suggests that it may occur in the 180–220°C range of heat-setting, especially if molecules under stress are more likely to break.

The explanation of heat setting in the 180–220°C range for nylon 66 and polyester (PET) and at lower temperatures for nylon 6 and polypropylene is still an open question. There is probably no single answer. Several of the mechanisms suggested above, and others not formulated, probably act together.

2.2.8 Fibre extension, bending and twisting

Most measurements of the mechanical properties of fibres are of their tensile properties. For the filaments of a textured yarn (Fig. 2.22) the load-extension curve starts with a period of easy crimp removal. The magnitude of this extension is determined by the crimp geometry, which is discussed

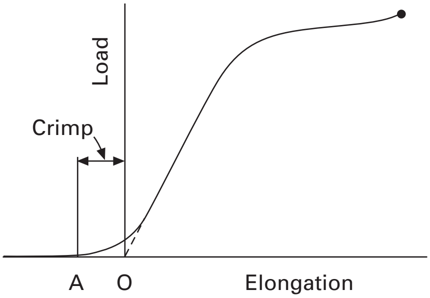


(a)

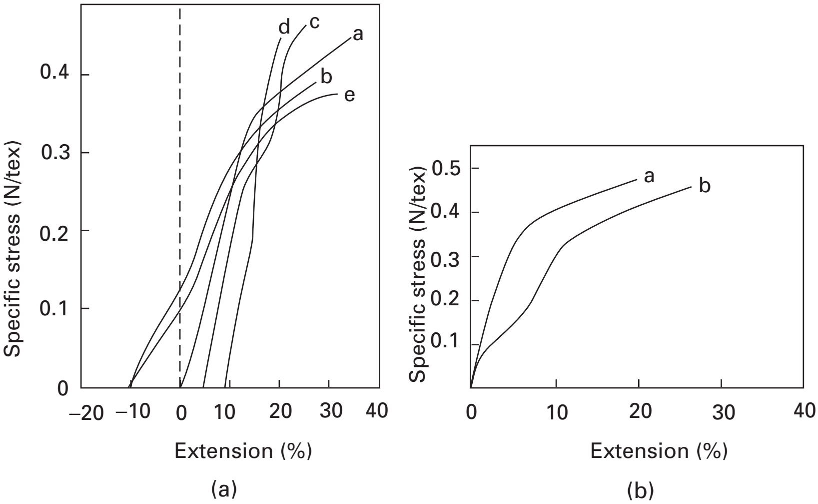
(b)

2.21 Two ways in which breaking and re-forming of tie-molecules could act as a mechanism of setting. (a) Interchange of free end; (b) Break and re-formation of tie molecules.

in Section 2.6, and the low level of tension by bending and twisting properties. When the crimp has been pulled out, the tension increases rapidly as the load–extension curve of the straight fibre is followed. Morton and Hearle (1993) give a comprehensive account of fibre tensile properties. In general, the response is non-linear, visco-elastic and shows imperfect recovery. In nylon, polyester and polypropylene, the initial shape of the curve is influenced by the mechanical and thermal set of the fibres. For example, Fig.



2.22 Load–extension curve of a crimped filament.



2.23 (a) Stress–strain curves of 78 dtex nylon yarns after various heat treatments: (a) as received; (b) 200°C, zero tension; (c) 200°C, 30 gf; (d) 200°C, 75 gf; (e) 200°C at zero tension, then relaxed in boiling water. (b) Stress–strain curve of polyester fibre: (a) as received; (b) after treatment in water at 95°C. From Morton and Hearle (1993).

2.23(a) shows the effect of various heat treatments on the stress–strain curves of nylon yarns, and Fig. 2.23(b) shows the effect of heating in water on polyester. The end of the stress–strain curve, which gives the tenacity (tensile strength) and extension at break, is dependent on the degree of molecular orientation in the fibre, which is determined by the drawing process. High draw increases tenacity and reduces breaking extension. These properties will influence the performance of yarns when subject to severe forces. The tensile modulus, which is given by the initial slope of the curve and also increases with molecular orientation, influences the bending stiffness, which together with torsional stiffness determines the crimp forces.

Bending properties are described by the relation between bending moment M and curvature c, which is the reciprocal of radius of curvature. For a simple, linear-elastic material, $M = (BC)$, where B is the bending stiffness (or flexural rigidity) and is given by:

$$B = (1/4\pi)(\eta ET^2/\rho) \qquad [2.2]$$

where η is a shape factor, E is the tensile modulus, T is the linear density and ρ is the density.[1]

The basis for this relation is that, in bending, the material on the outside is under tension and on the inside under compression, with a central neutral plane. The shape factor is 1 for a circular fibre, but will be higher for a multilobal fibre with material further out. For a flattened cross-section, as may result from false-twist texturing, bending stiffness will be low in one direction and high in the other direction, which will influence the form of buckling. The maximum and minimum values are the principal bending stiffnesses, B_1 and B_2. The dependence on the square of linear density or fourth power of fibre diameter, is important; stiffness increases rapidly as fibre thickness increases. There will be big differences between yarns of the same total linear density as the number of filaments, and hence the linear density of the individual fibres, is changed.

Twisting involves shear, which increases in magnitude from zero at the centre of a circular fibre to a maximum at the outside. Consequently, similar relations apply. Torque is proportional to twist, with a torsional rigidity R given by:

$$R = \varepsilon nT^2/\rho \qquad [2.3]$$

where ε is a shape factor equal to 1 for a circular fibre and n is the shear modulus.[2]

These expressions will be used in the discussion of the structural mechanics of textured yarns, but because so many factors influence the values of the moduli, it has not been possible to make quantitative predictions based on an input of fibre property values. However, some generic differences between fibre types can be noted, as shown in Table 2.2, which also includes values of density. The low modulus of nylon means that the forces developed in stretching nylon yarns are less than for polyester. This, combined with the good recovery from large deformations, makes it more suitable for use as a high-stretch yarn in form-fitting garments. The higher

---

[1] These equations are in a consistent set of units, such as strict SI. The equations also apply without numerical factors with M in N m, c in mm^{-1}, which gives B in mN m, E in N/tex, T in tex and ρ in g/cm^3.

[2] This assumes consistent units, but is also correct with torque in N m and twist in mm^{-1}, which gives R in mN m, with n in N/tex, T in tex, and ρ in g/cm^3.

Table 2.2 Comparative values of density and moduli in bending and torsion. From Morton and Hearle (1993)

Fibre type	Density	Bending: tensile modulus *E*		Torsion: shear modulus *n*	
		GPa	N/tex	GPa	N/tex
Nylon (3 types)	1.14	1.9–3.8	1.7–3.3	0.33–0.48	0.29–0.42
Polyester (PET)	1.39	6.2	4.5	0.85	0.62
Polypropylene	0.91	3.4	3.7	0.75	0.82

modulus of polyester gives a crisper handle, more suitable for non-stretch products.

The relationships change when the deformations are large. Severe bending leads to yielding on the inside at a low compressive stress, so that the neutral plane moves outwards. Severe twisting at constant fibre length means that axial lines at the fibre surface become longer and make the tensile resistance more important than the shear resistance. Finally, there is the complication that the fibres in textured yarns have been set in twisted and bent forms, which will influence the directional effects in mechanical properties.

2.2.9 Fibre surface properties

The coefficient of friction plays an important part in texturing processes, but its value depends on the spin finish applied by the fibre producer. This is a 'black art' with little public information on the formulations used. Friction varies with the surfaces in contact and with the rate of slip. The two combinations of most importance are:

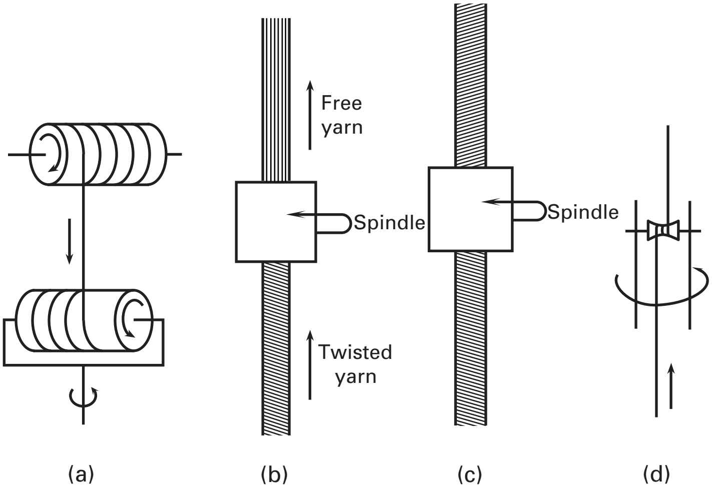
1 at high speed between yarn and drive surfaces, including friction discs, where friction must be high enough;
2 at low speed between filaments to allow fibre migration to occur in twisting, for which friction must be low enough.

Fibre producers have found finishes which satisfy both these contrasting requirements.

2.3 Mechanics of twisting

2.3.1 False-twist

In true twisting, either the supply package or the take-up package is rotated relative to the other, as shown in Fig. 2.24(a). False-twisting, Fig. 2.24(b),



2.24 True and false-twist. (a) Positive uptwisting with take-up package twisting and winding. In downtwisting, the yarn direction is reversed: the supply twists and unwinds. (b) False-twisting. (c) 'False-twist' with a stationary yarn. (d) Positive insertion of false-twist with an axially rotating pulley on a torsionally rotating spindle.

combines both actions. This is most easily appreciated by thinking about the original pulley spindles (Fig. 2.24(d)). On the input side, the pulley acts as a rotating take-up package; on the output side, it acts as a rotating supply package. In continuous running, the inserted twist runs back to a twist stop on the supply side, but is removed as the yarn goes to the take-up side. If the spindle is running at a rotation speed of n rpm and the yarn forward speed is v *m*/min, the twist will be equal to n/v.

The situation is different for a stationary yarn (Fig. 2.24(c)), when both sides are twisted. This means that there is a transient effect at start-up. In the first rotation of the spindle, one turn will be inserted on each side – in the required direction upstream and in the reverse direction downstream. In the second rotation, turns are again inserted on each side. This increases the upstream twist, N_1, but downstream the yarn coming off the spindle has some twist and therefore the increase in the magnitude of the reverse twist, N_2, will be less than in the first rotation. The reverse twist will build up at a reducing rate, until the incoming length of twisted yarn has more turns than the same length of outgoing yarn; the reverse twist will then reduce until it asymptotically reaches the zero twist level of continuous running. An analysis by Denton (1968) of the idealised situation, which neglects some factors such as yarn contraction on twisting, shows that the change with time t would follow the equations:

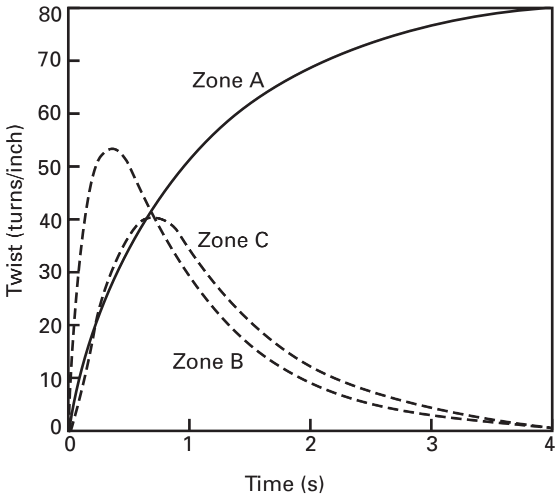
$$N_1 = N[1 - \exp(-\nu t/a)] \qquad [2.4]$$

and

$$N_2 = [N(1 - b/a)][\exp(-\nu t/a) - \exp(-\nu t/b)] \qquad [2.5]$$

where N is the final twist in the twisted zone, a and b are the lengths of yarn upstream and downstream, respectively and ν is the yarn speed.

Figure 2.25 shows changes of twist with time in typical commercial processing on this model. The third plot is for the zone between the output rolls and the take-up, which depends on the length in this zone. In practice, this means that there is a certain length of unsuitable yarn at start-up. A more important point is that any variation in continuous running will lead to a transient change of twist. On the upstream side, this means that the conditions of twist-setting will alter with some change in textured yarn properties. More seriously, some real twist will be formed on the downstream side and pass through into the textured yarn. This can limit crimp and bulk development, or, in some cases, cause the formation of tight spots. Slippage of twist on the spindle is one cause of such a transient, but there could be other causes, such as yarn variability, which leads to changes in twist distribution along the yarn. Extensive theoretical and experimental studies of transient phenomena have been reported by Thwaites (1978a,b; 1984a) and Thwaites and Hooper (1981a,b).



2.25 Variation of twist with time in zones A upstream of spindle, B downstream of spindle, and C between output rolls and take-up. *Note*: 10 turns/inch = 25 turns/cm. From Denton (1968).

2.3.2 Friction twisting

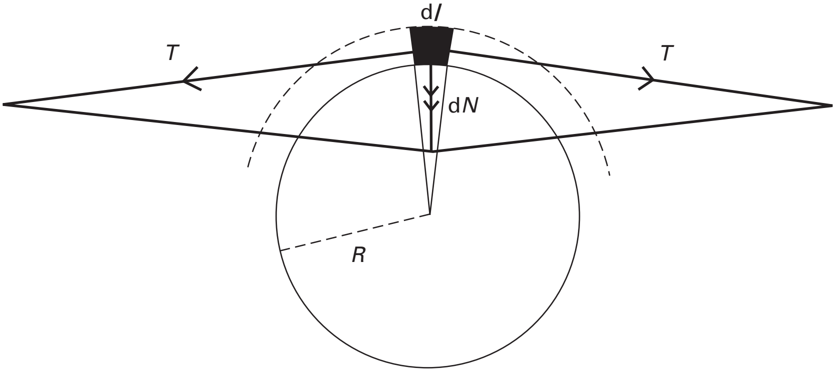
2.3.2.1 Twisting actions

Two actions take place at the spindle: yarn twisting and yarn forwarding. With the original pulleys, as shown in Fig. 2.24(d), the mechanics is simple. The yarn is fully gripped on the pulley, so that twist is forcibly inserted, but the pulley bearings allow the forward motion to take place. As Hearle (1979b) pointed out, what happens in a rotating-pin spindle is more complicated. The yarn has to be free to slip over the pin to move forward, but must be gripped sufficiently to insert twist. Twist insertion may be driven by normal forces as well as frictional forces in a slipping mode, but the mechanics has not been worked out. In practice, there was positive twist insertion with one turn of twist for each turn of twist, so that analysis is only of academic interest, especially as pin spindles are no longer used. What happens in friction twisting needs to be considered. In disc spindles a controlling factor is the ratio of disc surface speed to yarn speed, which is known as the D/Y ratio.

Two types of force need to be taken into account: the normal force, N, which acts at right angles to the yarn axis, and the frictional force, F, which contributes to tension and torque. The frictional force on a length $\mathrm{d}l$ of yarn under a normal force $\mathrm{d}N$ is given by $\mu \mathrm{d}N$, where μ is the coefficient of friction. Although μ is a convenient ratio to use, it is not a universal constant, even for two given surfaces, but may vary with speed and contact pressure. In belt twisting, $\mathrm{d}N$ comes from the fraction of the externally imposed pressure between the belts that falls on the yarn. In disc spindles, and the older types shown in Fig. 1.8, the normal force arises from the curvature of the yarn path, which gives an inward component of tension. As shown in Fig. 2.26, $\mathrm{d}N = T\,\mathrm{d}l/R$, where T is the yarn tension and R is the radius of the curved path.

The curious nature of the frictional force cannot be emphasised too often. There can be only one force of friction acting between two surfaces: it is impossible for there to be slip in one direction and grip in another direction in the plane of contact, though there is positive resistance to movement perpendicular to the plane. In static friction, which is subject to the condition that the magnitude must be less than μN to prevent sliding, the frictional force takes whatever direction and magnitude is needed to balance the applied forces. In dynamic friction, where surfaces are sliding over one another, the magnitude equals μN, and, for isotropic surfaces, the direction is opposed to the relative motion of the surfaces. For surfaces with a directional character, the direction of the force may be at a different angle.

Friction twisting can operate in two modes: a slipping mode, in which yarn is everywhere sliding over the surface, and a rolling or positive mode, in which the yarn is gripped on at least part of the surface. The distinction



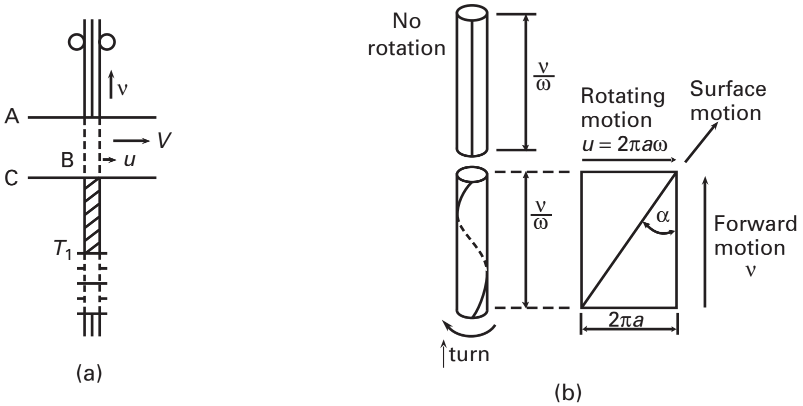
2.26 Normal load d*N* due to curvature of yarn path.

between these modes is best described by comparison with an automobile. In normal driving conditions, the tyres grip the road. The frictional force, which acts in a direction to drive the car forward, balances the driving torque applied by the engine to the wheels, which rotate and lead to the forward movement. In a slipping mode, the dynamic friction opposes the relative movement, which comes from the turning of the wheels, if they are turning but failing to grip, or from the skidding if the wheels are locked.

There have been a number of analyses, notably by Thwaites (1970, 1984b) of friction twisting in three-dimensional forms applicable to particular spindle types. These are complicated and, because of the complexity and uncertainty of input parameters, have been of limited value for quantitative design purposes. In future, more general CAD (computer-aided design) programs may be written. Here we follow a treatment that brings out the essential nature of friction twisting, first in the slipping mode, and then in the positive mode. In a slipping mode, the frictional force is known and may be used to calculate the motion; in a rolling mode, the motion is known and may be used to calculate the frictional force, which must, of course, be less than the limiting force of static friction. Changeover from one mode to the other will occur when the frictional force necessary for the rolling mode exceeds the frictional force actually available. There are many simplifying assumptions in this model, which, in order to give a straightforward presentation of principles, are glossed over. A critical account of the assumptions and details of the mathematics is given in Hearle (1979a) and Hearle and Beech (1980).

2.3.2.2 The slipping mode

A simple system, in which the speed differences are such that the yarn is always slipping on the friction surface, is illustrated in Fig. 2.27(a). A

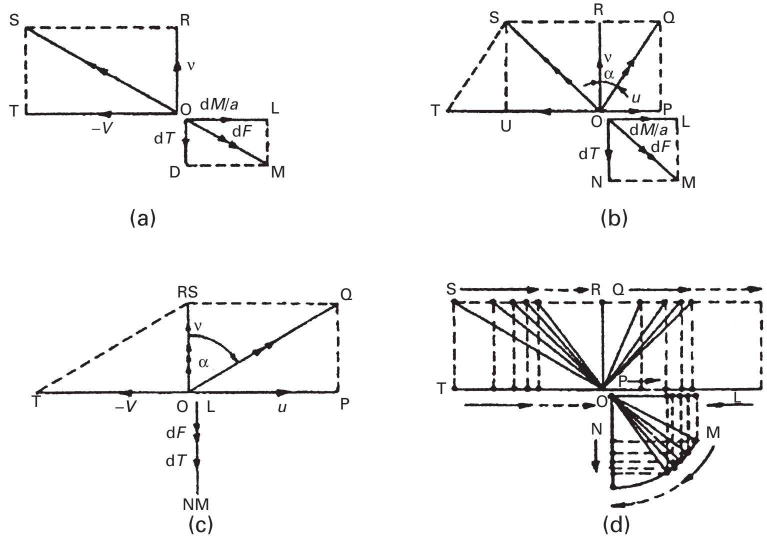


2.27 (a) Yarn running past a twist stop onto a moving belt. (b) Vector diagram of motions. From Hearle (1979a).

'yarn' of radius, a, which for simplicity may be thought of as a circular rubber rod, travels with a velocity, ν, across a friction belt moving with a velocity, V, perpendicular to the yarn motion. The two surfaces are regarded as held in contact by a constant normal load per unit length, generating a frictional force, $\mathrm{d}F$, on an element of the yarn. A single belt would lead to a sideways drag on the yarn, pulling it out of its straight-line path. However, this could be compensated for by a similar belt on the opposite side of the yarn moving in the opposite direction. The transverse component of $\mathrm{d}F$ thus causes only a moment in the yarn and not a transverse force.

As illustrated in Fig. 2.27(b), the system is assumed to be operating in a steady-state false-twisting mode, so that the yarn leaving the belt has zero twist. Owing to the frictional drag of the belt, the twisted portion of the yarn which comes onto the belt must be rotating with a rotational velocity, ω, such that a point on the yarn surface is moving along the direction of the surface helix angle with a forward velocity, ν, and a transverse velocity, u, equal to $2\pi aT$.

Figure 2.28 shows force and velocity vector diagrams at successive positions along the yarn. At the output point, A in Fig. 2.27, the yarn is not rotating, so that the yarn surface velocity relative to the belt is given by vector **OS** obtained by compounding the yarn forward-velocity vector **OR** with the negative of the belt-velocity vector **OT**, as shown in Fig. 2.28(a). The frictional force $\mathrm{d}F$ can be represented by a vector **OM**, opposed in direction to **OS**, and resolved into a component **OL**, causing a transverse force, $\mathrm{d}F_t$, giving a yarn-torque increment, $\mathrm{d}M = a\mathrm{d}F_t$, and **ON**, causing a yarn-tension increment $\mathrm{d}T$.



2.28 Force and velocity vector diagrams. (a) At outlet from belt, A in Fig. 2.27. (b) At intermediate position B. (c) Limiting case. (d) Change with position. From Hearle (1979a).

The torque increment means that there must be a yarn twist, so further back along the yarn from A the yarn will be twisted and rotating. The vector diagram at B is shown in Fig. 2.28(b). The yarn surface-velocity vector **OQ** is now a compound of the rotational velocity vector **OP** and the forward-velocity vector **OR**. The vector **OQ** has to be compounded with ***OT*** to give the relative velocity of the surfaces ***OS***. (An alternative construction subtracts ***OP*** from ***OT*** to give ***OU***, which is then compounded with ***OR*** to give ***OS***.) As a result, the vector ***OS*** has swung closer to the yarn forward direction, and the frictional-force vector ***OM*** has swung round to give a reduced torque increment ***OL*** and a larger tension increment ***ON***.

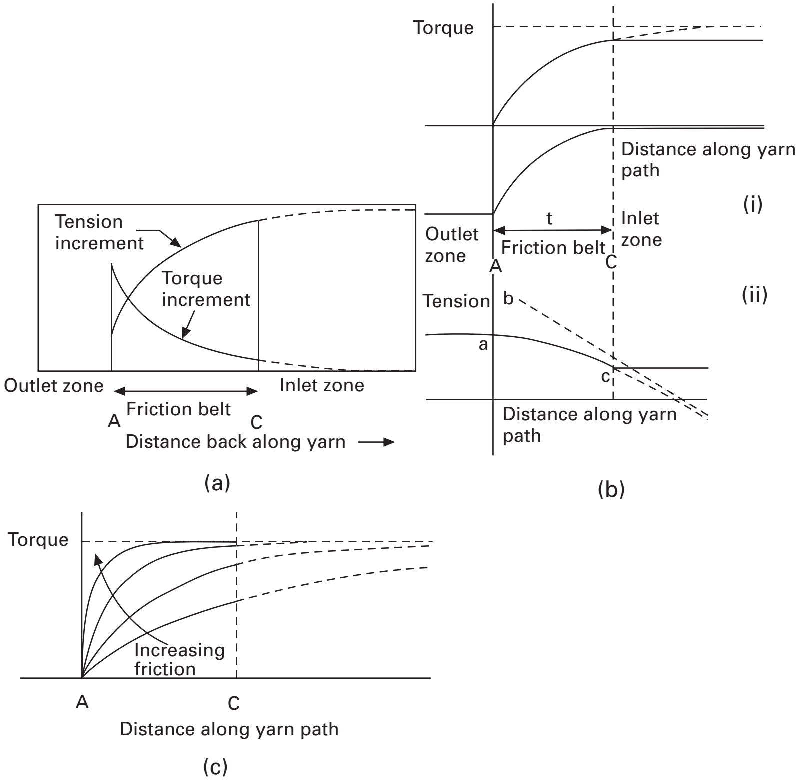
The limiting situation is shown in Fig. 2.28(c). When the yarn twist reaches a value such that the rotational velocity of the surface, u, equals the belt velocity, V, the relative velocity of the surfaces is along the yarn axis, and as a result the frictional force contributes a tension increment but no torque increment. The progressive change in the vector diagram as we move back along the yarn from A is illustrated in Fig. 2.28(d).

Figure 2.29(a) indicates how the torque and tension increments will change along the yarn back from A. The exact form of the change will depend on the more complicated relations in real systems, which govern the interaction:

$$\begin{array}{llll}
 & & & \text{torque} \\
\text{torque} & \rightarrow \text{twist} & \rightarrow \text{rotational} & \rightarrow \text{increment} \\
\text{increment} & \text{change} & \text{velocity} & \\
 & & \text{change} & \rightarrow \text{tension} \\
 & & & \text{increment.}
\end{array}$$

However, the analysis does lead to two general theorems of false-twist friction twisting.

As the length of the friction surface increases in a friction-twisting system in the slipping mode: 1) *The torque and twist in a yarn at the input end approach asymptotically the values that would be given by an assumption of no rotational slip;* 2) *the tension in a yarn at the input end approaches*



2.29 (a) Tension and torque increments. (b) Integrated values: (i) torque, upper curve is for an elastic rod, lower curve is for complete stress relaxation; (ii) tension. (c) Effect of increasing friction on torque generation. *Yarn runs from right to left in both diagrams.* From Hearle (1979a).

asymptotically a line of slope such that the whole frictional force is giving rise to changes in tension.

The total torque and tension values are given by integrating the increments, as shown in Fig. 2.29(b). In the simple case of a rubber rod passing through a false-twist system, the torque would be zero in the outlet zone, where the rod was untwisted, and it would vary according to the top curve in Fig. 2.29(b). The other simple situation, which is closer to a texturing system, is that the torque is completely relaxed by the heater and is zero as it enters the spindle. This gives the middle curve, which shows that the outgoing zero-twist yarn is twist-lively due to its high torque. Since there is some torque in the twisted yarn, due to the effect of tension, the real line will be between the two. The lowest curve in Fig. 2.29(b) shows the tension variation, located to fit the given input tension, T_i. The effect of increasing frictional force on torque generation is shown in Fig. 2.29(c).

If the helix angle of the twisted yarn is α, we note from Fig. 2.27 that, in the limiting asymptotic situation:

$$\tan\alpha = u/\nu = V/\nu \qquad [2.6]$$

This is the hypothetical twist that would result if the yarn were able to be operated on by the belt in such a way that it moved forward with a velocity, ν, but there was no rotational slip between the yarn surface and the belt velocity, V, as would happen if a rod with longitudinal splines were taken over a toothed gear wheel (corresponding to an extreme case of anisotropic friction). For the simplest case of a yarn of radius, a, on a surface of radius, R, with a rotational velocity, ω, equation [2.6] becomes:

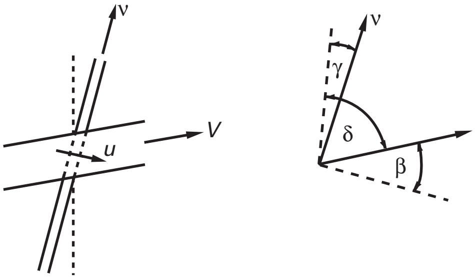
$$\tan\alpha = 2\pi R\omega/\nu \qquad [2.7]$$

The twist τ is then given by the hypothetical 'no-slip' prediction:

$$\tan\alpha/(2\pi a) = (R/a)(\omega/\nu) \qquad [2.8]$$

In a commonly used notation, the disc speed $2\pi R\omega = D$ and the yarn speed $\nu = Y$, so that $\tan\alpha = (D/Y)$ and the twist $\tau = (D/Y)/(2\pi a)$.

In actual friction-twisters, the geometry is more complicated. In belt-twisters, the belts are at an angle, as shown in Fig. 2.30, and if this is large enough the friction can drive the yarn forward and reduce tension. In disc systems, the path is three-dimensional. The shortest route over the sequence of discs would be the equilibrium static path for a yarn under tension, but when the discs are rotating the path will be displaced by the sideways drag. As with belt-twisters, the angle on the surface will influence the tension change. The effect of change of direction can be indicated in the following way.



2.30 Angled yarn and belt directions. From Hearle (1979a).

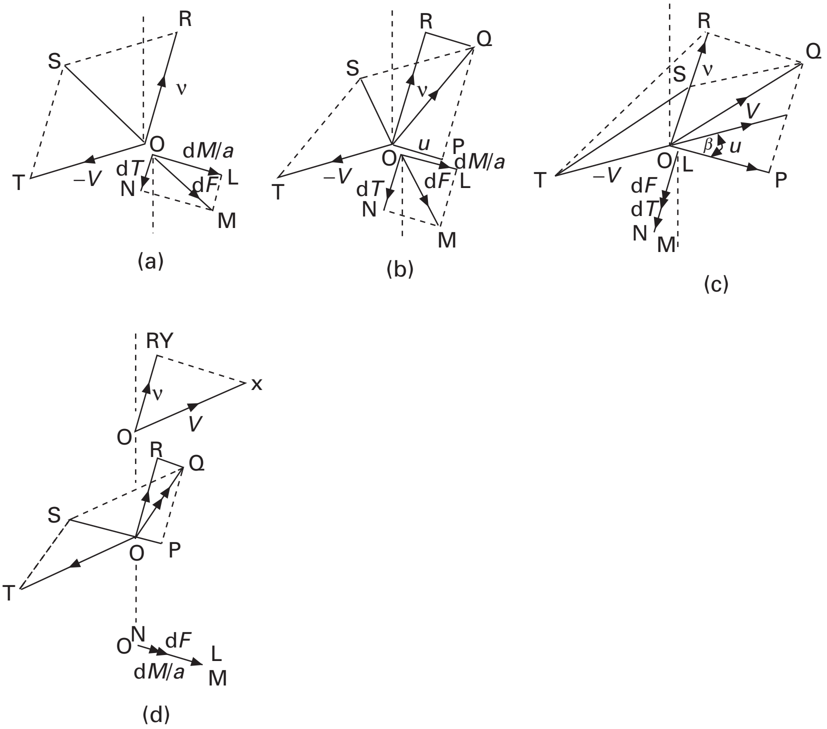
In the simple geometry of Fig. 2.30, the yarn makes an angle γ with the straight line through the device and the friction-surface makes an angle δ, then the angle β between the surface movement and the normal to the yarn direction is given by:

$$\beta = \gamma + \pi/2 - \delta \qquad [2.9]$$

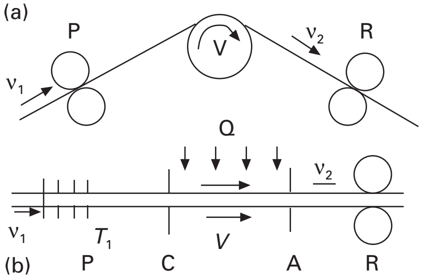
The vector diagrams of Fig. 2.28(a)–(c) are then modified as shown in Fig. 2.31(a)–(c). Depending on the angles, the tension may increase, decrease, or, as shown in Fig. 2.31(d), be unchanged. The condition for change from tension drag to tension push is $V \sin \beta = \nu$. There is also a limiting case, in which there is no relative movement in either direction. The frictional situation is then indeterminate. Near this condition the analysis of the slipping mode is invalid and the positive or rolling mode must be considered.

2.3.2.3 The positive mode

Understanding of the positive mode is best introduced by examining a simple forwarding system, which is also directly relevant to the drive rolls on texturing machines. In Fig. 2.32(a), yarn is fed in at velocity, ν_1, and removed at velocity, ν_2, but in between passes over a roller rotating with a surface velocity, V. If the yarn is anywhere gripped by the roller, then the yarn velocity between P and Q is V. As was done for the slipping mode, the geometry may be simplified to the belt drive shown in Fig. 2.32(b). The yarn with an outlet velocity, ν_2, is forwarded (or retarded) by a linear belt running with a velocity, V, in the same straight-line direction as the yarn (or in the opposite direction). There is uniform normal loading, so the available frictional-force increments are equal. The input is controlled by a tension device providing a tension T_1. In contrast to the analysis of the slipping mode, it is necessary to take account of extension in the yarn. Yarn strain e is introduced as a function of tension $e = f_1(T)$. A notional velocity ν_0 is introduced to define the mass flow in unstrained yarn.



2.31 Force and velocity vector diagrams with angled directions. (a) At outlet from belt. (b) At intermediate position. (c) Limiting case. (d) With no change in tension. From Hearle (1979a).



2.32 (a) A simple yarn-forwarding or braking system. (b) Idealized yarn-forwarding or braking system. From Hearle and Beech (1980).

When this system is operating in a slipping mode, it merely changes the tension from T_1 to $(T_1 \pm F_A)$, where $F_A = \mu N$ is the total available frictional force (positive or negative, depending on which way the belt is running). This changes the yarn strain, and hence, in order to keep the mass flow constant, alters the yarn velocity. If the frictional force is large enough, the yarn will be gripped in the positive mode by the belt over at least part of the length in contact. If F is the actual, frictional force, which is related to the yarn extensions on either side of the belt, the choice of mode is given by:

$-F_A < F < F_A$ for the positive mode, changing from retarding to forwarding at $F = 0$ $F < -F_A$ (retarding) and $F > F_A$ (forwarding) for the slipping mode

In the positive mode, the velocity in the input zone PC must be V. Other conditions in the input and output zones will be as shown in Table 2.3. The situation is determined if T_1, V, v_2, and the relation $e = f_1(\omega)$ are known. The velocity and not the frictional force exerted by the belt needs to be known. The operative frictional force, $F = T_1 - T_2$. This is positive for a forwarding effect, when V is greater then v_2, and will be negative when the belt is slower than the output velocity as occurs when yarn is being drawn.

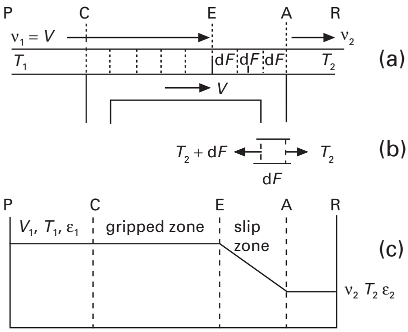
Where does the frictional force act in the positive mode? The situation is illustrated in Fig. 2.33. Since the yarn is being forwarded, its velocity, v_2, where it leaves the belt, must be less than the velocity, V, of the belt. Therefore it must be slipping at this point. This generates a friction increment, dF, which changes the yarn extension and hence its velocity. The increments continue back along the belt until the yarn velocity equals the belt velocity. For the rest of the length of the belt back towards the input side, the yarn and belt are moving at the same speed. This is effectively a gripped zone, though paradoxically no frictional force is acting – all the force needed to change the tension is applied in the slip zone. The change in yarn tension, and thus on yarn strain and velocity, is shown in Fig. 2.33(c). In the general case, there will be a non-linear variation of strain and velocity. The change to a fully slipping mode will occur when the length of the gripped zone decreases to zero and the slipping zone extends from A right back to C.

If yarn is being stretched, rather than forwarded, the yarn is moving faster as it leaves the belt, so that the frictional forces act in the opposite direction to increase the tension. In general for drive-roll systems, the yarn runs at the input velocity over the gripped zone on the input side until it reaches the slip zone and friction acts to change the tension and the speed.

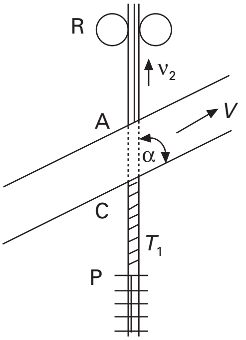
Table 2.3 Positive mode without twist

Zone:	PC	AR
Tension	T_1	$T_2 = \text{arc}\, f_1(e_2)$*
Strain	$e_1 = f_1(T_1)$	$e_2 = (v_2/v_0) - 1 = [(1 + e_1)v_2/V] - 1$
Velocity	$v_1 = V = (1 + e_1)v_0$	$v_2 = (1 + e_2)v_0$

* arc f_1 is the inverse of f_1, i.e. T_2 has the value satisfying $e_2 = f_1(T_2)$.



2.33 (a) Forces and velocities on the driving surface. (b) Tension change in first increment from A. (c) Variation of parameters along driving surface. From Hearle and Beech (1980).



2.34 Idealised friction-twisting system. From Hearle and Beech (1980).

How does the positive mode act in false-twisting? The yarn enters the spindle in a twisted state with both torque and tension. In order to twist the yarn, the drive, which we again take as a belt, must be running at an angle α to the yarn axis, as shown in Fig. 2.34. The yarn must enter at C with the same surface velocity as the belt and this continues through the gripped zone. On the output side, there will be a slip zone in which the frictional force changes the yarn torque and yarn tension.

The operating conditions for a yarn of radius a are shown in Table 2.4. For the tension effects, the only difference from Table 2.3 is that V is replaced by $V\cos\alpha$. For the rotational effects, we introduce the twists, τ_1 and τ_2, the resulting torques, M_1 and M_2, which are given as functions of twist by $f_2(\tau)$, and the angular velocities, ω_1 and ω_2, which define the rate of rotation of the yarn. If a rubber rod was passing through the system, M_2 would be zero, because the twist is zero, but, when yarn has been set in a twisted state, torque is needed to untwist it. The twist in the gripped zone

Table 2.4 Positive mode with twist

Zone:	Input side, gripped	Output, after slip
Tension	T_1	$T_2 = \text{arc}\, f_1(e_2)$
Strain	$e_1 = f_1(T_1)$	$e_2 = [(1 + e_1)\nu_2/V\cos\alpha] - 1$
Velocity	$\nu_1 = V\cos\alpha$	ν_2
Twist	$\tau_1 = \tan\alpha/2\pi a = \omega_1/V\cos\alpha$	$\tau_2 = 0$
Torque	$M_1 = f_2(\tau_1)$	$M_2 = f_2(\tau_2) = f_2(0)$
Angular velocity	ω_1	$\omega_2 = 0$
Surface velocity	$V\sin\alpha = 2\pi a\omega_1$	$2\pi a\omega_2 = 0$

* arc f_1 is the inverse of f_1, i.e. T_2 has the value satisfying $e_2 = f_1(T_2)$.

must equal the ratio of rotational and forward speeds; it is also given by $\tan\alpha$ and a. The system is determined if α, a, V, and the relation $M = f_2(\tau)$ are known.

The total frictional force, F, will have perpendicular components F_T, causing the tension change, and F_M, causing the torque change. The following relations will apply:

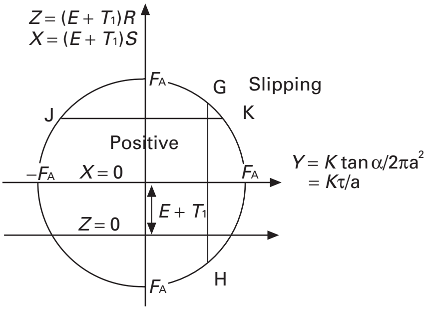
$$F_T = T_1 - T_2 \quad F_M = (M_1 - M_2)/a \qquad [2.10, 2.11]$$

$$F = \left(F_T{}^2 + F_M{}^2\right)^{1/2} \qquad [2.12]$$

The positive mode will operate when the required frictional force, F, is less than the maximum available frictional force, F_A. A detailed analysis (Hearle and Beech 1980) shows that the boundary between the slipping and positive modes can be represented as in Fig. 2.35. The yarn parameters, assumed to follow Hooke's Law, are: $T = Ee$, where E is the yarn modulus; $M = k\tau$, where k is the torsional rigidity of the yarn. The velocity parameters are: R = forward-velocity ratio = $\nu_2/V\cos\alpha$; S = velocity-difference ratio = $(\nu_2 - V\cos\alpha)/V\cos\alpha$. The coordinate parameters are: $X = (E + T_1)\,S$; $Y = k\tau/a$; $Z = (E + T_1)\,R$.

The limits of the positive zone are shown by the circle in Fig. 2.35. A line such as GH then represents the range of forward-velocity conditions for which a positive mode is possible with given twist conditions; and a line such as JK represents the range of twist conditions for given forwarding conditions.

One special case is of interest. When $V_2 = V\cos\alpha$, so that the yarn and belt have equal velocity components in the forward direction, the yarn will undergo no change in tension.



2.35 Summarising plot of conditions for positive and slipping modes. From Hearle and Beech (1980).

2.3.2.4 The reality of false-twist texturing

The effects in false-twist texturing differ in many details from the idealised system discussed above, whether in the slipping or the positive mode, although the principles presented help us to understand the mechanics of the practical systems. The differences come from the complications of fibre material properties, from the effects of high yarn twist, and from spindle geometries. There are too many uncertainties to make it worth attempting detailed analysis of real systems. The complications, which would have to be taken into account, are listed in Table 2.5. The nature of most of these is self-evident, but two require comment, because they introduce important principles.

The first is the possible shear zone. The frictional force causes the underlying material to be sheared. On the yarn side the thickness is so small that this will be negligible. But if the drive side is soft, there may be appreciable shear. The amount of slip will be reduced, since shear accommodates some of the yarn extension and change of speed. In the limit, which is probably true for rubber tyres, a shear zone completely replaces a slip zone.

The second is the anomalous torque-twist relation in twisted yarns. In false-twist texturing, the torque situation lies between the two possibilities indicated in Fig. 2.29(b) and repeated as O′P′ and C′D′ in Fig. 2.36. The yarn is set in the twisted form and so might be expected to fit the curve C′D′ with torque in the output zone but zero torque in the input zone. However, some torque would be needed to create the twist, even if this is resisted only by viscous drag. More important, the presence of tension in the twisted yarn dominates the situation and means that change is, in fact, from a torque in one direction in the input zone to a smaller torque in the opposite direction in the output zone, as in A′B′. These torque variations are all based on an assumption of linear torque-twist relations, namely, OP,

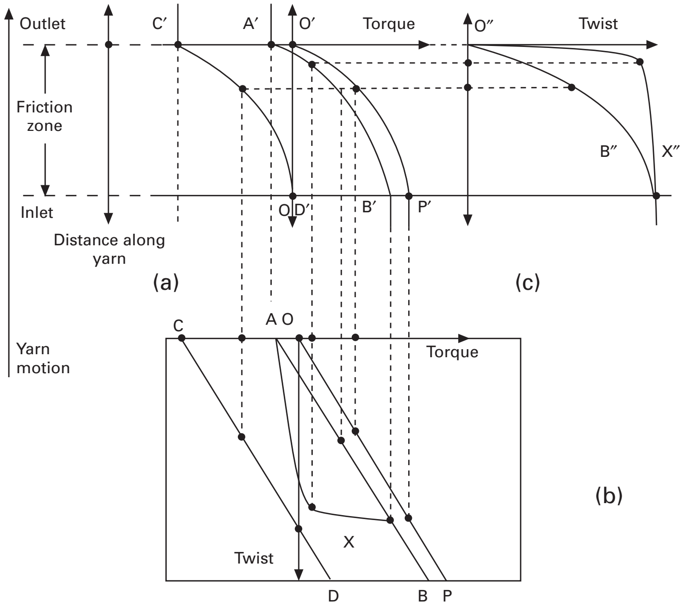
Table 2.5 Complications in real false-twist texturing systems

- the yarn path is often not straight, even in the static path over the friction surface
- the yarn may be displaced laterally by frictional forces
- the friction surfaces may have varying radii, giving different surface speeds
- the frictional force in disc and other curved drives comes from the yarn tension and not from an external normal load
- most fibre materials do not follow Hooke's Law, but will show large non-linear deformations with hysteresis and viscoelasticity
- setting will relax torque on the input side but lead to a torque at zero twist on the output side
- tension will cause torque in the twisted yarn on the input side
- the torque-twist relations in untwisting are highly non-linear
- there are large length changes associated with twist changes
- shear effects in the yarn or disc surfaces may cause a shear zone in the positive mode to be important
- the input side is usually governed by feed rollers and not by a tension device
- in draw-texturing, the tension will be determined by the force required to draw the yarn
- the friction law may be non-linear
- there may be a difference between static and kinetic friction, which gives stick-slip effects
- there will be inertial effects as yarn changes speed, but these are probably negligible
- there will be interactions between different parts of the system, which may change the overall response

AB, and CD in Fig. 2.36(b), and all relate to the same twist variation O″B″ in Fig. 2.36(c).

However, the form of the torque-twist relations in the untwisting yarn goes beyond a qualitative change and leads to a grossly different behaviour. The line AX in Fig. 2.36(b) shows the form of the torque-twist relation reported by Thwaites *et al* (1976). If we assume that the torque increments are unchanged, so that the torque changes along A′B′, we find the twist variation shown as O″X″. The effect is to sharpen up the twist change and to cause the twist to be substantially constant over much of the surface. In reality, the change in twist variation would cause a change in torque increments, and consequently a further sharpening of the twist variation would occur.

In the false-twist texturing system, it may therefore be reasonable to assume that the twist changes instantaneously at the point at which the yarn leaves the twister, **but this is a consequence of the torque-twist properties of the material and not of the mechanics of friction twisting**. It is a result of the fact that a very small change of torque is sufficient to take the yarn



2.36 (a) Torque variation for different locations of zero torque, on assumption of linear torque-twist relations. (b) Torque-twist relations: OP, AB, and CD are linear; AX is as reported by Thwaites *et al* (1976). (c) Twist variation: O″B″ is for linear torque-twist relations; O″X″ is a first approximation for the non-linear torque-twist relation, AX. From Hearle (1979a).

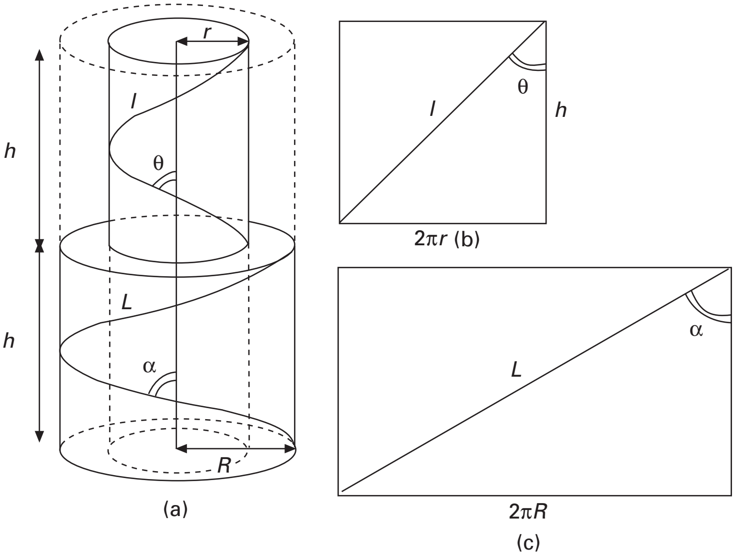
very close to its final twist value. This result would justify the treatments in the literature that deal with the friction twister as a whole instead of considering it in increments.

2.4 Structural mechanics of twisted yarns

2.4.1 Yarn geometry

The structure and mechanics of continuous-filament yarns have been extensively studied in relation to twisted yarns and cords used in tyres and other industrial applications, but the information also applies to the highly twisted yarns that are being set in false-twist texturing. Only an outline of the analyses, which lead to some useful equations, will be given here. Details can be found in other publications (Hearle *et al*, 1969; Hearle *et al*, 1980; Goswami *et al*, 1977).

Figure 2.37 illustrates the geometry of a twisted yarn with idealised geometry, in which filaments follow helical paths of constant pitch around



2.37 Idealised yarn geometry. (a) Twisted yarn. (b),(c) 'Opened out' diagram at surface. From Hearle *et al* (1969).

cylinders of constant radius. One problem is immediately apparent from the fact that the yarn is formed from parallel filaments, which are all of the same length, but the lengths in the twisted form increase from the centre to the outside. In practice, this is relieved by fibre migration. The filaments progressively change in radial position, as shown in Fig. 2.38. Over a short length, the geometry can be taken to be the idealised form, but over long distances the lengths are averaged out to be equal.

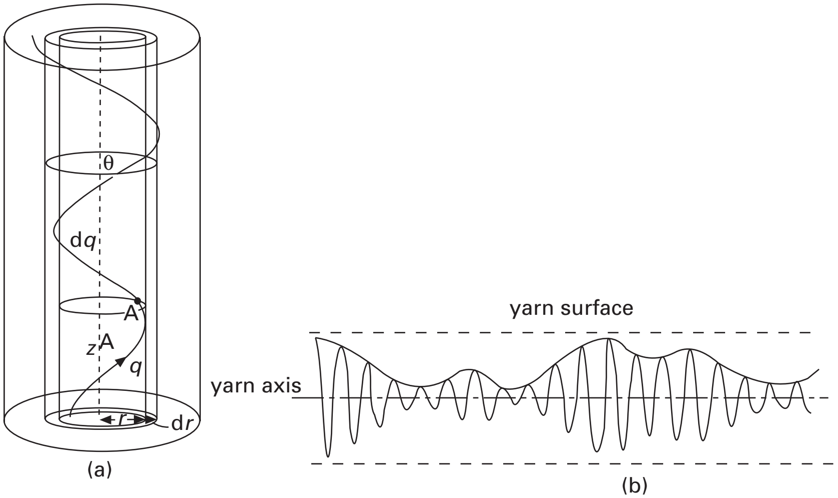
The geometry of the idealised form is easily seen by imagining cuts to be made along the cylinders of Fig. 2.37(a), and then opening them out flat to give Fig. 2.37(b,c). The sort of equations used in the analysis of the structural mechanics are Pythagoras's theorem and trigonometrical relations:

$$l^2 = h^2 + (2\pi r)^2 \quad L^2 = h^2 + (2\pi R)^2 \qquad [2.13, 2.14]$$

$$\tan\theta = 2\pi r/h \quad \tan\alpha = 2\pi R/h \qquad [2.15, 2.16]$$

$$l = h\sec\theta \quad L = h\sec\alpha \quad \text{etc.} \qquad [2.17, 2.18]$$

where l and L are the filament lengths and θ and α are the helix angles at intermediate radius, r, and at the yarn surface with radius, R. The length of one turn of twist is h, which is also the length of the straight fibre at the centre of the yarn.



2.38 (a) Short section of a migrating fibre in a twisted yarn. (b) Typical pattern of migration (*vertical scale increased relative to horizontal scale*). From Hearle *et al* (1969).

These geometrical equations are related to the practical quantities of yarn linear density, C, and twist, $N = 1/h$, through the yarn density ρ_y or its reciprocal, the specific volume ν_y:

$$C = \pi R^2 \rho_y = \pi (R^2/\nu_y) \qquad [2.19]$$

and

$$\tan\alpha = 2\pi RT = 2\pi^{1/2} \nu_y^{1/2} C^{1/2} N \qquad [2.20]$$

The above relations apply with a consistent set of units, such as strict SI. With C in tex, N in turns/cm, R in cm, ρ in g/cm^3 and ν_y in cm^3/g, they become:

$$R = (\nu_y C)/(10^5 \pi)^{1/2} \qquad [2.21]$$

and

$$\tan\alpha = 0.0112 \nu_y^{1/2} (C^{1/2} N) \qquad [2.22]$$

The quantity ($C^{1/2} N$) in tex$^{1/2}$ turns/cm is the twist factor of the yarn. It is a practical measure of the intensity of twist, since, for yarns of given specific volume, it defines a geometry with a particular twist angle α. Note that these quantities are given in terms of the twisted yarn dimensions. Corrections must be made for twist contraction, as described below, to express results in terms of the untwisted yarn linear density and the number of turns inserted into a length of zero-twist yarn.

The yarn density and specific volume are given by:

$$\rho_y = \phi \rho_f \quad \nu_y = \nu_f/\phi \qquad [2.23, 2.24]$$

where ϕ is the packing factor of fibres in the yarn, namely the fraction of the yarn cross-section occupied by fibre material.

If the filaments have a circular cross-section, the tightest geometry is hexagonal close-packing, for which $\phi = 0.92$. Any disturbance of the packing gives lower values of ϕ. However, as shown in Fig. 2.4, the distortion of filament cross-sections in draw-texturing means that the spaces between the fibres in the false-twisted state are almost completely squeezed out, and ϕ is close to one.

2.4.2 Twist contraction and twist limits

When the geometry of Fig. 2.37(c) is analysed, it turns out that all the filament lengths are present in equal numbers. In going from the centre to the outside of the yarn, the increase in area of elements of width d*r* is compensated for by the rate of change of length. This leads to a simple expression for the mean length l_m of the filaments:

$$l_m = (h + h\sec\alpha)/2 \qquad [2.25]$$

Yarn contraction on twisting can be expressed in two ways. The contraction factor, c_y, is the ratio of the untwisted length to the twisted length. The retraction, R_y, is the fractional reduction in length on twisting. This gives:

$$c_y = l_m/h = \tfrac{1}{2}(1 + \sec\alpha) \qquad [2.26]$$

$$R_y = (l_m - h)/l_m = \tan^2(\alpha/2) \qquad [2.27]$$

There is good agreement between these theoretical relations and experimental results for simple yarn twisting. In draw-texturing the filaments themselves will be stretched, so that the notional lengths of drawn filaments in untwisted yarns are applicable.

If it is specified that a given number of turns is inserted into a given length of yarn, and then the twisted yarn length is calculated from the above equations, a quadratic equation results. This has two roots which have a physical significance. The behaviour is similar to a trellis, which can be jammed tight in tension or compression. At intermediate positions there is space between the rods. The yarn differs in that only the solution in tension is of practical importance. The solution in compression has the same mean length of filaments, but a different distribution of lengths. The separation of filaments is seen if a twisted yarn is pushed into a shorter length.

The practical importance of this to twist-texturing is what happens as the number of turns is increased. Eventually, the yarn is jammed both ways. Mathematically, the quadratic equation has become a perfect square. In the trellis analogy, the thickness of the rods has increased to the extent that they are at right angles with no space between. This situation defines the maximum number of turns that can be inserted while maintaining the yarn geometry. If the machine forces more turns to be inserted, either the fibres must be stretched more, but this is limited by the draw ratio, or the yarn changes geometry into the double-twisted or over-twisted form, as in the cylindrical snarl of Section 2.6.2.

The twist angle in the limiting state is 70.5°. The maximum twist factor will be given by ($C^{1/2}N$) is equal to ($2500/v_y^{1/2}$) $\text{tex}^{1/2}$ turns/cm. Remember that this is expressed in terms of the twisted yarn dimensions. Since both the yarn linear density and the twist are reduced by a factor ($1/c_y$) if expressed in terms of the fully extended, zero-twist yarn, the twist factor will be reduced by $(1/c_y)^{3/2}$, or $1/(1 + \sec\alpha)^{3/2}$. In the limiting case, this reduces the maximum twist factor by 1/8 to ($310/v_y^{1/2}$) $\text{tex}^{1/2}$ turns/cm, or about 100 turns/cm for 10 dtex yarn. The twist insertion in false-twist texturing approaches close to these maximum possible values.

2.4.3 Fibre deformation in twisted yarns

Ignoring for the moment the effects of drawing and heat-setting in false-twist texturing and assuming that the material is perfectly elastic, we first deal with a twisted yarn under tension, in which fibres will experience extension, twisting and bending.

If the yarn extension is e_y, the fibre extension is approximately ($e_y \cos^2\theta$), decreasing from e_y at the centre to ($e_y \cos^2\alpha$) at the surface. The yarn-tension at a given extension is given approximately by multiplying the fibre tension at the same extension by $\cos^2\alpha$. There are more exact relations applicable to large extensions, but we do not need to worry about these details here.

When a yarn is twisted, the fibres in the yarn are also twisted, but because their radius is much less the twist angle is much lower. For a straight fibre at the centre of the yarn, the fibre twist factor is ($C_f^{1/2}N$) or [$(C_y/n)^{1/2}N$], where C_f is the fibre linear density and n is the number of filaments in the yarn. Thus, if there are 32 filaments in the yarn, the value of $\tan\alpha$ at the twist limit would be reduced to [$\tan(70.5°/\sqrt{32})$] in the fibre, which gives $\alpha = 26.5°$. For filaments away from the centre, the twist is further reduced by a factor of $\cos\theta$, rising to $\cos\alpha$ at the surface, due to the interaction of bending and twisting in a helix, which is discussed in Section 2.6.1. For a small, linear-elastic twist, the fibre torque is proportional to the shear modulus times the fourth power of the radius, but for larger twists the increase in length away from the centre of the yarn has a larger effect.

Fibre bending is derived in the following way. The length of fibre in one turn of the helix is $h\sec\theta$. If this length was bent into a circle, the radius would be $(h\sec\theta)/2\pi$. The curvature, c, which is the reciprocal of the radius of curvature, would be $(2\pi\cos\theta)/h$. However, due to the interaction of bending and twisting, it is reduced in the helix to $(2\pi\sin\theta\cos\theta)/h$, or, from equation [2.15], to $(\sin^2\theta/r)$. The bending curvature thus increases from zero at the centre of the yarn to $(\sin^2\alpha/R)$ at the surface. At the limiting twist, this equals $0.89/R$. A bending moment results from the fibre curvature.

Yarn torque is an important factor in false-twist texturing. It is made up of three components:

1 The sum of the torques in the fibres.
2 The sum of contributions from the bending moments.
3 The sum of contributions from the circumferential component of tension in the filaments.

In a twisted yarn under tension, the last term is the most important. Each fibre will contribute $(T_1 r \sin\theta)$ to this torque.

The above relationships provide the framework for consideration of the mechanics of the complete thread-line in false-twist-texturing, but we shall have to take account of facts, such as fibre tension equalling draw-tension, relaxation of twist and bending moments, and then their regeneration on untwisting.

2.5 False-twist texturing process

2.5.1 The sequence of zones

During false-twist texturing, the yarn passes through a series of zones, all of which have an influence on the final product. These are as follows:

1 An entry zone, where yarn is removed from the package and passes to the delivery rolls; the main effect here is to provide a small tension to control the yarn.

First-stage setting:
2 A cold zone, where the yarn is first twisted as it emerges from the delivery rolls.
3 A hot zone, where it passes through the heater and is more highly twisted.
4 A cooling zone.
5 The false-twist spindle.

Then either, for stretch yarns:
6 A post-spindle zone, leading to take-up rolls and wind-up.

Or, for set yarns with low stretch, second-stage setting:
6 A post-spindle zone.

7 The second heater.
8 A cooling zone.
9 A cold zone, leading to take-up rolls and wind-up.

For straight fibre paths and non-contact heaters, it follows that the yarn tension and torque will be constant through the zones in the first stage, and then again in the second stage. There will be minor changes if there is friction in the heaters or the yarn passes over guides.

2.5.2 Drawing, twisting and setting

In draw-texturing, the yarn tension in the first stage will be determined by the draw-tension of the hot yarn, which provides the lowest resistance to stretching. This will increase to some extent as the draw ratio, given by the relative speeds of take-up or intermediate rolls, is increased. The false-twist spindle, which acts as described in Section 2.3, generates the required twist, which is usually close to the twist limit. However, this twist varies back through the zones due to the differing torsional resistances.

The cold yarn emerging from the delivery rolls has a high resistance to extension and twisting. The fibres are not drawn and only a fraction of the yarn twist is inserted. Nevertheless, this twist is sufficient to establish the migration pattern of fibres in the yarn. Remember that if we twist a bundle of parallel filaments without migration, the straight centre path will be shorter than the outer helical paths. At the limiting twist angle of 70.5°, the surface path is three times longer than the central path. If there was no migration, this would lead to wide variations in fibre draw. It is essential to ensure that there is a sufficiently rapid interchange of position to avoid this. Some migration occurs because there is some change of position of filaments in the yarn as it enters the system. The major cause of migration is due to interchange of position in the small region where twist is being inserted. Fibres going into the core are being overfed, whereas those at the surface develop tension. Consequently, there is a drive to interchange position, particularly as the central fibres buckle.

It is important that the finish on the fibre should be low enough for migration to occur, and also to allow slip between central and outer fibre segments when draw takes place. Finishes on POY polyester are designed to give a low fibre-to-fibre friction at the low relative speeds involved and a higher friction between fibre and the friction-spindle surface at high relative speed.

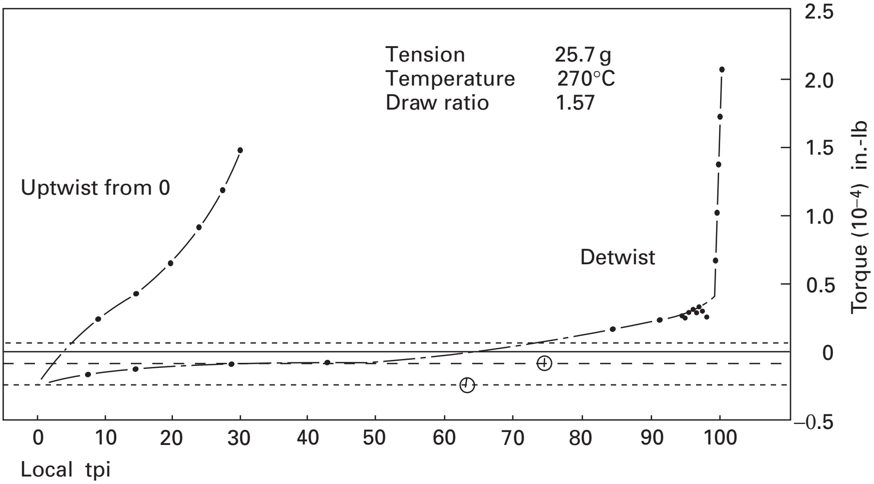
As the yarn comes onto the heater, the resistance to drawing drops, so that there is an increase in length. The torque and bending-moment contributions to yarn torque reduce, so that there is a twist increase. The yarn-tension component remains and controls the twist over the heater. This twist level is close to the final level, but there is a small change in the cooling zone, due to the change in mechanical properties of fibres with temperature, before the final level is reached.

There is another important change that occurs as the yarn comes onto the heater. The fibre tensions in the twisted yarn have substantial transverse components. The resulting lateral pressures on the soft, hot fibres deform their cross-sections, especially as the molecules are moving due to drawing. As shown in Fig. 2.4, the spaces between the fibres are almost completely eliminated. At the centre, the fibres are compressed to a hexagonal cross-section, but, near the outside, the obliquity due to the twist angle leads to more elliptical forms. The variation in shape and some variation in draw ratio between fibres have an influence on the detailed forms of fibre buckling and other features of the final product.

For the reasons described in Section 2.2.6, the sequence between the delivery rolls and the spindle sets the yarn in its twisted state. Heating is the obvious cause of setting, but the molecular rearrangement in drawing also plays a part. However, cooling is perhaps even more critical. If a hot yarn is untwisted, it would become set in the untwisted state. It is necessary to cool to stabilise the set. The effect of the heat is to relax the internal stresses the fibres, which are thus set in a twisted and bent helical form. If yarn is snatched from the end of the cooling zone, it remains in the twisted state, with a slight change if tension is removed.

2.5.3 Untwisting

Although, as discussed in Section 2.3, it is the spindle which causes the yarn to twist, from the point of view of the yarn, the spindle is an untwisting zone. However, unlike a simple elastic rod, the torque-twist response in untwisting is highly non-linear. Thwaites *et al* (1976) measured the untwisting of a draw-textured polyester yarn, which had been snatched from the cooling zone before the spindle (Fig. 2.39). Initially, at the twist of 100 units, the torque is high, but it falls rapidly from two units to 0.4 units as a very small amount of twist, only about one unit, is taken out. Then over the remaining 99 units of untwisting, the torque falls steadily to about –0.2 units when it is fully untwisted. On twisting up again, the torque increases almost linearly. Thwaites *et al* (1976) point out that this untwisting response has two important consequences. Firstly, it means that most of the twist is removed just before the yarn leaves the spindle, as discussed in Section 2.3.2.4. Secondly, it means that, roughly between the lines (a) and (b) in Fig. 2.39, a high twist level in partially untwisted yarn can be in equilibrium with a low twist level in retwisted yarn. This explains why twisted tight spots can persist in a yarn that is mostly untwisted.



2.39 Torque-twist response of polyester yarn snatched from the cooling zone. *Note*: 25.7 g = 252 m N; 10^{-4} in-lb = 11.3 μN m; 100 tpi = 39 turns/cm. From Thwaites *et al* (1976).

2.5.4 Beyond the spindle

In a single-heater machine, the yarn emerging from the spindle, which is held straight under tension, will contain the torque resulting from the untwisting of the fibres which have been set in the helical form. This torque remains in the yarn as it is wound on the package, but, particularly for nylon, it will be reduced over time by stress relaxation. The stretch characteristics need to be reactivated by heat, moisture or mechanical action.

In a double-heater machine, the yarn is re-set in another form. It is allowed to contract by 10–20% with a form of buckling which is discussed below. Tension is low, so that non-contact heaters are used. As discussed in Section 2.2.6, the temperature needed to re-set polyester yarns can be less than the temperature of setting on the first heater.

Because of the heat, internal stresses are relaxed, and, because the twist is zero, there is no tension contribution to yarn torque, which must be zero between the spindle and the take-up rolls. However, as mentioned above, the yarn emerging from the spindle would contain torque at zero twist. Consequently, for the torque to drop to zero, the yarn must reverse twist as it comes from the spindle and then twist back again to zero on the heater. Once again, there are small changes as the yarn cools after the heater. Wind-up runs faster than the take-up rolls, in order to pull the yarn straight on the package. Removal of the crimp in the yarn generates a torque in it.

2.5.5 Heating and cooling

Two factors must be taken into account in considering the action of yarn heaters:

1 the time taken to heat the yarn to the required temperature;
2 the time taken to generate the necessary changes at the molecular level.

For the first heater, in draw-texturing, the second factor is unimportant because deformation controls the molecular rearrangement. On the second heater, only partial relaxation may be needed, so that again the second factor is less important. The first factor must also be taken into account in cooling, though, since this is a stabilisation rather than a relaxation, the second factor is not involved. Heat transfer can involve all three modes of heating: radiation, conduction and convection.

In contact heaters, which are usual for the first heater, the main mechanism will be conduction from the hot surface to the contacting yarn. Since the yarn is rotating, heat will come in from all sides and the surface temperature of the yarn will equal the heater surface temperature. The yarn is highly twisted and, in draw-texturing, the filaments are squashed, so that the yarn is almost a solid rod of polymer material. In a uniform homogeneous cylinder in the absence of internal heat generation, the temperature, T, at time, t, at a radial position, r, is governed by the following equation, in which the right-hand side shows the thermal gradient and the left shows the rate of heating:

$$\rho c(\partial T/\partial t) = k[(\partial^2 T/\partial r^2) + (1/r)(\partial T/\partial r)] \qquad [2.26]$$

where ρ is fibre density, c is specific heat and k is thermal conductivity.

The important determining factors, which govern the rate of approach to equilibrium, are the thermal diffusivity, $(k/\rho c)$, which is the ratio of thermal conductivity to thermal capacity per unit volume, and the yarn radius. In the simplest model, the boundary conditions are:

1 that the yarn enters the heater at a constant temperature throughout;
2 the yarn surface temperature equals the heater temperature.

The solution of this equation is an exponential approach to a constant temperature.

In reality there are various complications. In draw-texturing, there is internal heat generation due to the heat of drawing. Part of this occurs at the feed rolls, so that the entry temperature may not be the same as the ambient temperature and, due to cooling in the cold zone, may vary through the yarn. Most drawing occurs as the yarn comes onto the heater and the rise in temperature reduces the draw tension. Effectively, this heating can be regarded as giving a higher temperature at the start of heat transfer.

There will be some additional frictional heating as the yarn passes over the heater.

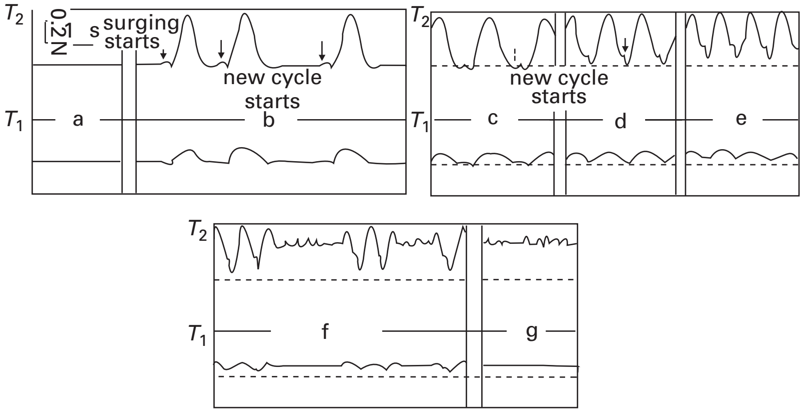
In order to reduce the length of heaters, the first section can be at a higher temperature than the last section. There is then a faster initial increase in temperature towards a higher asymptotic value, which is followed by slower approach to the final temperature.

In non-contact heaters, which are used for the bulky yarn on the second heater, heat is transferred to the yarn by radiation from the internal surface of the heater and by convection from the hot air. The fibres are separated from one another, so that the most important factors will be the heat transfer coefficients. Conduction through the small fibre thickness will be rapid.

2.5.6 Surging

In the early years, the speed of false-twist texturing machines was limited by mechanical factors, principally the rate at which spindles could twist yarn. With the development of friction twisting and high-speed winders, this limitation no longer exists. Machines could be engineered to run at several thousand meters per minute, though there might be problems with the length of heaters. The current limitation is a process problem. At some critical speed, large fluctuations in tension start to occur and defective yarn is produced. This phenomenon is known as surging. In commercial operations the onset of surging is typically between 700 and 1000 m/min. The exact speed depends on the particular machine, operating conditions and yarn, but no matter what type of machine is used, surging is unavoidable. Experience indicates that the shorter the yarn path, the higher the surging speed.

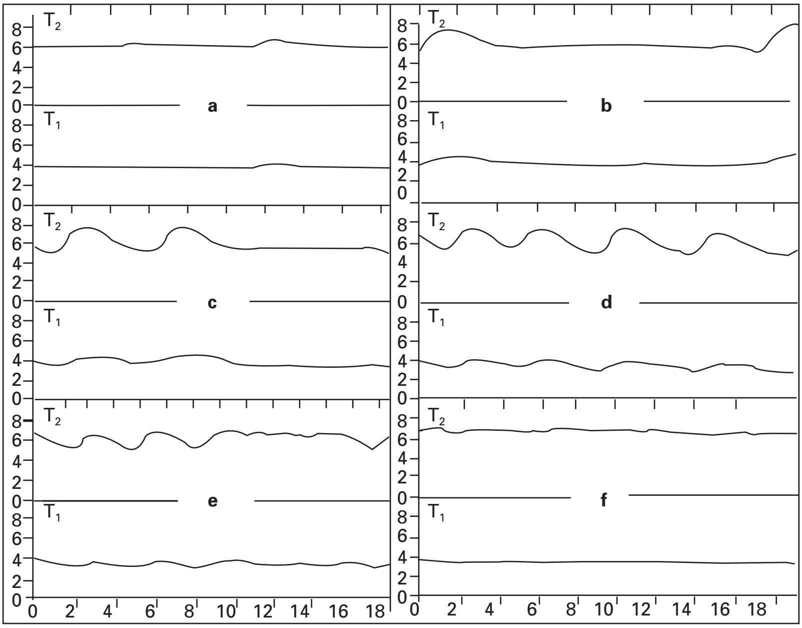
Du and Hearle (1989a,b) have reported a study of the incidence of surging. Figure 2.40 shows plots of tension, T_1 before and T_2 after the spindle, at increasing speed when texturing polyester yarn on a single-heater, commercial machine. At 710 m/min, the tensions are almost constant and good yarn is produced. Then at 720 m/min, there are bursts of high tension, which become continuous fluctuations at 740–800 m/min. At 820 m/min, the large fluctuations alternate with periods of reduced tension variations. Finally, at 830 m/min, the system has settled down into a new, steady state with a small, irregular variation in tension. This shows that surging in itself is not the problem that needs to be explained. The major effect is that the process can operate in two modes. Below a critical speed, the process operates properly. Above a higher critical speed, it operates in a different mode and produces bad yarn. Surging occurs over a limited range of speeds, when the system is flipping between the two modes. The unsolved problem is to know how the system is operating above the critical speed.



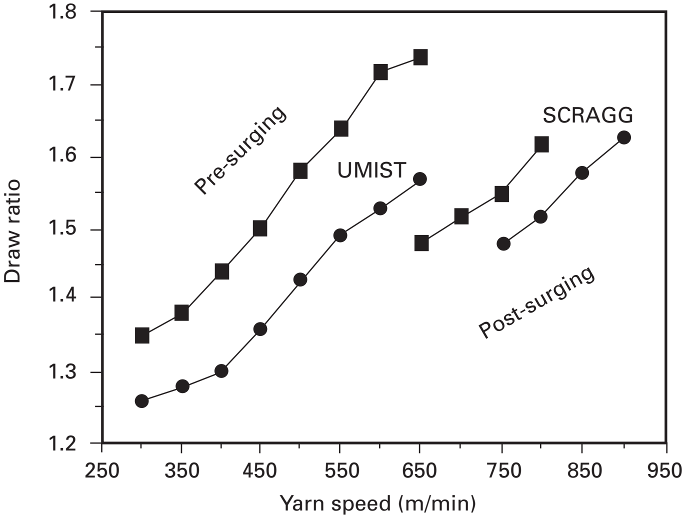
2.40 Profiles of tension T_1 before spindle and T_2 after spindle at increasing speeds, when texturing polyester yarn on a commercial machine. Yarn speed in m/min: (a) 710; (b) 720; (c) 740; (d) 770; (e) 800; (f) 820; (g) 830.

A more extensive study was made on a laboratory rig with a horizontal, single-heater arrangement. Figure 2.41 shows that the change from the pre-surging to the post-surging mode occurs with decreasing draw ratio at a constant speed. The beginning and end of surging occur at lower and higher critical yarn speeds, and Fig. 2.42 shows how these vary with draw ratio in the experimental and commercial set-ups. Other effects investigated in the research study included the effect of different factors on the critical speeds, the amplitude and wavelength of surges, yarn twist levels, and the characteristics of the yarn produced. From a practical viewpoint, the most interesting results were that the critical speeds were greater at higher D/Y ratios, see Section 4.3.3 (Fig. 2.43). Surging was found with both disc spindles and crossed-belt twisters, and with drawn yarn feed as well as POY. In surging conditions the yarn produced was very irregular, which causes *barré* in dyed fabrics. In post-surging, the yarn crimp and bulk were lower and there was an alternation of residual S and Z twist along the yarn.

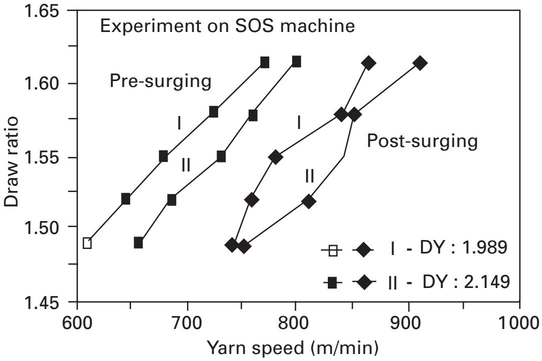
There are many possible causes of unstable texturing operation. Intermittent twist slippage occurs if there is an inadequate grip of the yarn on the spindle. At low tension and high twist, there may be intermittent double-twisting, which is another name for the cylindrical snarling described in Section 2.6.2. However, even when these causes are eliminated by suitable operating conditions, instability occurs above a critical speed, which decreases as yarn tension decreases. The causes of the post-surging mode of operation have not been resolved, but it appears to be a dynamic interaction between the yarn and the machine, which leads to intermittent loss



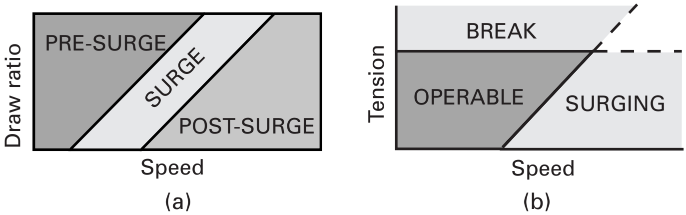
2.41 Profiles of tension T_1 before spindle and T_2 after spindle at decreasing draw ratio at 650 m/min, when texturing polyester yarn on a laboratory rig. Draw ratios: (a) 1.73; (b) 1.71; (c) 1.70; (d) 1.65; (e) 1.60; (f) 1.57.



2.42 Critical speeds and draw ratios for the laboratory (UMIST) and commercial (Scragg) experiments.



2.43 Effect of D/Y ratio on critical surging speeds on a commercial machine.



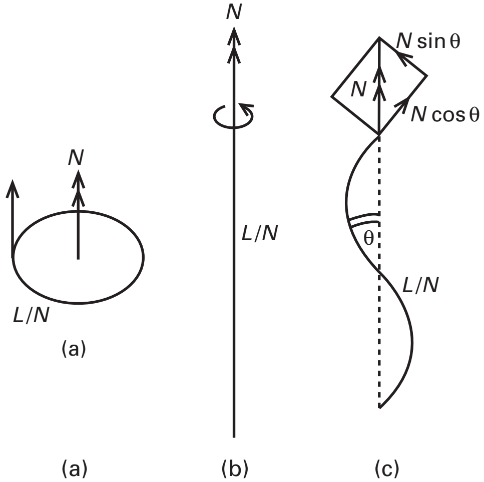
2.44 (a) Schematic of conditions for surging. (b) Operable zone for texturing.

of twist control. The occurrence of the three modes of operation is summarised in Fig. 2.44(a) and the practical operating conditions in Fig. 2.44(b). In order to maximise production speeds, the yarn tension should be high, but cannot exceed the limit that causes yarn breakage.

2.6 Twisting, bending and buckling

2.6.1 Interaction of twisting and bending

In two dimensions, planar bending is an independent action, (Fig. 2.45(a)). In one dimension, as seen in Fig. 2.45(b), uniaxial twisting is an independent action. Both diagrams have one turn over the length shown. Between these two extremes, there is the helical form of three-dimensional buckling, shown in Fig. 2.45(c), which combines twisting and bending in proportions given by the vector diagram. For N turns per unit length, the twist N_t is given by $N\cos\theta$, going to N when $\theta = 0°$. The bending depends on $N \sin\theta$, going to N when $\theta = 90°$. The length of one complete turn in



2.45 Interaction of twisting and bending. (a) Pure bending. (b) Pure twisting. (c) Mixed bending and twisting. From Hearle and Yegin (1973).

Fig. 2.45(a) is $1/N$ and this equals $2\pi r$, where r is the radius of curvature. Hence the bending curvature, c, which is the reciprocal of r, is given by $N/2\pi$, reducing to $(N/2\pi)\sin\theta$.

It is, of course, possible to impose an additional twist, or reduce twist, on a yarn in a bent configuration. Indeed different ways of forming a circular loop may lead to the presence or absence of twist. The above expressions relate to the condition in which the circular loop has zero twist. In detailed treatments of this subject, it is necessary to distinguish between two modes of expressing torsion and curvature (Konopasek, 1980). These are based on different coordinate systems, both of which change in direction as they move along the curve by a distance, s. First we define the curved path through space in purely geometric terms. The tangent to the curve defines its local direction, x. Perpendicular to the tangent in the plane containing the curve is the normal, y, and perpendicular to both of these is the binormal, z. Second we define the physical deformation of the fibre, yarn or rod. The local direction, u, is the same as, x, but the two orthogonal coordinates, u and v, are in fixed directions in the material. In general, the choice of direction for u and v is arbitrary, but, for simple shapes, there will be natural directions to choose. For example, for an elliptic cross-section it is convenient to take the directions of the major and minor axes. The rotation of these axes gives the twist in the fibre, and the direction of the geometric curvature relative to u and v defines the direction in which the fibre is bent.

From the twist and curvature, it is possible to calculate or measure the twisting torque and the bending moment, as discussed in Section 2.2.8. However, the twisting and bending energies are more useful quantities for analysing buckling mechanics. We will represent the twist energy by $\mathcal{J}$ and the bend energy by $\mathcal{B}$. In general these will be non-linear functions, but for the small-strain, linear-elastic case, with torsional rigidity, R, and bending stiffness, B, the energies for a length, L, are given by:

$$\mathcal{J} = \tfrac{1}{2}(\text{torque}) \times (\text{twist in radians}) = \tfrac{1}{2}(2\pi)RN^2L \tag{2.27}$$

and

$$\mathcal{B} = \tfrac{1}{2}(\text{bending moment}) \times (\text{curvature}) = \tfrac{1}{2}Bc^2L \tag{2.28}$$

For circular fibres, these equations give the energies in Joules as:

$$\mathcal{J} = \left(\pi n C_\mathrm{f}^{\,2} N^2 / \rho\right) L \times 10^{-7} \tag{2.29}$$

and

$$\mathcal{B} = \left(E C_\mathrm{f}^{\,2} c^2 / 8\pi\rho\right) L \times 10^{-7} \tag{2.30}$$

where n and E are shear and tensile moduli in N\tex, C_f is linear density in tex, ρ is density in g/cm^3, N and c are twist in turns per unit length and curvature in cm^{-1} and L is length in cm.

For non-circular cross-sections, the shape factors ε and η must be included. If the fibre cross-section is asymmetric, the bending stiffness will vary with the direction of bending. There are two principal bending moments, B_1 and B_2, which are the maximum and minimum values at right angles. For an ellipse, these would correspond to bending about the major and minor axes. In other directions the bending stiffness will be $(B_1^{\,2}\cos^2\phi + B_2^{\,2}\cos^2\phi)^{1/2}$, where ϕ is the angle to the direction of maximum stiffness. It is easier for the fibre to bend over the narrowest cross-section and this will influence the form of buckling.

For boundary conditions, specified by the position and direction of the fibre ends, the fibre will take up a form that minimises the sum of the twist and bend energies. If tension, torque or bending moments are included in the boundary conditions, as alternatives to position and direction, potential energy terms are added to the sum of the energies. Qualitatively, the important points to note are that twisting energy increases with the square of the twist and the shear modulus, bending energy increases with the square of the curvature and the tensile modulus, and both increase with the fourth power of the fibre diameter (square of linear density). For large deformations, the energies will be given by the area under the load-deformation curve, instead of by the simpler form $\frac{1}{2}$(stress × strain). For high twists, extension of the outer layers contributes more to twist energy than the shear.

In torque-stretch yarn, whether produced by false-twist texturing or the old long method, a yarn is set in a twisted configuration and then untwisted.

In the set state, the fibres are both twisted and bent. When the yarn is untwisted and held straight, the fibres will therefore have high bending and twisting energies. This can be relieved by allowing the yarn to contract into a buckled form. In order to explain what happens, we first deal with the two simpler cases of fibres set in pure twisted and bent states, and then consider the response in the combined state.

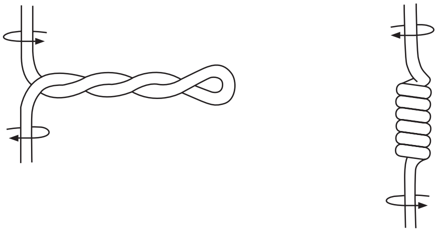
2.6.2 Snarling of a straight twisted filament

A fibre which is untwisted from a set state behaves like a twisted rubber rod. The response is easily demonstrated by twisting a length of rubber from an elastic band between the fingers. In order to hold the rod straight, tension must be applied. If the rod is allowed to contract, it forms a pig-tail snarl, as shown in Fig. 2.46(a). This has been called a '*normal*' snarl, because it is the common form and because it is perpendicular to the rod. Similar pig-tails are found in false-twist textured yarns.

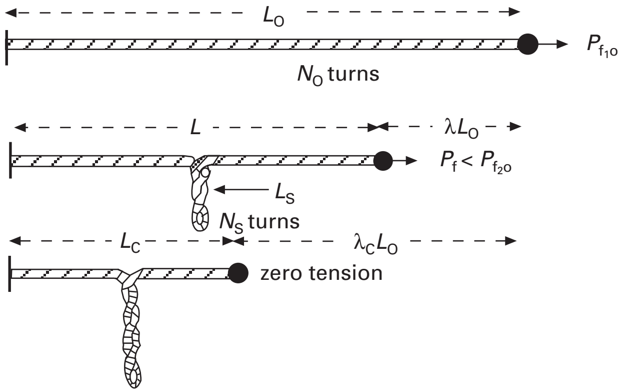
If the rod is very highly twisted, it buckles in a different way and forms a '*cylindrical*' snarl as shown in Fig. 2.46(b). The latter is not relevant to textured yarns as products, but it is the form taken up if an attempt is made to insert excess twist during texturing. This is referred to in Section 2.5.6 as an over-twisting instability.

Both of these problems have been solved, for the rubber rod, by energy minimisation (Hearle, 1966; Hearle and Yegin, 1972a,b, 1973) and confirmed by experiment. Since fibres have more complicated mechanical properties, the mathematics is not directly applicable, so only the essential principles of the argument will be given here.

Figure 2.47 shows a twisted filament held straight under tension $P_{f,o}$, which then contracts to form a snarl with a helix angle θ. Each turn of the snarl removes one turn of twist from each end of the filament, but because of the interaction of bending and twisting, additional turns are generated in each arm of the snarl. The net effect is a reduction of twist of $2\cos\theta$ turns for each turn of the snarl. The bending energy in the


(a) (b)

2.46 (a) Normal or pig-tail snarl. (b) Cylindrical snarl.



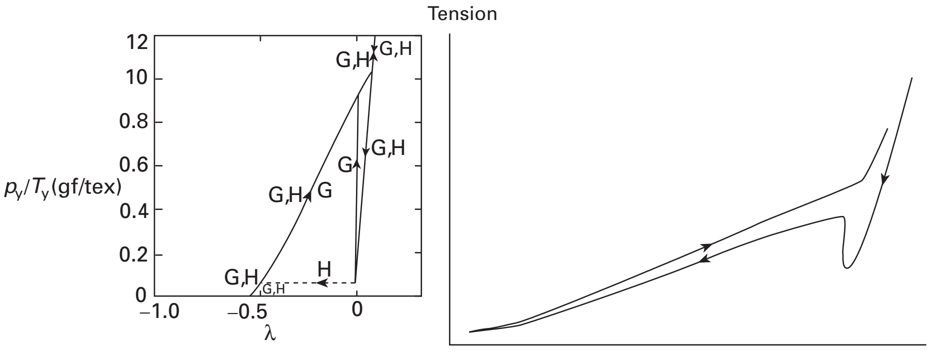
2.47 Snarling in a twisted rod at reducing tension. (λ is extension ratio).

snarl must also be taken into account. The overall effect is that the total energy $\mathcal{E}$, when the length reduces from L_o to L as the tension drops to P_f, is given by:

$$\begin{aligned}\mathcal{E} &= \text{potential energy}\uparrow + \text{twist energy}\downarrow + \text{bending energy}\uparrow \\ &= P_f(L_o - L) + \mathcal{J} + \mathcal{B}\end{aligned} \qquad [2.31]$$

The arrows show which terms are increasing and which are decreasing as the filament contracts. There are two variables to take into account: the length, L, which is given by the extension ratio, $\lambda = (L - L_o)/L_o$, and the helix angle θ in the snarl. In the mathematical analysis of the linear-elastic case, the minimum energy state is given by $\partial\mathcal{E}/\partial\lambda = 0$ and $\partial\mathcal{E}/\partial\theta = 0$. Two different cases are considered: zero-friction, in which the snarl helix angle can continuously readjust and infinite friction, in which each turn of the snarl is locked in as it is formed.

The analysis indicates what will happen during extension and contraction when a snarl is present. However, the initial formation of a snarl requires a critical condition to be overcome. This is similar to the buckling of a beam under compression: as the force is increased, a critical point is reached at which the beam buckles, but during recovery on reduction of the force the buckle is gradually removed. The theoretical prediction of the contraction and recovery curves is shown in Fig. 2.48(a), arbitrarily placed between the models for locked and redistributed twist. Figure 2.48(b) shows an Instron trace of the contraction of a highly twisted rubber rod. At the start, it is straight under tension. As the length reduces, the tension drops rapidly, due to the reduction in tensile strain of the straight rod, until the critical point A is reached. At A, the snarl forms and the tension rises. This is followed by the long contraction in length as the snarl grows with a slow reduction in tension. There is a small amount of hysteresis, due to friction, as the snarl



(a) (b)

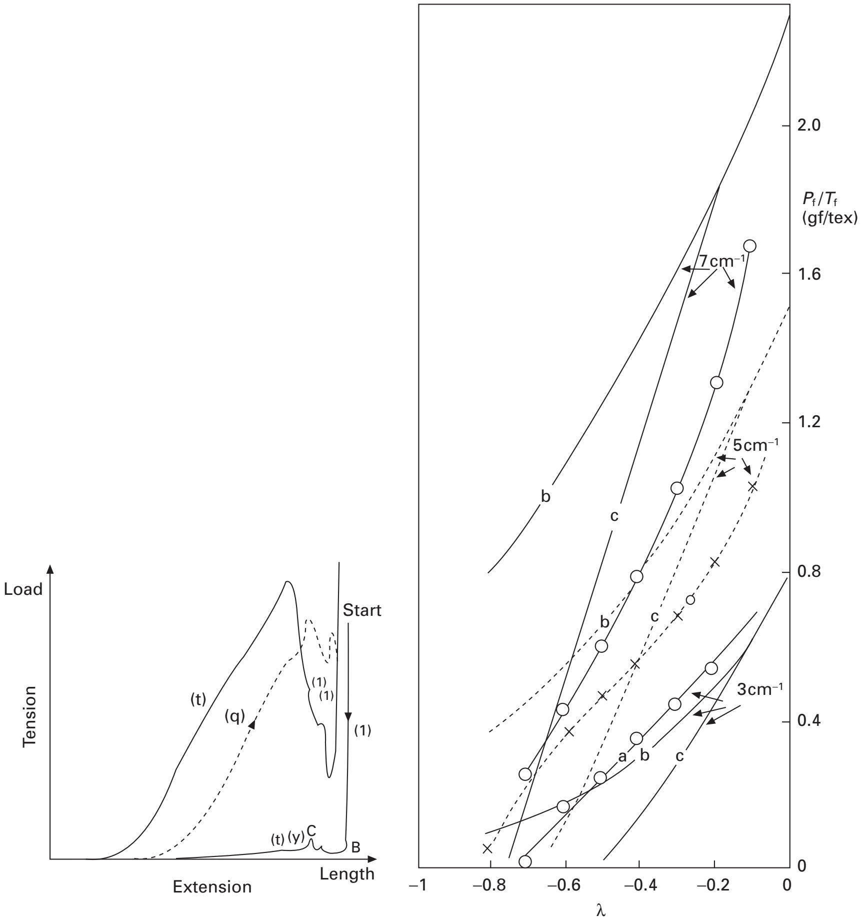
2.48 (a) General form of predicted relations. G–G is the expected form in constant rate-of-extension testing and H–H is expected in constant rate-of-loading. The recovery line is put between those for locked and redistributed theory. From Hearle (1966). (b) Observed response of a twisted rubber rod. From Hearle and Yegin (1972a).

is pulled out. Because of the visco-elastic properties of the material, the behaviour of a nylon monofilament (Fig. 2.49(a)) is rather different. Some intermediate buckled forms appear between B and C when the main snarl forms. The rise in tension is much less. There is a high level of hysteresis between contraction and extension of the snarl, and the ninth cycle of pulling out of the snarl shifts appreciably from the first cycle. Figure 2.49(b) shows a comparison of theoretical and experimental plots for the nylon filament at different twist levels as the snarl is pulled out.

The energy equation for a cylindrical snarl has the same form as equation [2.32]. However, as can be seen from Fig. 2.46, the length of one turn of the snarl is much less than for the normal snarl. The reduction in twist energy is therefore much greater. Consequently this form of snarling is preferred at high twist levels, despite the greater increase in bending and potential energy.

2.6.3 Buckling of a straightened bent rod

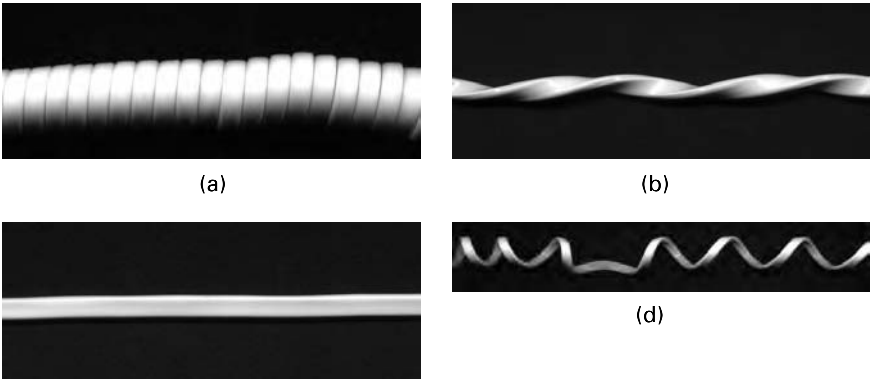
The second case to consider is the behaviour when the set deformation is bending without twisting. If a virtual rod is bent round at constant curvature, it would form a series of overlapping identical circles. Mathematically, this is possible, but the closest in reality is a closely packed coil, such as the telephone cord shown in Fig. 2.50(a). If the rod is pulled out without allowing the ends to rotate, it becomes twisted, as shown in Fig. 2.50(b). However, the case that we want to deal with is what happens when the cord is straightened out and untwisted (Fig. 2.50(c)), and then allowed to contract. In order



(a) (b)

2.49 (a) Observed stress–contraction response of nylon monofilament in the 1st and 9th cycles. (b) Stress–contraction curves for nylon monofilament at different twist levels: a, experimental; b, theoretical with redistributed twist; c, theoretical with locked twist. From Hearle and Yegin (1972a).

to reduce its energy, the cord wants to bend back into its set form, but it cannot do this without inserting twist. The way out is to form two helices of opposite sense, with the centre point rotating to provide the twist in each section (Fig. 2.50(d)). Equation [2.31] again applies, and the minimisation of energy determines the amplitude and period of the helices and the amount of rotation at the centre.



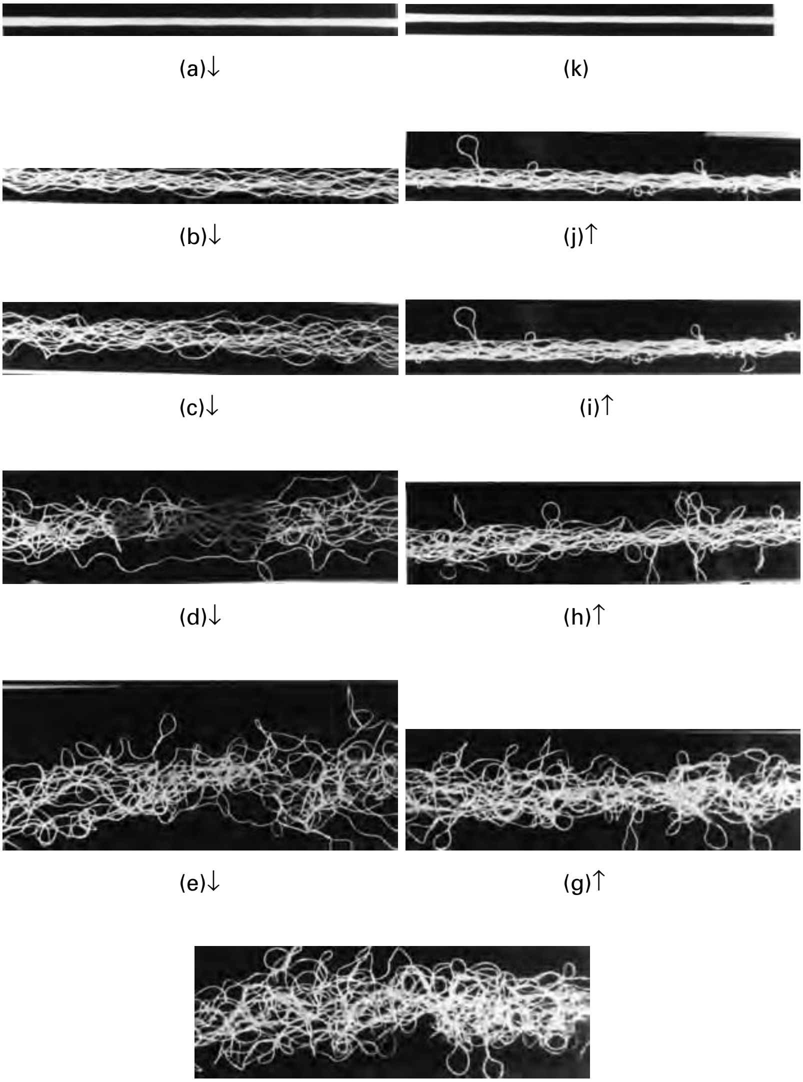
(a) (b) (c) (d)

2.50 (a) A telephone cord which is a close-packed coil without twist along the cord. (b) Pulled straight. (c) Untwisted. (d) Contracted from the untwisted state.

2.6.4 Buckling of fibres in torque-stretch yarns

The untwisted, straight filaments in a torque-stretch yarn are in more complicated and varied states of strain than the two cases considered so far. In the set yarn, fibres at the centre will be purely twisted, but those out from the centre will be both bent and twisted with the helix angle increasing to a maximum at the yarn surface. Furthermore, due to migration, the forms will alternate along a fibre, and the differences in fibre cross-section, shown in Fig. 2.4, will influence the buckling behaviour. Yegin (1969) analysed many idealised situations to determine minimum energy forms. However, it is more useful to see what happens in practice.

Figure 2.51 shows the change in form of a torque-stretch nylon yarn as it is allowed to contract and is then pulled out again. In the fully extended state (Fig. 2.51(a,k)) the yarn is densely packed with a small diameter. At 10 and 20% contraction (Fig. 2.51(b,c)), the relief of bending stresses is dominant and the filaments take up a crimped form. The crimp gives a high bulk to the yarn and is the form in which the yarn is set on the second heater in the production of low-stretch, high-bulk, set-textured yarns. At 40% contraction (Fig. 2.51(d,e)) the relief of twist energy comes in and pig-tail snarls start to form. At 60% and under zero tension at 70% contraction (Fig. 2.51(f,g)) there is extensive snarling. This provides the high-stretch character of single-heater, false-twist-textured yarns. Based on the contracted length, the yarn would have a stretch of 233%. The behaviour in extension is different from that in contraction. As the yarn is extended (Fig. 2.51(h–k)) the pig-tails pull out one-by-one and the alternating helix form does not appear.



(a)↓ (k)

(b)↓ (j)↑

(c)↓ (i)↑

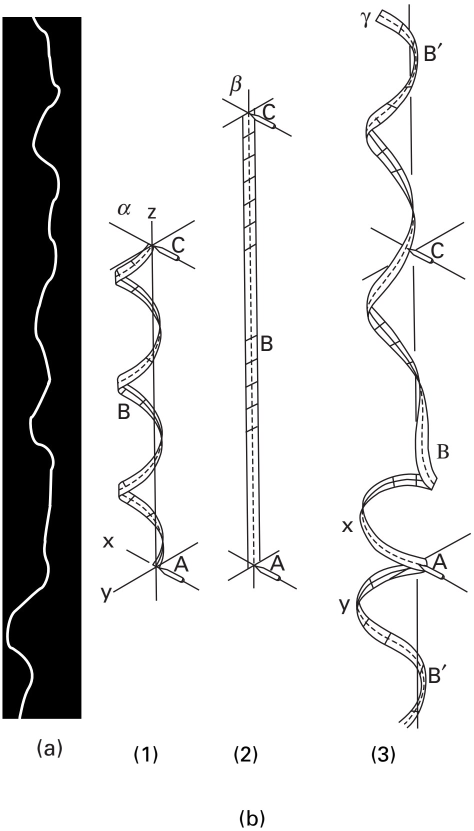
(d)↓ (h)↑

(e)↓ (g)↑

(f)↑

2.51 Appearance of a nylon torque-stretch yarn in contraction and extension. Contracting: (a) 0%; (b) –10%; (c) –20%; (d) –40%; (e) –60%; (f) –70%. Extending (related to fully extended length): (g) –60%; (h) –40%; (i) –20%; (j) –10%; (k) 0%.

A close examination of the crimp at 10–20% contraction shows that the filaments form alternating right- and left-handed helices with reversals between (Fig. 2.52(a)). Because of the twist, the helices are asymmetric, as is clearly seen in the computed model as Fig. 2.52(b).



2.52 (a) Filament extracted from nylon torque-stretch yarn at –20% contraction. (b) Theoretical computation by Konopasek (1980) of fibre form: (1) heat-set, force-free form; (2) untwisted straight under tension; (3) a longer length of fibre allowed to contract.

Yarn bulk is given by measurements of yarn volume, but the usual way of characterising textured yarns is in terms of the difference between the contracted and extended lengths. Test standards differ on the precise measurement conditions, but the general definition[3] is:

$$\text{crimp contraction} = (\text{straight length} - \text{bulked length})/\text{straight length}$$

---

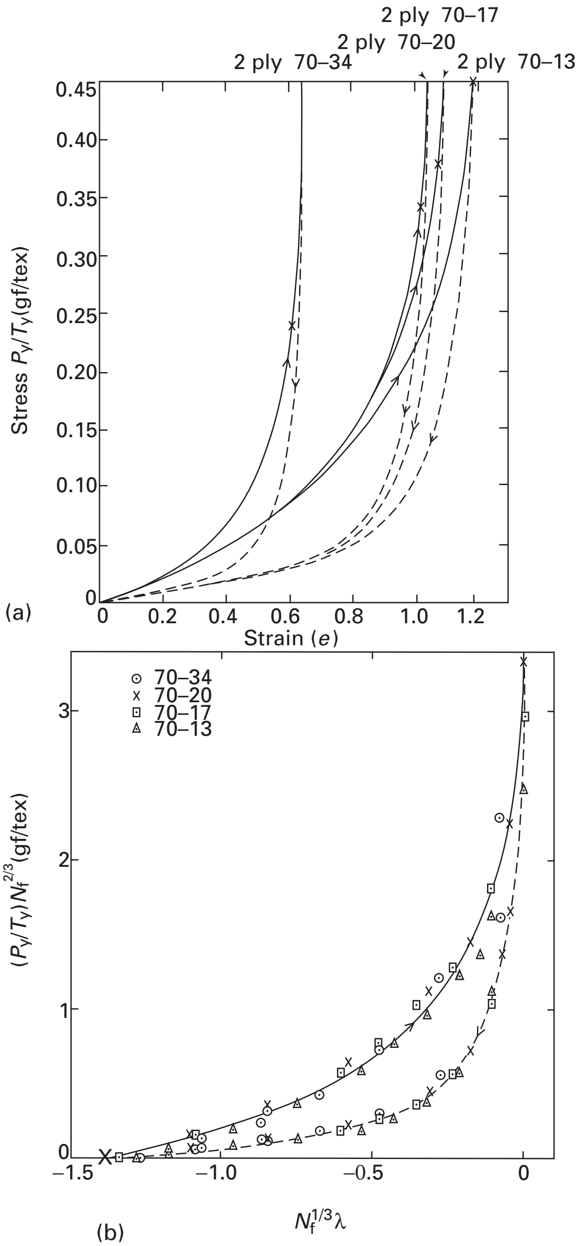
[3] Terminology is various. '*Crimp contraction*' or '*crimp retraction*' is the preferred term in Europe; '*crimp rigidity*' relates to a particular test method for crimp contraction. In the USA, textured yarns are usually characterised by the '*skein shrinkage*' (sometimes called '*residual shrinkage*'), which is the actual shrinkage, i.e. reduction in length, of filaments when heated.

Filament size is important in determining yarn properties. Figure 2.53(a) shows plots of the stress–strain curves of nylon torque-stretch yarns, which are all of the same linear density (77 dtex), but have different numbers of filaments (13, 17, 20, 34). The yarns with fewer and thicker filaments show higher degrees of stretch. The curves do not go to high enough stresses to show the extension of the straight yarn, but the crosses, which show estimates at the same fractions of the stress needed to pull out the crimp, indicate that more force is needed for the thicker filaments. Both the stretch and the power are increased by reducing the number of filaments in the yarn. Although, because of non-linearity and other factors, the theory of pig-tail snarling in Section 2.6.2 is not directly applicable to predictions of torque-stretch yarn properties, the theory shows a dependence on a reduced stress, $(P_y/T_y)N_f^{1/2}$, and a reduced strain, $N_f^{1/2}\lambda$, where P_y is tension, T_y is yarn linear density, N_f is number of filaments and λ is the extension ratio (negative in contraction). When the estimated fibre extension is subtracted and the data are replotted in terms of the reduced variables, all four curves fall on the same lines (Fig. 2.53(b)).

2.7 Variability

Variability can arise in false-twist textured yarns from many causes – in the feed yarn, in process conditions, or in subsequent handling and manufacturing. There may be differences in fibre linear density (tex) and fibre internal structure, which then show up in bulk and crimp. The major problem is that very small differences in shade, which are not easy to pick up by analytical methods, can be detected by the eye, particularly in uniform shades of critical colours. These differences may be due to physical form, e.g. bulk differences affecting lustre, or to variability in dye uptake. The consequence consists of faults called *barré* or streakiness in fabrics. Where there are multiple feeds, as in warps, the fault will occur if there are variations between packages. With single feeds, as in much weft-knitting, it will result from differences along a yarn.

Even where there are differences, their manifestation as visible faults depends on randomness in two ways. The first concerns the random placing of yarns in the fabric. A difference in a single yarn from its neighbours may be of too small a size to be resolved by the eye and so will not be detectable, but when several similar yarns happen to come together, the *barré* will be objectionable. The second is the paradox that variability can mask the effects of variability. If each yarn is itself very regular, then differences between yarns are very apparent; but, if the yarns have appreciable short-term variability, which is not objectionable, then the differences between yarns are less apparent. For this reason, the shape differences between fibres, which occur in draw-texturing and are shown in Fig. 2.4, are an



2.53 (a) Stress–strain curves of textured 77 dtex nylon yarns with varying numbers of filaments. (b) Replotted in normalised form. From Hearle (1966), based on data from Chemstrand (1963).

advantage. A detailed study of the human perception of streakiness in fabrics, which includes practical remedies, has been given by Davis *et al* (1996). Small intensity fluctuations over lengths that subtend an angle of 1° at the eye are the source of streaks, but similar differences over longer lengths are not noticeable.

3

Scientific and engineering principles in other texturing processes

3.1 Introduction

Many of the comments in Chapter 2 apply to other methods of texturing. From Section 2.2, the fibre science is the same and most methods involve heat-setting, though in forms different from that in twist-texturing. The one process that has major differences is air-jet texturing, which involves a mechanical locking of loops that project from the yarn. Heat-setting, if applied after texture formation, is a secondary stabilising factor.

3.2 Bending, buckling and setting

3.2.1 Planar crimp

In knit-de-knit texturing (and if gear-crimping was used), the fibres are forced into a planar, or almost planar, wave-like form and heat-set. The bulk and stretch features come from the amplitude and period of the crimp, with subtler differences due to the shape of the waves. Since these processes are applied to yarns, the crimp will tend to be in register in neighbouring filaments. The tension to extend the yarns from the crimped state results from the unbending forces (Section 2.2.8).

3.2.2 Bicomponent bulking

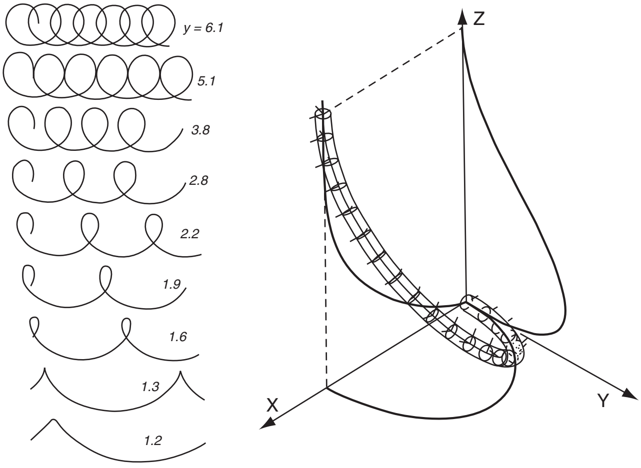
Two methods of producing textured filament yarns depend on producing differences between opposite sides of filaments. Neither are primary concerns of this book, but the principles should be mentioned briefly. In the obsolete *Agilon* process, this was achieved by passing the yarn over a sharp edge, which resulted in a change of fibre structure in the part nearest the edge. In bicomponent-fibre yarns, fibre producers extrude two different components side-by-side. Fibres of these types act like a bimetallic strip and differential contraction causes them to take up bent forms. The behaviour is that described in Section 2.6.3 and leads to the formation of alternating right- and left-handed helices with reversal regions in between, which can be seen if Fig. 1.1(b) is examined carefully. Figure 3.1 shows the complicated form taken up by a nylon/elastomer bicomponent fibre after break. The high level of differential contraction leads to tight coils.

3.2.3 Stuffer-box and related processes

Another basic technique is to overfeed yarns into a situation where they are forced to take up buckled forms, in which they are heat-set. The distorted forms result from collapse due to mechanical restraint. In the *Ban-Lon* process, which is now obsolete, yarns were forced into a stuffer box and then withdrawn more slowly through a restricted outlet: the input end of the box was hot and the output end was cold. Stuffer-box yarns tend to have an irregular, planar zig-zag form of crimp.

Another method that has been used in the past is the moving-cavity process. Here yarn is blasted on to a screen, where it is fed as a caterpillar through hot and cold zones, in order to set the yarn. The forms taken up here will depend on the way in which yarns buckle as they collapse on the screen. This has not been subject to academic study, but there may be relevance in experimental and theoretical studies of collapse, which were made in the context of laydown of filaments in spun-bonded processes (Hearle *et al*, 1976a,b,c). Figure 3.2(a) illustrates how the form varies with the relative speeds of feed and collector and Fig. 3.2(b) shows a theoretical computation by Konopasek (1980) of the form taken by a fibre as it is fed onto a plane. The mechanics of this analysis was based on force and moment equilibrium along a fibre under given boundary conditions. Methods such as this, or more likely energy-minimisation techniques, would need to be combined with the effect of aerodynamic and solid-contact forces, in order to predict the forms taken by fibres in processes of this type.

3.1 Monvelle, which was a nylon/elastomer bicomponent fibre, after rupture.



(a) (b)

3.2 (a) Predicted forms for collapse of a thread on a moving belt, with decreasing overfeed from top to bottom. From Hearle *et al* (1976b). (b) Computed three-dimensional form during lay-down. From Konopasek (1980).

3.2.4 Hot-fluid texturing

In the jet-screen process used in the production of BCF carpet yarns, yarns are fed through a hot-air or steam jet onto a revolving drum. Although the collapse on the drum may have some influence on the crimped form taken by the fibres, the dominant cause of buckling is the action of the hot jet. The same principle applies to the old *FibreM* process, in which yarn is fed by a hot jet into a tube.

Inevitably, in a turbulent jet, fibres will be heated unevenly. Shrinkage on one side of the fibre will be greater than on the other. Individual segments of filaments will thus act as bicomponent fibres. However, the boundaries between the two sides will change in direction along the fibre. Because of the differential shrinkage, which probably varies in magnitude, the fibre segments will bend into curvatures that minimise energy. However, because of the irregularity, the fibres will crimp into irregular helical sequences. The twist will be compensated for by the tendency of fibres to bend in different directions. The aerodynamic forces may also influence the form of buckling. The developments have been empirical and the behaviour of fibres in jets, which lead to the distorted paths, has not been studied. The movement of fibres under aerodynamic forces is important in many textile processes, and computational approaches are being developed. In the future, these may lead to predictive engineering design for jet-texturing, which takes account of the differential heat transfer to the fibres.

3.2.5 The value of a reservoir

Despite its limitations in yarn character, the stuffer-box process has one particular advantage. In false-twist texturing, a tightly twisted yarn, which is held straight under tension, has to be heated and cooled. Inevitably, this means long heating and cooling zones. However, in a stuffer-box the speed of the plug of yarn is less than that of the yarn throughput speed by a factor equal to the ratio of plug linear density to yarn linear density. For orders of magnitude of yarn and box diameter of 0.1 and 10 mm, and ignoring differences in packing factor, this ratio would be 10^4 times. Consequently, in principle, high throughput speeds could be combined with reasonable dimensions of hot and cold zones. The box acts as a reservoir for the heating and cooling operation. In practice, high-speed winders were not available when the stuffer-box process was current.

The caterpillar in jet-screen texturing and the tube in *FibreM* also act as reservoirs for cooling, which is important to prevent bulk being pulled out. If necessary to give enough set, heat can be applied to the zero-tension bulked yarn at the start of the reservoir. Although the speed ratio for the hot-jet region is not as great as for a stuffer-box, the filaments are following distorted paths, so that the yarn throughput speed is reduced. More important, the filaments are separated and so can be directly heated by the hot fluid. The distance for thermal conduction is reduced by a factor equal to the ratio of fibre diameter to yarn diameter, which roughly equals the square root of the number of filaments. This is one reason why jet-screen bulking is preferred to false-twist texturing for coarse carpet yarns; the other reason is that the ratio of fibre twist angle to yarn twist angle is small in twist texturing of yarns with many filaments.

3.3 Air-jet texturing

3.3.1 Trapping of fibre loops

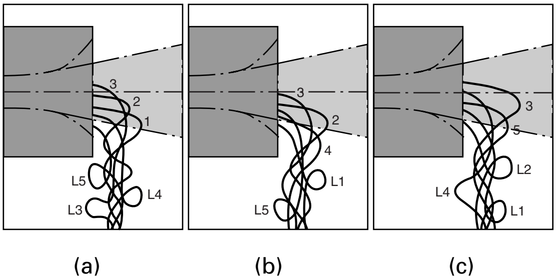
The principle of air-jet texturing, originally introduced as *Taslan*, is clear. Yarn is overfed into a jet and the excess length of filaments appears as projecting loops. In the original process, the yarn was twisted on take-up, in order to lock in the loops. Although much of the development of jets has been empirical, two principles have become clear in later advances. First, the yarn should make a right-angled bend as it emerges from the jet. This is the point at which the loops are forced out of the main body of the yarn.

Second, interlacing of filaments in the jet can cause the loops to be locked into the yarn, so that twist is unnecessary. If two yarns are fed in, the one with lower overfeed will be more important for the core and the one with higher overfeed will be more important for the loops.

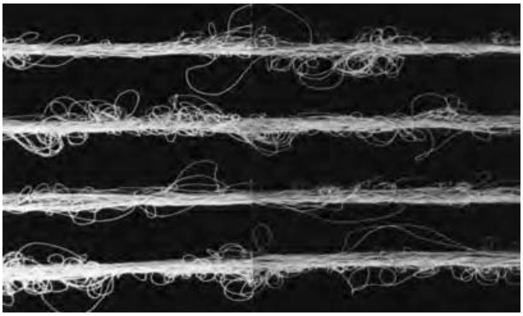
Differences in jet-design and process conditions lead to different patterns of loop formation. In addition to the practical experience of commercial manufacturers, there have been academic studies of the action of jets (Acar and Wray 1986a,b; Acar *et al* 1986a–e), which consider the air-flows and the forces acting on the fibres. Other studies have observed yarn forms and how they depend on process parameters (Kollu 1982, 1985; Demir 1987). Some of these studies have used yarns with dyed tracer fibres. When these are viewed microscopically with immersion in a liquid of similar refractive index to the fibres, they show the interlacing of fibre paths within the core of the yarn.

Acar *et al* (1986e) postulate the following mechanism of loop formation. Owing to differences in air-drag forces, some fibres will be moving faster than others. They will slip past slower moving fibres and, at the right-angle bend, be forced forward as loops. The leading ends will be trapped in the interlaced core and will move forward at the relatively slower speed of yarn take-up, whereas the trailing ends will be blown at high speed by the air-jet. Figure 3.3 is a schematic illustration of the sequence. In Fig. 3.3(a) loops L3–L5 have already been formed and trapped, and filaments 1–3 have been pulled forward by the air-stream. Eventually, trailing ends become trapped and loops L1 and L2 form (Fig. 3.3(b,c)). However, the point of loop formation depends on the degree of freedom of the filaments. Consequently, filament 3 is still moving out in Fig. 3.3(c), but filament 4 has been trapped as L4 ahead of L2 (Fig. 3.3(b,c)).

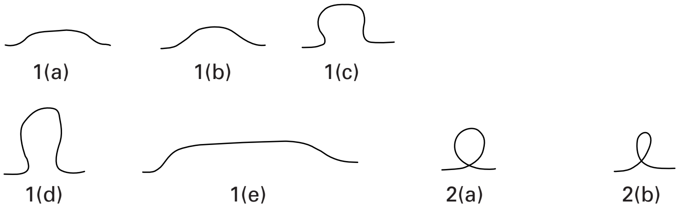
Figure 3.4 shows a typical yarn with many filaments. The various forms of loops have been categorised by Kollu (1982), as shown in Fig. 3.5. Any representative length of yarn can be characterised by a core diameter and



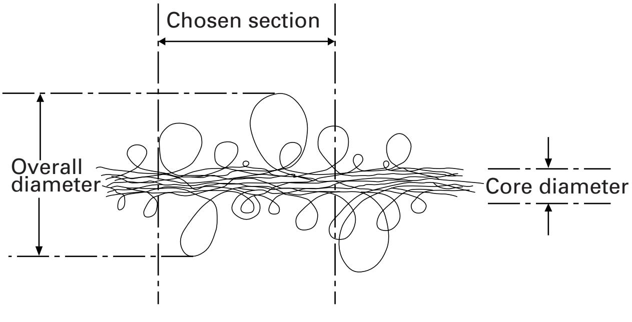
3.3 Schematic illustration of loop formation with five filaments. From Acar *et al* (1986e).



3.4 Polyester air-jet textured yarn with dual overfeeds of 25% and 33%. From Kollu (1982).

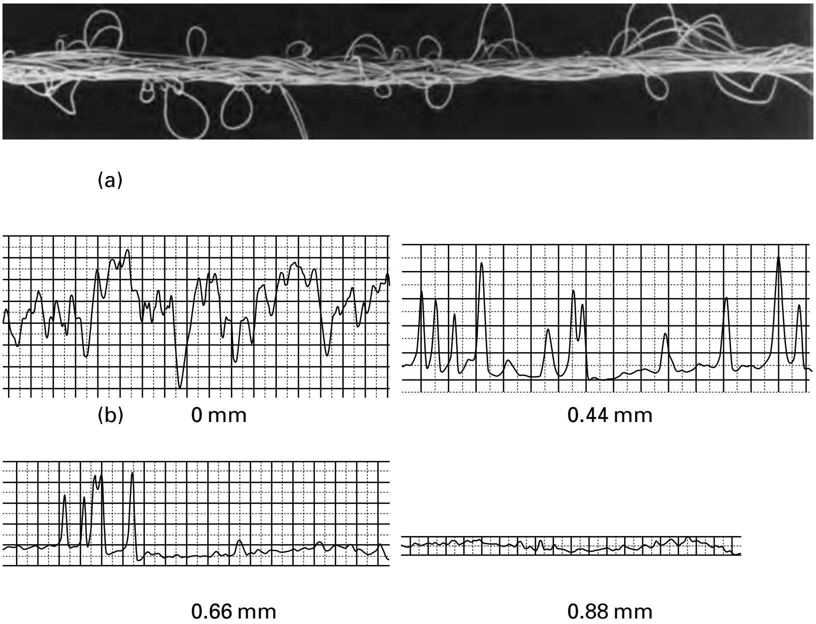


3.5 Categories of loops. From Kollu (1982).



3.6 Characterisation of yarn diameter. From Kollu (1982).

an overall diameter, as shown in Fig. 3.6. A more detailed analysis can be made by scanning an image, such as Fig. 3.7(a), with a microdensitometer to give the plots in Fig. 3.7(b). At the core of the yarn, most of the signal is high, indicating the presence of white fibres, but there are occasional low values where fibre is missing from the image. At 0.44 mm out from the centre, the peaks indicate loops and the low levels indicate their absence. At 0.66 mm out, there are fewer loops and at 0.88 mm there are none.


(a)

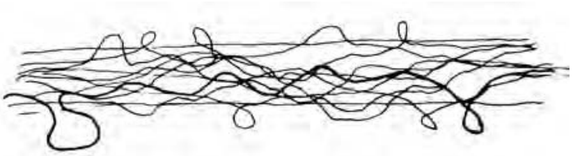
(b) 0 mm

0.44 mm

0.66 mm

0.88 mm

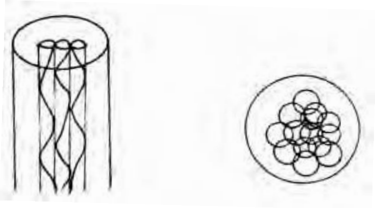
3.7 (a) Air-textured yarn. (b) Microdensitometer scans at distances shown from yarn centre. From Kollu (1982).


3.8 Schematic illustration of yarn structure. From Kollu (1985).

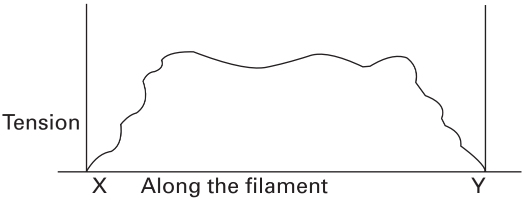
3.3.2 Yarn geometry

Figure 3.8 is a schematic illustration of the yarn structure. The total yarn linear density, C_y, can be regarded as being made up of two parts, the main core of the yarn, $C_{y,c}$, and the loops, $C_{y,l}$. The bulk of the yarn is determined by the effective radius round the loops, though in fabrics, this will depend on the extent to which the loops are squashed by the neighbouring yarns. The packing factor in the core can also be low, especially with mixed yarns.

Within the core, the fibres are interlaced. One structural feature consists of the angles θ which fibre elements make to the yarn axis. The other feature, the nature of the interlacing, is less easy to characterise. Kollu (1985), in a mechanical analysis, represented it by a collection of interconnected helices (Fig. 3.9).



3.9 Schematic indication of fibres in core as overlapping helices. From Kollu (1985).



3.10 Tension along a fibre from X to Y in Fig. 3.11. From Kollu (1985).

3.3.3 Yarn tensile properties

A critical question for air-jet textured yarns is whether the loops are locked into the yarn or whether they are pulled out when tension is applied. This is related to the prediction of the tensile stress–strain response of the yarns. Both the uncertainty about the structural details and the difficulties of modelling the complexities mean that no exact analysis has been carried out. However, the approximate treatment that follows brings out the important principles. The analysis follows the treatment of the mechanics of spun-staple yarns (Hearle *et al*, 1969). The projecting loops act in the same way as free fibre ends. The only differences are that the loops occur only at the surface of the core yarn, whereas fibre ends may be outside or inside staple yarns – and that, if there is complete slippage, the yarn finally acts as a strong, continuous-filament yarn instead of breaking. The essential similarity is that the tension is zero in both fibre ends and loops and builds up as the fibres are gripped within the yarns, as illustrated in Fig. 3.10. In predicting the yarn stress at a yarn extension, e, we start with the fibre stress, f_f, at the same strain, and then see how this is reduced in the yarn. In the approximate analysis given here, the same equations apply to the relationship of yarn strength to fibre strength, when yarn breakage results from fibre breakage.

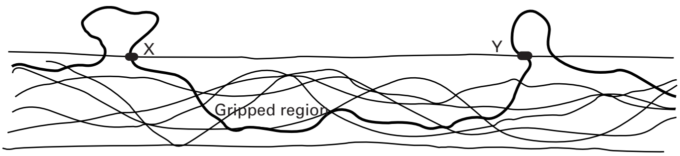
First, we take out the fibre mass in the loops, since these will not contribute to yarn tension. This introduces the factor $(C_{y,c}/C_y)$. Next, we take account of the obliquity of the fibres in the core of the yarn, which reduces both the fibre strain and the axial component of tension. Approximately, this is given by the mean value $\overline{\cos^4\theta}$. Then we have to allow for slip from the ends of the loops, given by a slip factor *SF*. This gives the yarn stress as (fibre stress at same strain × non-contributing factor × obliquity factor × slip factor):

$$f_y = f_f \times (C_{y,c}/C_y) \times \overline{\cos^4\theta} \times SF \qquad [3.1]$$

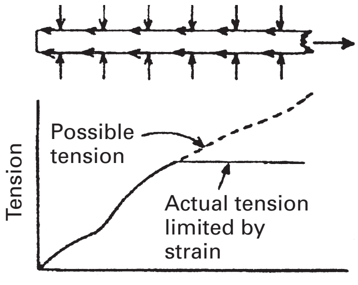
The slippage is the factor of most interest. If we consider a fibre, as shown in Fig. 3.11, slip will start from the points X and Y, where the fibre comes out into loops. At these points the fibre tension is zero. Within the core yarn, the fibre is gripped by transverse forces from neighbouring fibres as indicated in Fig. 3.12, and consequently there will be a frictional resistance to slip. The tension will build up as indicated in Fig. 3.13 until it reaches the value $f_f\,\overline{\cos^4\theta}$ determined by yarn extension and fibre obliquity in the central, fully gripped region. If the length over which slip takes place is *S* and the length between loops is *L*, there is a loss of a fraction *S*/*L* compared to the tension without slip. Hence:

$$SF = 1 - S/L \qquad [3.2]$$

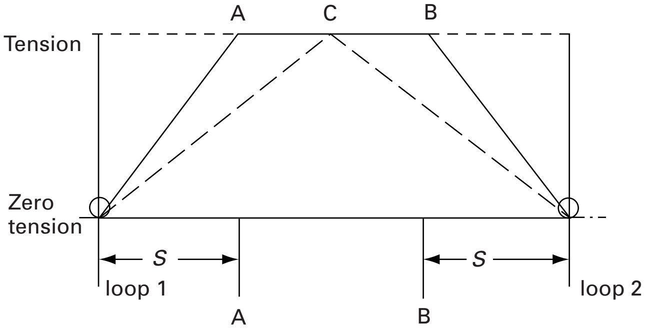
The slip length is given by equating the tensions at the junction of the slip and gripped zones. The resistance to slip is given by the frictional force acting on an area equal to the fibre circumference, $2\pi a$, where a is the fibre



3.11 Fibre between loops in yarn.



3.12 Build-up of tension due to friction. From Hearle *et al* (1969).



3.13 Linearised indication of tension variation along a fibre between loops. From Kollu (1985).

radius. The frictional shear stress is given by the coefficient of friction, μ, multiplied by the transverse stress from the neighbouring fibres. Roughly, this can be put equal to $\mathcal{F}f_y$, where $\mathcal{F}$ is an operational factor that determines how the yarn tension is converted into transverse forces within the entangled core. The tensile stress in the gripped region is put equal to the fibre area multiplied by the yarn stress. Hence, we obtain the following equations and can substitute for *S* in equation [3.2]:

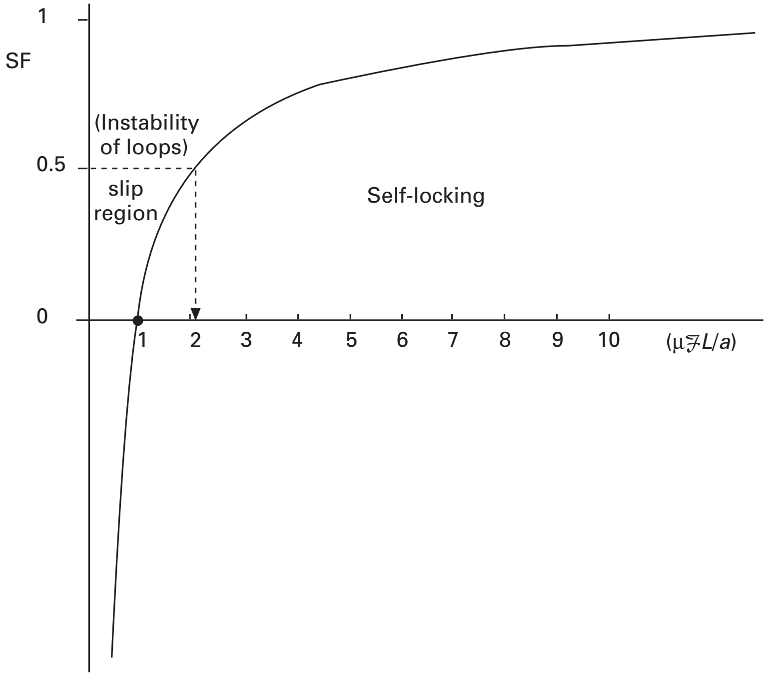
$$(2\pi a)S\mu\mathcal{F}f_y = (\pi a^2)f_y \qquad [3.3]$$

and

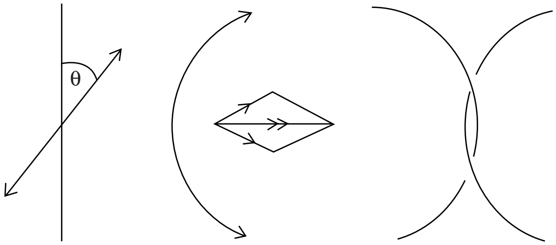
$$SF = 1 - \tfrac{1}{2}(a/\mu\mathcal{F}L) \qquad [3.4]$$

The factors which minimise slip are thus fine fibres, long lengths between loops, high friction and high conversion of tensile stress into transverse stress between fibres. The form of equation [3.4] is shown in Fig. 3.14. However, a critical situation is reached when $SF = \tfrac{1}{2}$. At this point, the two slip lines in Fig. 3.13 would meet at the grip tension, so that the fibre would no longer be gripped anywhere. In spun yarns, where the transverse forces result from yarn twist, this corresponds to the boundary between self-locking yarns and draftable rovings. On the simplest argument, the tension would drop to zero; in practice there will be a low frictional resistance to slip. In order to prevent slippage of loops, it is therefore necessary that $(\mu\mathcal{F}L/a) > 1$.

The discerning reader will pick up various inaccuracies in the above argument. Some of these can be corrected by more detailed analysis, which brings in numerical factors, powers and correction terms. However, the general form of the dependence of resistance to slip on μ, $\mathcal{F}$, *L* and *a* is valid. The problem which remains is what determines the operational factor, $\mathcal{F}$. How is yarn tension converted into transverse gripping forces? As shown in Fig. 3.15(a,b), it is not fibre orientation that leads to transverse forces,



3.14 Form of equation [3.4] for slip factor plotted against $(\mu \mathcal{F} L/a)$. From Kollu (1985).



(a) (b) (c)

3.15 (a) Tension in a straight fibre at angle θ does not generate transverse forces. (b) Resultant normal force from tension in a curved fibre. (c) Interlocking fibres.

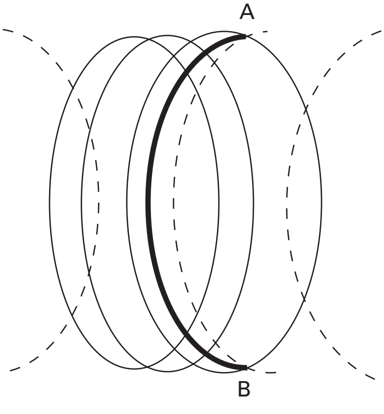
but change of orientation along fibres. Where fibres are following a curved path, as in Fig. 3.15(b), a component of tension acts at right angles to the fibre axis. Consequently, if two fibres are interlaced, as in Fig. 3.15(c), there will be a gripping force between them. This sort of local interaction may play a part in the core of air-jet textured yarns. However, it is more likely that groups of fibre will be wrapping round each other, so that there is a build-up from outer layers to inner layers. In simple twisted yarns, with successive helical layers, this build-up can be calculated. It is more difficult to see how to deal with the problem in an irregularly interlaced core.

Kollu (1985) adopted the model of interlacing helices, shown in Fig. 3.9. In order to make analysis possible, filaments with a linear density, C_f, are assumed to follow regular helices, with a radius, r, and a helix angle, θ, which will equal the orientation angle of filaments in the yarn. Assuming that n helices surround a fibre and that a fraction, F, of them are 'effective', Kollu calculated the transverse stress acting on the fibre. His equation is equivalent to:

$$\mathcal{F} = F(nC_{\mathrm{f}})\sin^2\theta/2\pi r^2 \qquad [3.5]$$

Considering the factors in turn, the notion of effective helices involves a technical, statistical effect. If, as in Fig. 3.16, we consider a fibre AB with surrounding helices, the transverse forces from the helices shown as full lines will contribute to the transverse pressure on X, but those shown dotted will oppose the build-up of transverse pressure. The parameters, n and C_f, are interrelated: if the fibres are larger, there will be fewer of them. The helix parameters, r and θ, are 'average' values. Any short, curved segment of fibre in the core of the yarn can be regarded as part of a helix with particular values of radius and angle. Average values could thus be calculated, if the fibre paths are known, though these are not easy to determine.

Kollu (1985), after considering models which indicate values of the effectiveness factor, F, and the interaction of geometrical factors, found a

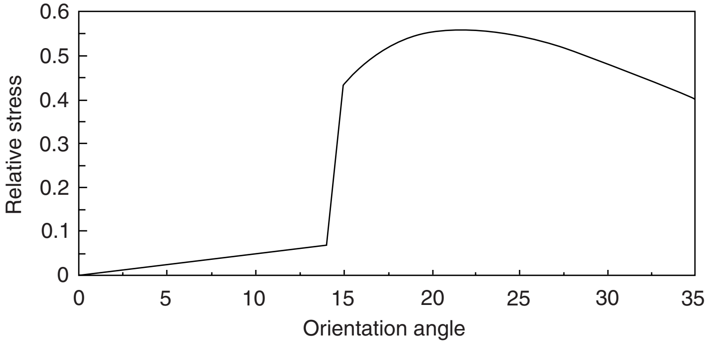


3.16 Portions of overlapping helices.

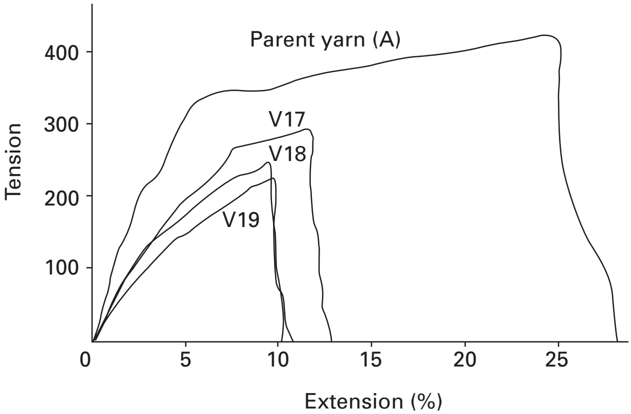
slippage factor for a yarn of radius, R. Noting that in this model the orientation angle is taken to be constant, this converts equation [3.1] into:

$$f_y = f_f \times (C_{y,c}/C_y) \times \overline{\cos^4\theta} \times \left[1 - K(a/\mu L)(r/R)^m \operatorname{cosec}^2\theta\right] \qquad [3.6]$$

where K is a numerical factor, which may depend on the number of filaments in the yarn, and m is a power between 1 and 2. Although there are many approximations and uncertainties in Kollu's analysis, it is likely that the dependence on r/R and θ probably shows the right trend. It is interesting that the dependence on θ has the same form as for spun-staple yarns



3.17 Dependence of yarn tensile properties as a fraction of fibre properties on helix angle θ.



3.18 Load–extension curves for parent yarn and yarn textured at 10% (V17), 15% (V18) and 20% (V19).

(Hearle *et al*, 1969). In practice, this model indicates that, in order to avoid slippage, the jet should provide interlacing in the core of the yarn with a small effective helix radius, though appreciably greater than the fibre radius, and a high helix angle, which gives a low value of $\text{cosec}^2\theta$. Figure 3.17 shows the dependence of f_y, the yarn stress at a given extension, on the orientation angle. Because of the counter-effects of obliquity and slip, there is an optimum degree of interlacing for maximum resistance to extension, and a critical condition for loops to slip. In the gripped region, the curve will also show the trend for strength variation, $f_y = f_y \times (C_{y,c}/C_y) \times \overline{\cos^4\theta} \times SF$. Figure 3.18 shows yarn load–extension curves with tension reducing as overfeed is increased.

4

False-twist process

4.1 Introduction

The fundamental principles behind the false-twist, draw-texturing process have been explained in previous chapters. Here, the way in which these principles are employed in a production environment will be examined. The process described is based on the production of polyester yarns, which account for the vast majority of false-twist textured yarn production in the world. However, it should be noted that these same principles could also be applied to the production of polyamide (nylon) and polyolefin yarns by the false-twist route.

In principle, enhanced textile properties, both tensile and tactile, are given to spun, continuous-filament POY by the simultaneous actions of drawing (stretching), heating and twisting the filament bundle. This subsequently is untwisted and then either:

1 collected directly on a bobbin after oil application (these yarns are variously referred to as 'high elastic' yarns or 'stretch' or 'single-heater' yarns); or
2 subsequently heated under controlled partial relaxation and wound on a bobbin (called a package) after oil application ('double-heater' or 'set' yarns).

The false-twist process can be broken down into three fundamental elements. It is the way in which these elements are employed and controlled that, when they are used in combination with each other, gives the resulting product its desired properties. These elements are the three Ts: tension, twist and temperature. By controlling these three fundamental variables a wide variety of different textured-yarn types can be made from one POY feedstock.

4.2 Draw-texturing machine

4.2.1 Machine profiles

Though coming in a wide variety of cross-sectional shapes, sometimes referred to as the machine profile, all draw-texturing machines consist of certain basic components. At this point the function of each of these components will be considered separately and its influence on the process described. These will be discussed in the order in which they would normally occur on the machine, i.e. the order in which they appear in the path or route of the yarn through the draw-texturing machine. Regardless of the manufacturer and the profile of the machine the basic principle is the same for all of them. The components consist of:

1 a creel for feed yarn storage;
2 two shafts, between which the yarn is heated, drawn, cooled and passed through a twist-insertion device;
3 two shafts between which the yarn can be subsequently heated under partial relaxation. Note that on some machines specifically designed for the production of nylon yarns, this heater may be omitted;
4 a device for the application of coning oil;
5 a yarn collection and winding system.

The profile of the machine was briefly referred to above. This is the designation given to the shape that the primary heaters and cooling plates make in profile. Commonly there are M, V, L and S profiles. All of these describe the cross-section of the machine, with the exception of S which simply stands for straight. Figure 4.1(a,b) shows line diagrams of M and V profiles. The profile of a machine has a definite influence on its performance with respect to capability for production speed and number of yarn breaks observed. The rule is that the lower the number of angles through which the yarn turns on its route (sometimes referred to as the thread-path or thread-line of the yarn) from the input shaft of the machine to the twist-insertion device, the lower the overall processing tensions. For this reason the V profile is preferred for high-speed machinery. The V profile is also preferred for the production of polypropylene yarns which have a high co-efficient of friction, even though process speeds are relatively low. Table 4.1 shows a comparison of M and V profiles.

4.2.2 Creels

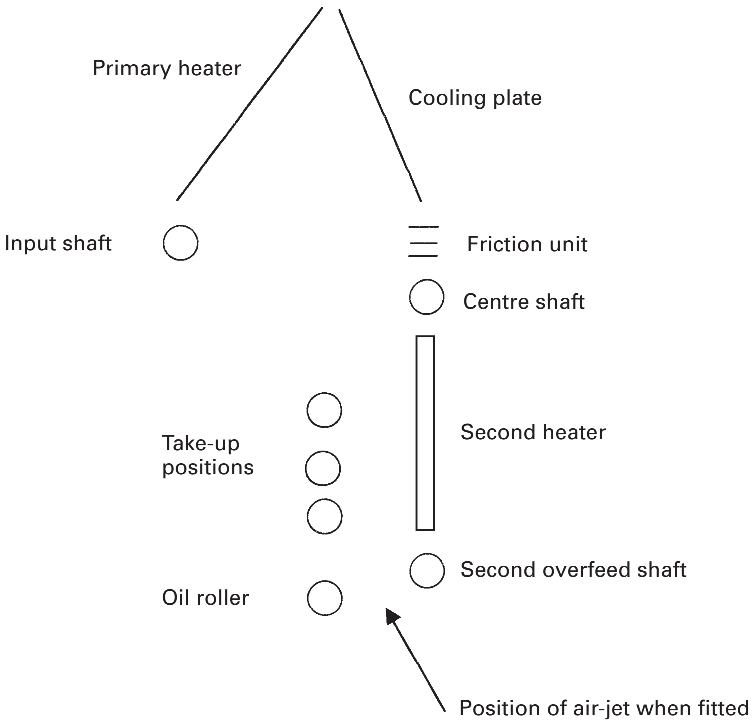
Often neglected, maintaining the creel in good repair with a high standard of cleanliness and good alignments is fundamental to an efficient process.

The creel itself should be of robust construction and be large enough to accommodate a variety of feed yarn package sizes; to be efficient, it should also be able to accommodate a reserve package, from which transfers can be made for a continuous process. To this end it is a decided advantage if the creel is of a rotary design so that POY can be loaded on to all arms within the creel from one position. This is far more efficient from the

Table 4.1 Comparison of M and V profiles. Fibre 167 dtex (150 denier) 132 filament; draw ratio 1.665; machine speed 700 m/min; D/Y ratio 1.9

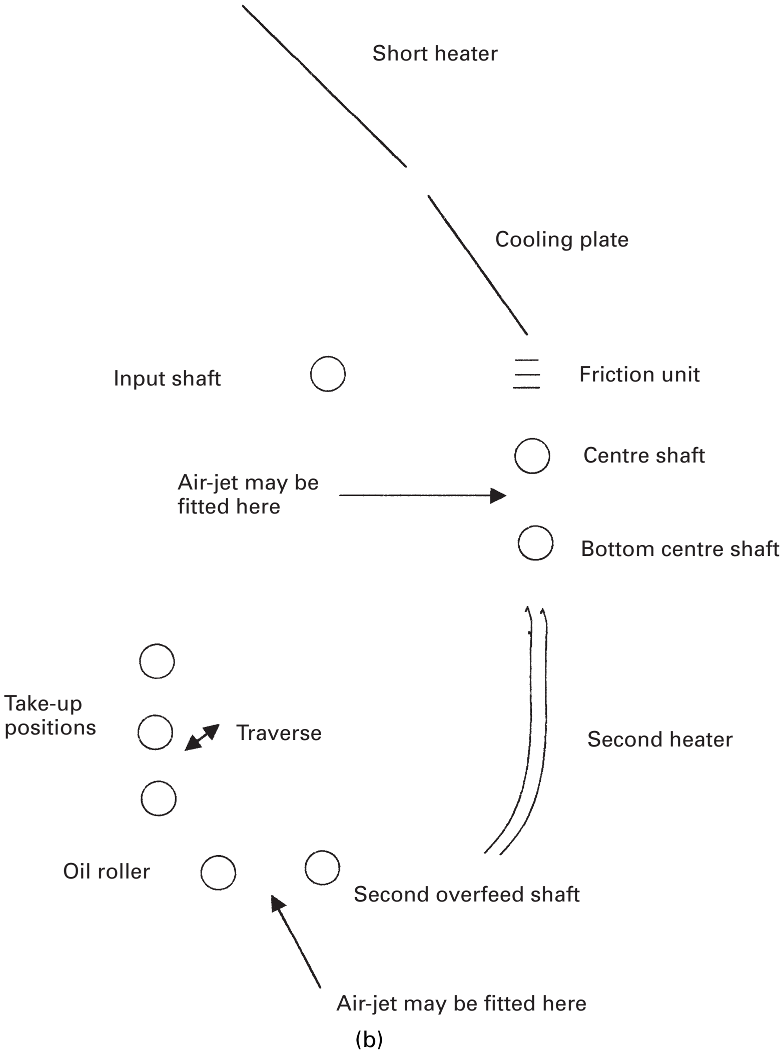
	M profile	V profile
Pre-draw tension (g)	40.2	24.8
Above-spindle tension (T_1)	74.0	63.5
Below-spindle tension (T_2)	65.0	58.7
Tension ratio (T_2/T_1)	0.88	0.76

Source: Courtesy of UNIFI.



(a)

4.1 (a) M profile machine. (b) V profile machine. Courtesy of Barmag-Saurer Group.



4.1 Continued.

standpoint of labour management and also reduces the risk of POY damage being incurred.

All ceramic surfaces within the creel should be in good condition and of a low friction surface. The support arm for the feed yarn package should be exactly centred on the guide in the central gathering strip in both the horizontal and vertical planes. There should also be sufficient room to allow the yarn to balloon freely off the feed yarn package.

The condition of the creel is of particular importance when processing nylon yarns, which commonly employ lower draw ratios than polyester yarns and are therefore susceptible to anything that may increase processing tensions within the creel.

4.2.3 Yarn cutter

At some point in the thread-line there will be a cutting device, usually situated between the creel and the first shaft of the machine. This device is designed to cut the yarn in case of an end break and so protect the machine from wraps, which occur when a free, broken end winds itself on to an opportune rotating shaft or roll. The cutters are usually fired by an electrical signal, which comes from a break sensor situated as close to the take-up device as possible. They are normally of robust construction and are generally trouble free requiring little maintenance apart from the replacement of worn components. In some cases the yarn cutter may be linked to an in-line monitoring device so that if an off-quality package is detected it may be automatically cut down. The cutter being activated by a signal generated by the monitoring system (see Section 8.3.1.2).

4.2.4 Yarn transport systems

The next component is the input shaft, which transports the yarn from the creel into the draw zone. Obviously all the shafts in the machine are usually of a similar type. The prime consideration is that the yarn is transported through the machine with no slippage. Normally the transport or feed unit will consist of a bright chrome metal surface and a rubber apron (sometimes referred to as a '*Casablanca apron*') or a nip roll.

Rubber aprons have the advantage of being cheap but they are easily damaged. Also if they have not been carefully manufactured, for instance if they have not been cut squarely or have some form of weight bias, they can cause problems. Nip rolls, though initially more expensive, have a much longer working life than aprons. However, these also have problems and great care must be taken to ensure that the running surface in contact with the yarn is perfectly round and parallel across its width. The life of the nip roll is significantly increased by periodically removing it from the machine and buffing to reveal a fresh running surface. If these rubber surfaces are not maintained in good condition, they can cause problems of dye faults, high yarn breaks and broken textured filaments.

4.2.5 Yarn displacement systems

Yarn displacement systems are considered here as they are an integral part of the transport systems described above. The yarn displacement prolongs the lifetime of the rubber components of the system by continuously traversing the yarn back and forth across its surface. The system commonly consists of a simple cam-driven bar, which runs the length of the machine with suitable guides attached. Should the displacement system fail, it is possible for the yarn to cut a groove in the rubber surface. This will lead to slippage and possibly damaging consequences including high yarn breaks or dye faults. Obviously the importance of having the rubber surfaces of the transport system in good condition is highlighted by this traversing action. If it is not of good and uniform surface it would be possible for the displacement system to traverse the yarn into and out of a faulty part of the surface, thus causing intermittent faults.

4.2.6 Twist stops

Some machines particularly those of V profile, or machines of any profile designed for the production of nylon yarns, may be equipped with a twist stop at the point where the yarn enters the primary (first) heater. The function of the twist stop is two-fold:

1. The twist stop prevents the twist, developed in the yarn by the twist-insertion device, running all the way back to the input shaft and hence causing yarn instability between the input shaft and the entrance to the primary heater and therefore increased yarn breaks.
2. The twist stop effectively traps all of the twist generated in the yarn between the top of the twist-insertion device and the entrance to the heater. This allows the twist to have maximum effect within the heater and hence to generate the maximum possible bulk in the textured yarn. An effective twist stop is particularly important in the production of yarn destined for ladies' hose.

The design of the twist stop, as well as the material from which it is constructed, can have a detrimental effect on the textured yarn. A poorly designed twist stop can result in increased break rate, loss of tenacity, loss of textured elongation and an increase in broken filament level. The twist stop is usually mounted on a small bearing to allow free rotation but in some instances it may be replaced by a stationary, high-friction, polished ceramic guide.

4.2.7 Primary or first heater

Until recently all first heaters were of the contact type. Now almost every major machine manufacturer will offer machines with short, non-contact, high-temperature first heaters. *Teijin Seiki* originally showed these at the

1990 ITMA and since that date development in the technology and efficiency of these heater types has been rapid.

4.2.7.1 Contact heaters

Contact heaters have been used for many years on texturing machines supplied by different manufacturers. They have the advantage of being reliable and cheap to operate but they have several disadvantages which make them unsuitable for use on high-speed machines. Primary contact heaters are usually liquid filled and work on the vapour phase principle. They have an electrical heating element in the base of the heater, controlled by a thermocouple or PT100 resistance thermometer, to regulate the temperature. The liquid is a eutectic or diphase mixture of two components, mixed in such a way that they produce vapour with a comparatively low pressure at the heater operating temperature.

The diphase liquid used in vapour phase heaters is often known as *Dowtherm*, which is one of the most common brand names. It is used in both the primary and secondary heaters. There are two types of *Dowtherm* in common use. One is *Dowtherm J*, which is most commonly found on machines making polypropylene yarns and has a guaranteed temperature range of 110–180°C. The other, standard *Dowtherm A*, comes with a guaranteed operating range of 180–235°C.

The heater is sealed and all air is exhausted so that a condition of vacuum applies internally. This allows the vapour to condense on the inside surface of the heater track once the heaters have brought the liquid to the operating temperature. The condensation causes the vapour to give up its latent heat and this enables the heater track to be held with an almost constant temperature profile within ±1°C of the set-point regardless of the yarn load.

Since vapour phase heaters operate at relatively low temperatures (110–235°C) they have a limited ability to transfer heat into the yarn. This means that the faster the machine speed the longer the heater is required to transfer sufficient heat into the yarn. At 900 m/min a heater of 2.5 m is the minimum length required, though a heater of 2.0 m length is sufficient at lower speeds. This puts pressure on the machine designer. The machine configuration becomes awkward and a greater amount of floor space and/or height is required for each machine. It will be appreciated that the larger the machine the more difficult it becomes to operate.

Contact heaters become dirty very quickly, since the spin finish from the POY accumulates on the surface of the heater. As the deposits of spin finish build up on the heater, the transfer of heat to the yarn becomes less efficient. There is also an increase in the number of yarn breaks on the machine.

The build-up of dirt on the heater also means that the machine has to be stopped frequently to clean off the deposits, leading to an increase in downtime and lost production.

Use of a contact heater brings with it an increase in T_1 tension before the spindle due to friction. This contributes approximately 4 g of tension for each increase of 100 m/min when producing a yarn of 167 dtex (150 denier). The contribution from friction also indicates that there is a natural resistance to inserting twist into the yarn which means that there is a limit to the amount of bulk that can be generated on a contact heater machine. All of the above factors combine to make contact heaters unsuitable for the production of yarn at high speed.

4.2.7.2 Short or high-temperature heaters

The first genuine short heater technology to make significant inroads into the textile machine market was from *Teijin Seiki*. The machine was previewed at the 1990 ITMA in Hanover. Since that time most of the major machine manufacturers have developed and supplied machines with short heaters, i.e. *Barmag, ICBT, Murata, RPR and Guidici.*

The advantages of short heaters that have pushed machine manufacturers in this direction are as follows: the short heater, by use of high temperatures, is capable of bringing the yarn to a working temperature in a much shorter space of time. From this simple statement it becomes obvious that the heater itself can be much shorter in length, usually 1.0 m, and the yarn can pass through the heater at a higher speed and maintain its working temperature.

Being what is termed non-contact (though there is minimal contact between the yarn and the guide surfaces within the heater) means that friction is dramatically reduced. This reduction in friction obviously assists in allowing the yarn to be processed at a much higher speed. Also, it has the benefit of allowing the twist, imparted by the friction unit, to transmit more effectively into the yarn leading to a higher bulk level being generated on short heater machines. Heater cleaning cycles can be dramatically lengthened leading to reduced downtime. Some extraordinary claims have been made about the running time achievable between heater cleans, but these should be treated with a degree of scepticism.

There is still much development work to be done in determining exactly what are the optimum temperatures for each yarn process. Obviously yarn type and machine speed and configuration are factors to be considered when optimising heater temperatures to give the best process. What is clear is that there is a narrow operating window for each yarn/process combination and if temperatures stray too far outside this window then process efficiency will decrease dramatically.

4.2.8 Fume exhaust

The main function of the fume exhaust is to help maintain the machine, and particularly the primary heaters, in a clean condition. Basically low-velocity air is drawn across the yarn path at the entrance and exit to the primary heater. It has to function at both points as, not only does the thermal effect cause fumes to be emitted at the highest point of the heater, but the speed of the yarn passing through the heater tends to drag fumes with it to the bottom. So fume exhaust is necessary at this point also. Note that this effect increases as the throughput speed of the yarn increases.

Though the main effect of the fume exhaust is to help maintain the machine in a clean condition, it can, on sensitive products, have an effect on the bulk of the textured yarn, producing variation around the machine. It is believed that this is caused by the effect of open and blocked fume exhaust ports, which change the amount of air drawn over the yarn, affecting the rate at which it cools. For this reason it is important that the fume exhaust systems are regularly cleared of any blockage.

4.2.9 Cooling plates

The cooling plate is situated between the exit of the first heater and the entrance to the twist-insertion device. It has two major functions:

1 It allows yarn bundle to cool, while still in a highly twisted state, between leaving the primary heater and entering the friction aggregate. Yarn temperature at the entry to the twist-insertion device is ideally in the range 86–90°C for polyester.
2 It gives stability to the highly twisted yarn bundle between exit from the primary heater and entry into the friction unit. This is very important since, if the cooling plate were not present, the yarn would be very unstable in this highly twisted state and have a tendency to balloon resulting in a high break rate.

The cooling plate is often neglected, but it plays an important part in ensuring that the yarn produced on the machine is of uniform good quality. If the cooling plate is out of alignment it can affect the yarn in the following ways:

1 With too little contact, the yarn is unstable and tension surges can result, giving dye faults, or the yarn can become so unstable as to cause breaks.
2 With too much contact the plate can restrict the amount of twist generated in the yarn running back up into the heater, causing lean or low bulk ends.

The cooling plate is normally made from nitrided steel and has a curved profile. Though other surfaces and profiles have been employed by various machine manufacturers, this shape and surface is the one most commonly employed.

The length of the cooling plate is proportional to the design speed of the machine. This means that the faster the machine goes, the longer the length of the cooling zone. This is to ensure that the yarn is at the optimum temperature when it reaches the friction unit. In efforts to reduce the length of this zone several methods of forced cooling have been tried in the past but to date none have been commercially successful. Both forced air and water-cooling have been tried. The main problem is in ensuring uniformity of cooling around the machine, otherwise positional variation in bulk and dyeability may result.

4.2.9.1 Twist insertion

The heart of the draw-texturing process is the twist-insertion device sometimes referred to as the friction aggregate or FTU (see Fig. 4.2). The action of twisting the drawn-heated filaments and then subsequently de twisting

4.2 Friction twist unit (FTU). Courtesy of Barmag-Saurer Group.

them are what gives the crimp character and bulk to the yarn. The name false-twist texturing follows from this.

Over the years there have been many methods employed to give yarn crimp and texture. Those commonly used are:

1 bush crimping;
2 spindle or pin crimping;
3 ring crimping;
4 crossed-belt crimp;
5 stacked discs.

The most successful of these, and the one most commonly used across the world, is the method using stacked discs.

In principle the yarn is twisted at high speed by the discs of the friction unit. The twist is transmitted back up the yarn path on to the primary heater where, as the yarn has been 'softened' by the heater and cooled on the plate, it is set into its molecular structure or 'memory'. This is why the yarns that are processed by the false-twist texturing process must be thermoplastic in nature. It is also the reason why the process is sometimes described as a torsion-texturing process in scientific journals.

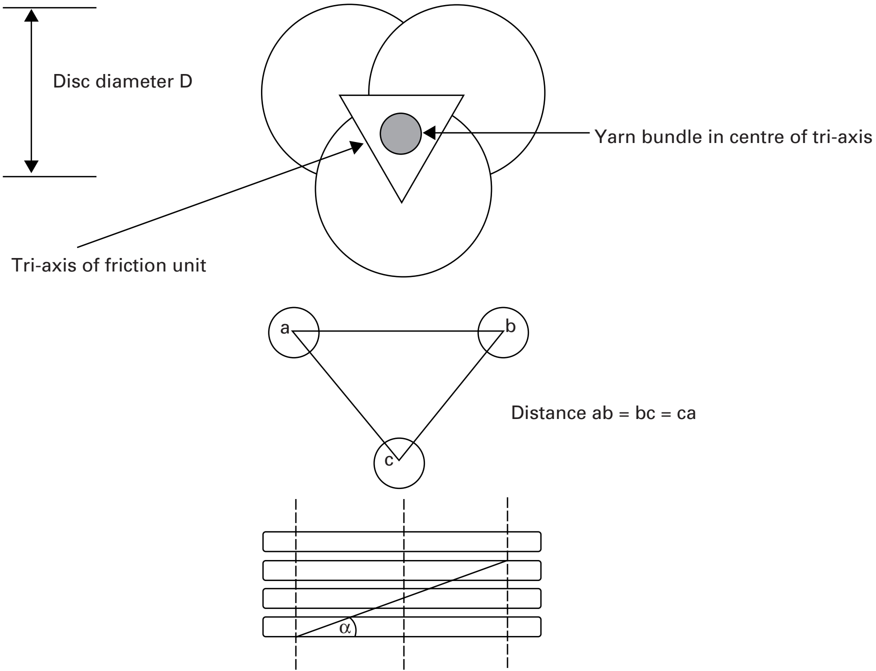
As the yarn exits the friction unit, it untwists in the opposite direction to that above the unit but, as the yarn is now cold, it does not affect the sense of twist or torsion set in the yarn's memory. The amount of twist inserted into the yarn is governed by two main factors:

1 the amount of contact between the yarn and the friction discs (angle of wrap);
2 the speed of the friction discs relative to the speed of the yarn, named the D/Y ratio (see Section 4.3.3).

To enlarge on these, the angle of wrap is defined by the total contact of the yarn with each disc in the friction unit. Thus the angle of wrap = $\Sigma(\alpha_1 \ldots \alpha_n)$ where α is the angle over each working surface and n is the number of discs. The angle of wrap can be varied by:

1 increasing or decreasing the diameter of the friction disc;
2 increasing or decreasing the horizontal distance between the friction discs;
3 increasing or decreasing the vertical distance between the friction discs;
4 increasing or decreasing the number of friction discs.

In practice, the most common methods of changing the angle of wrap are 3 and 4 above, with 4 being the preferred method (see Fig. 4.3). Dimensional set-ups for two typical friction units are shown in Table 4.2.



Where T = thickness of friction disc

S = inter disc spacing

A = axial spacing

Then yarn angle $\alpha = \dfrac{3T + 3S}{2\Pi P}$ Where $R = 2\Pi\left(\dfrac{D}{2} - \dfrac{A}{\sqrt{3}}\right)$

4.3 FTU geometry.

Table 4.2 Set-up of two typical tri-axis friction units

Unit type	Temco 471	Barmag type 8
Axial spacing (mm)	33.77	36.9
Disc overlap (mm)	11.23	15.2
Disc overlap area (mm^2)	41.9	101.6
Cylinder diameter (mm)	6.01	9.5
Triangle area (mm^2)	184	425.4
Yarn angle on disc (°)	45.9	43.7
Max bearing (rpm)	15 000	16 000
Whorl diameter (mm)	25	28
Disc dimensions		
Diameter (mm)	45.0	52.11
Thickness (mm)	6.0	9.0
Bore (mm)	12.0	12.0 or 14.45

Source: UNIFI.

4.2.9.2 Choice of friction material

Several types of materials have been used for the manufacture of friction discs, the most common ones being:

1 ceramic;
2 polyurethane;
3 nickel/diamond;
4 plasma-coated ceramic.

Of these the most common ones used commercially are ceramic and polyurethane. Their advantages and disadvantages are shown in Table 4.3.

Although both types have their individual strong points, polyurethane is usually the preferred choice. This is a soft, high-friction material that 'grips' the yarn better than ceramic, i.e. less slippage, therefore for a given D/Y ratio will impart more twist into the yarn, thus lowering the T_2 tension.

A new type of ceramic disc is now finding favour with some yarn manufacturers. This type is generally referred to as soft ceramic. The discs have many of the advantages of the standard type but are claimed to generate less snow. However, it must be stated that snow generation is still significantly

Table 4.3 Advantages and disadvantages of ceramic and polyurethane discs

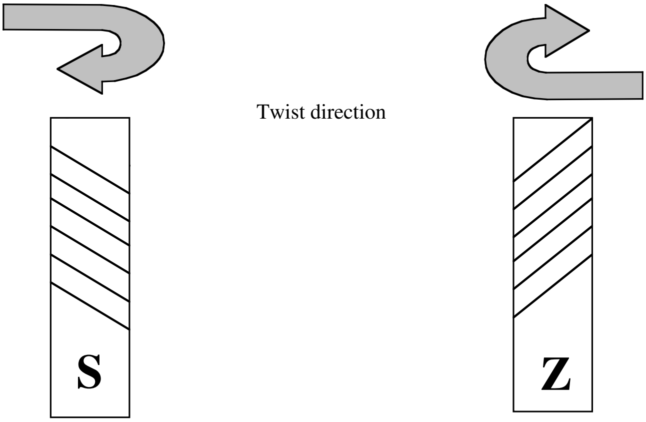
Ceramic discs	Polyurethane discs
Advantages	**Advantages**
Cheap (long-term)	Low snow* generation
Long life	Soft handle to fabric
Crisp handle to fabric	High bulk character to yarn
	Kinder to yarn
Disadvantages	**Disadvantages**
High snow* generation	Expensive
Low bulk character	Limited life
Mechanical damage to yarn	Easily damaged

*Snow is the term used to describe the white deposit that forms on the texturing machine, particularly around the twist-insertion device and cooling plates. This deposit consists of very low molecular weight polymers (oligomers) and spin finish deposits. These are formed by a combination of heat and the abrasive action of the surface of whatever twist-insertion device is employed on the surface of the yarn.

higher than that seen with polyurethane discs. The basic principle is that the yarn is passed through the centre of the overlaps of discs mounted on spindles, whose centres form the apexes of an equilateral triangle. Twist is inserted in the yarn in the direction of rotation of the discs (see Fig. 4.4).

As the yarn exits the friction unit, it untwists in the opposite direction to that in which the twist was inserted above the unit – hence the name false-twist texturing. The diameter and thickness of the disc, the spacing between the discs, the type of disc material and the speed of rotation all have an effect on the amount of twist that is inserted in the yarn.

The disc diameter and spacing between the discs influence the angle of wrap over each surface. The thickness of the discs affects the amount of contact between the yarn and the disc. The number of discs determines both the total angle of wrap and contact. The speed of the disc (D/Y ratio) affects the amount of twist put into the yarn at a given speed for a given disc configuration, i.e. as the disc speed increases twist increases. Some examples are given in Table 4.4. For calculation of disc speed see Appendix 2.



4.4 S and Z twist directions.

Table 4.4 Relationship between D/Y ratio, yarn and unit speeds

D/Y ratio	Yarn speed (m/min)	Unit speed (rpm) (52 mm disc)
1.6	800	7835
1.8	800	8815
2.0	800	9794

The twist inserted can be calculated to a theoretical value when considering other factors such as the yarn diameter, the twist contraction ratio and friction unit geometry. This value is of academic interest only as far as the day-to-day production of textured yarn is concerned.

4.2.9.3 Disc stacking

When it comes to choosing the correct disc stacking for a yarn, two things must be considered:

1. How much bulk (cover or crimp) is required in the product?
2. Will the disc stacking affect the break rate?

Two rules apply:

1. The higher the number of working discs used, the higher the resultant bulk will be.
2. The higher the number of working discs used, the higher the break rate will be.

To enlarge on these, as previously stated, the more discs that are used, the greater will be the angle of wrap between the yarn and the discs and the greater will be the total amount of contact between the discs and the yarn. Both of these factors increase the efficiency of twist insertion at a given D/Y ratio and hence more twist runs back up the yarn into the heater to develop the bulk in the yarn.

Regarding yarn break rates, polyester, along with other yarn types, is to a certain extent 'lazy', i.e. it does not like to be forced to do work. Increasing the number of angles the yarn is put through and increasing the amount of twist are both work as far as the yarn is concerned and, hence, there is a risk of increasing the break rate.

4.2.9.4 Guide discs

Why do we use a guide disc on the top and bottom of the friction unit stack? The guide discs are used to protect the polyurethane discs and increase their lifetime. They do this by effectively reducing the stress placed on the first and last polyurethane discs by reducing the angle of contact. The first guide disc also initiates the twist insertion in the yarn and so no longer leaves the first polyurethane disc to do all of the work. This increases the lifetime of the polyurethane disc significantly.

4.2.9.5 Disc size and diameter

As production speeds on texturing machines increased, more efficient means of transmitting twist into the yarn were required to maintain its required tensile and tactile qualities. As the speed of the friction unit is restricted by purely mechanical considerations such as bearing capability and vibration, both the thickness and diameter of the friction disc have been increased to insert more twist into the yarn. Increases in these two dimensions expose the yarn to a greater contact area between it and the working surface of the friction disc, enabling a more positive twist insertion to take place.

Friction discs now are available in a bewildering variety of sizes. However, some of the most frequently used are:

Diameter (mm)	Thickness (mm)
45	4*
45	6
50	6
52	6
52	9
53	9

* More commonly used on fine denier nylon hosiery yarns.

Friction discs are now being manufactured with a thickness of 12 mm. However, these have yet to find widespread acceptance.

4.2.9.6 Crossed-belt twisters

Of the five methods of twisting listed in Section 4.2.9.1, spindle and pin crimpers were rendered obsolete by the much greater twist-insertion rate of friction twisting by stacked discs, enabling much higher production speeds to be achieved. Although there were many trials of geometrical variants of ways of providing a normal force by means of a curved yarn path, none proved more acceptable than discs. The one alternative method that has been successful in commercial use is the crossed-belt twister, sometimes referred to as a nip twister, in which the normal force that generates friction is externally applied. The *Barmag Ringtex* twister, which is no longer produced, used the same basic principle. Belt twisters were pioneered by *Murata* and are used on their *Mach Crimper* machines, which are among the market leaders, particularly in Asia, with a reported installed productive capacity of around 30%. Nip twisters were introduced by *Murata* in 1979. Some early problems, concerned with life of belts, drive systems, inter-belt pressure and yarn cooling, were then solved in the first few years of industrial use (Isaacs, 1990). The claims for the *Mach Crimper* are superior yarn quality, high productivity, precision control of twist over a wide range, and versatility in control of yarn characteristics, including production of novelty and speciality yarns (Murata Machinery, 1993).

The units have two belts, between which the yarn passes, mounted at an angle, which may be varied (see Fig. 1.9). Rotation of the belts imparts both twist and a forwarding action to the yarn. This unit can itself be driven by a common tangential belt drive, which uses the same principle as conventional stacked discs. More recently individual units driven by inverter-controlled motors have been introduced. The twist-insertion rate is controlled by three factors: the angle of the belts to each other, the contact pressure applied to the belts and the velocity ratio (V/R), which is the equivalent of the D/Y ratio for stacked discs. It is possible to run two yarns with opposite twist through a single unit, and combine them at wind-up.

The widespread acceptance of this type of unit was hampered in the early days by problems with excessive belt wear and with belt supply. Concerns were also voiced about the length of time it took to ensure that all positions on a machine were making a uniform product. Small adjustments were required on individual units to both belt angle and contact pressure, either of which can dramatically affect the resulting tension and crimp level, in order to be assured of uniform position-to-position production. This was an obvious disadvantage for mass production compared to using stacked discs, where all parameters are fixed using discs of constant dimension and spacers of uniform settings between the discs, leaving little or no room for human error. Some problems occurred in obtaining consistent belt speeds and hence twist level on alternate S and Z twist positions on units driven by a tangential belt when producing two-ply yarns. There were also some within-spindle problems in maintaining constant belt speed, with slippage and the occasional tendency to surge being seen. Companies with extensive experience of disc twisters have therefore been reluctant to adopt belt twister machines.

The system did, however, offer advantages; it leant itself in particular to the production of high-tenacity yarns destined for use in sewing thread or similar end uses. The greater tenacity was attributed to the much gentler twisting action on the yarn than is seen with stacked discs, leading to less physical damage to the yarn bundle. This system was also capable of generating a yarn that showed more textured bulk than one produced by using stacked discs, due to its efficiency at inserting twist into the yarn. This high bulk generation in turn led to the development of special POY feed yarns for use on these machines, the measured textured denier of the yarn produced being higher than one made by other means. This was particularly important for sewing threads where the final product is sold by length and not by weight. The high twist insertion capability also leant itself to the production of heavy, i.e. greater than 300 denier, yarns, which at realistic production speeds are difficult to process with conventional stacked disc units due to the difficulty of gaining sufficient twist-insertion rates. There was also a cost advantage, as the wear rate on polyurethane discs with heavy denier yarns is excessive, leading to more frequent changes of discs being required.

Belt or nip twist units are, in more recent times, being used with some success in producing speciality or novel yarns where the high twist-insertion rate and high bulk character of the yarn produced can be exploited. This type of production is normally made on machinery where supplementary feed shafts and additional heating elements have been fitted (see Sections 4.5.3 and 5.6). This particular type of end use is now being actively marketed by *Murata* and may well lead to wider use of nip twister machines by companies that have so far exclusively used disc twisters.

A development that has been important in promoting the use of *Mach Crimpers* for regular production of textured yarn is a tension control system (TCS) to improve yarn quality and uniformity. The operation of the T_2 control consists in monitoring the tension T_2 in the yarn coming from the twister and using this tension as input to a feed back control, which acts on the air control valve for the pneumatic pressure applied to the belts. This adjusts the normal force N acting on the yarn, and hence the friction force μN, which provides the component that controls yarn tension. The control loop compensates for any variation in coefficient of friction μ between belts, over the period of belt use, or due to yarn finish, by keeping the value of μN within target limits. Although acting directly to maintain constant tension, the component of the friction force that generates yarn torque is also maintained constant, which controls the twist level. It is important, however, that the use of TCS should not mask problems in the POY feed-stock by automatically compensating for unsatisfactory quality, which would otherwise be detected as variations in tension T_2.

4.2.10 Secondary heater

After the yarn has passed through the centre shaft, it is passed through a heater tube usually between 1.0 and 1.3 m in length, where it is heated under controlled relaxation. The reason for subjecting the yarn to this is to reduce the amount of skein shrinkage or crimp and stretch left in it after exiting the twist-insertion device. If this is not done, i.e. no secondary heat is applied, it is known as either single-heater or high-extension yarn. Though suitable for certain end uses in this condition, particularly where a fabric of dense construction or stretch fabric is required, it is not suitable for many other applications.

To reduce the amount of crimp (or to modify) the yarn it is heated to temperatures usually between 150 and 235°C in a conventional, closed tube design. Non-contact, high-temperature heaters operate at significantly higher temperatures, the rule being the higher the temperature in the secondary heater the lower the amount of crimp left in the yarn. These are called double-heater or set yarns. They find use in all types of fabric manufacture and, because of their low shrink character, give a 'crisper feel' to the fabric and drape better than single-heater fabrics (see also Section 5.3.5).

The secondary heaters are usually of the vapour phase heated, enclosed tube design of approximately 1.0–1.3 m in length though there is now a trend towards electrically powered, high-temperature, non-contact secondary heaters. The principle of the vapour phase heater has been described in Section 4.2.7.

The non-contact type heaters have the advantage of being easy to thread by the operator, and indeed may be seen as a step toward a fully automatic, self-threading machine. They are normally in the region of 600 mm in length and operate at significantly higher temperature than vapour phase heaters. However, they have one major disadvantage which is that they are very prone to problems caused by static electricity in the yarn. This problem manifests itself as a tendency for the yarn to waver from its desired thread-path as it travels through the secondary heater. If the yarn wavers sufficiently away from the central path through the heater it can come into contact with the walls of the high-temperature heater itself. If this should happen, the walls of the heater are hot enough to cause those filaments that come into contact with it to melt. In the worst case this leads to dye flecks being apparent in the fabric and it may also cause the yarn to break.

4.2.11 Coning oil application

Coning oil is applied to the yarn to enable it to be processed more efficiently during knitting or weaving. It does this by reducing the friction present between the yarn and the metal components of either the knitting or weaving machine. It also helps reduce the friction caused by two ends of yarn rubbing against each other, particularly as part of a warp during shedding. The oils applied are usually mineral based, though in recent times, there has been a trend toward the use of synthetic, biodegradable oils. With both types significant amounts of emulsifier, corrosion inhibitor and anti-splash agent are added. The most common method of oil application is probably by roller and trough but more sophisticated methods are available, e.g. *Metoil* developed by *Rieter-Scragg*. The latter is a metered application system governed by the size of the orifice in the application head and the pressure head applied to the system.

The rate at which the oil is added to the yarn with a roller and trough system is governed by four factors:

1 the speed of the oil application rollers;
2 the area of contact between the yarn and the oil roller;
3 the viscosity of the oil;
4 the type of surface of the oil application roller.

The amount of oil applied to yarn depends upon its end use but values typically lie between 1 and 3%.

Note: A dyepack (a yarn package that is to be dyed) is an important exception. Oil applied to yarns destined for package dyeing would result in uneven dye pick-up and serious contamination of the dye vessel would follow (see Section 4.4).

4.2.12 Take-up/package build

It is impossible to separate the take-up system on texturing machines from its influence on the package build. All take-up systems consist of a package support, a drive for the package and a traversing system for laying the yarn on to the package. There will also be a mechanism where some controlled disturbance is employed on the traversing system to prevent the formation of pattern regions in the wound package (see Section 4.3.5). The influence of these factors, both mechanical and yarn-related, will be described in greater detail in Sections 4.3.5.1 to 4.3.5.11 inclusive.

4.3 Process variables

In this section the effect of the various parameters employed during the production of a textured yarn will be discussed, and their influence on the properties of the yarn examined. For an overview of the effects of changing process variables, see Appendix 1. For calculations relevant to changing these process parameters on the texturing machine see Appendix 2.

4.3.1 Draw ratio

The draw ratio is the amount the yarn stretched between the input shaft and the centre shaft, and is calculated as a ratio of the speeds of these two shafts (see Appendices 1 and 2), i.e.

$$\text{draw ratio} = \frac{\text{centre shaft speed (m/min)}}{\text{input shaft speed (m/min)}} \tag{4.1}$$

The draw ratio determines:

1 the final textured yarn extension;
2 the denier of textured yarn;
3 the tenacity of the yarn, which is a value calculated from the yarn breaking strength and resultant denier.

Draw ratio also affects:

4 broken filament levels (too high a draw ratio, excess broken filaments);
5 yarn process stability (too low a draw ratio, yarn unstable, high break rate and surging);
6 dye uptake and uniformity: high draw ratio → low dye uptake; low draw ratio → high dye uptake.

Finally:

7 an effect in residual yarn shrinkage may also be seen (higher draw ratio increases the molecular orientation and hence reduces the residual shrinkage).

Draw ratios are normally set to give yarn extensions in the range 22–28%.

4.3.2 Primary heater temperature

Primary heat is applied to the yarn between the input and centre shafts. This assists the mechanical action of stretching and twisting the yarn by softening (making more malleable) the yarn bundle. Primary heater temperatures directly affect the following:

1 bulk (crimp generation);
2 dyeability;
3 broken filament levels;
4 yarn break-rate.

In general the effects of changes in primary heat can be summarised as shown below.

Increasing primary heat	Decreasing primary heat
Increases bulk	Decreases bulk
Increases filament breaks	Decreases filament breaks
Decreases dye uptake	Increases dye uptake

The chosen primary heater temperature is normally a compromise to allow both uniform dyeability and achievement of the required bulk level and the minimisation of broken filaments and yarn breaks. The temperature normally lies in the range 190–230°C for contact heaters.

It should be noted that there are some important exceptions when considering primary heater temperature. Modified polymers are by their nature more susceptible to filament damage. Those that have been modified to produce, for example, cationic dyeable yarns or have flame-retardant properties are usually run approximately 15–20°C cooler than normal disperse dyeable polyester in the primary heater to reduce this risk.

Bright yarns, i.e. those with low titanium dioxide content, are also run at lower primary heater temperatures. In this case the temperature is kept low in order to produce a leaner, less bulky yarn (note that the low primary heat may be used in conjunction with high second heater temperatures for both polyester and polypropylene yarns). The reason for this is that a lean yarn reflects more light back to the eye and therefore appears to be brighter and more lustrous. This is due to the lower crimp amplitude allowing more light to be reflected from the fibre rather than bouncing around within its wave-like structure (for a more detailed explanation see Section 5.7).

Also it should be noted that the nylon 6 products are processed at lower heater temperatures than either polyester or nylon 6.6 and polyolefin (polypropylene and polyethylene) fibres are processed at even lower temperatures.

4.3.3 Twist insertion or D/Y ratio

The most common method of changing the amount of twist inserted in the yarn is by changing the speed of the discs, keeping the number of discs and the spacing between them constant. This changes the ratio of speeds between the friction discs and the linear speed of the yarn. This is known as the D/Y ratio and is calculated as follows:

$$\text{D/Y ratio} = \frac{\text{circumferential speed of discs (m/min)}}{\text{throughput speed of yarn (m/min)}} \qquad [4.2]$$

The rotation of the friction unit or other twist-insertion device is commonly provided by one of two means. The most common is a motor-driven tangential belt system, which circles around the machine and transmits the drive to each spindle by pressure against a jockey pulley in the base of the friction unit. Alternatively, on more modern machinery, it is possible to have each individual friction unit driven by its own motor, which is linked to an inverter-controlled power supply.

In the case of a tangential drive, the rotational direction of the friction unit is set by placing the jockey pulley in the base of the friction unit either to the front or to the rear of the tangential belt thus imparting either ‘S’ or

'Z' twist. In the case of an individually motor-driven unit it is simply a matter of turning a switch to reverse the direction of the motor.

The yarn tension before the friction unit (T_1) and the yarn tension after the friction unit (T_2) govern the value of the D/Y ratio employed. When setting the D/Y ratio, the objective is to balance these tensions, to have a stable situation in the yarn either side of the friction unit, i.e.

$$\frac{\text{output tension } T_2}{\text{input tension } T_1} = 1.0 \quad \text{(referred to as the tension ratio)} \qquad [4.3]$$

What happens if the tension ratio is unbalanced?

1 Output tension T_2 lower than input tension T_1, i.e.

$$\frac{T_2}{T_1} < 1.0$$

This situation is caused by a high D/Y ratio; i.e. the friction discs are revolving too quickly. If you consider the friction unit to be not only a device to impart twist but also a yarn conveyor, it means that the yarn is literally being pushed through the friction discs by their forwarding action. In turn this means that the friction unit is trying to 'store' too much yarn between the entry and exit discs. This is an unstable situation and, if the tension ratio falls to below 0.8, non-uniform twist insertion may be seen in the yarn. This may take the form of:
(a) surges which cause long lengths of highly twisted yarn;
(b) tight spots which are very short lengths of highly twisted, untextured yarn (see sections 5.7.8 and 5.7.9).
Both of these lead to apparent fabric faults.

2 Output tension T_2 greater than input tension T_1, i.e.

$$\frac{T_2}{T_1} > 1.0$$

Here the friction discs are revolving too slowly; i.e. the D/Y ratio is too low. In this case the yarn is literally being pulled through the friction unit, i.e. the discs are revolving so slowly as to hinder the yarn as it is being pulled through the top half of the machine by the centre shaft. This is, of course, a highly stable situation within the friction unit, but gives rise to mechanical damage to the yarn, i.e. broken filaments and increased yarn breaks, and in the case of polyurethane discs, increased disc wear.

4.3.4 Second heater temperature and overfeed

The second heater temperature and overfeed must be considered as one relationship since the combination of temperature and overfeed has a pronounced effect on the resultant yarn shrinkage. Before the yarn enters the second heater it has a very high skein shrinkage; too high for many fabric end uses. To lower this shrinkage secondary heaters are employed, the conventional, enclosed-tube type at temperatures commonly between 150 and 240°C and the high-temperature, non-contact type at significantly higher temperatures up to 350°C, dependent upon the process. The higher the temperature in the second heater the lower will be the final yarn shrinkage. The secondary heater overfeed can enhance or reduce the effect of the temperature by altering the tension on yarn in the heater (see Section 5.3.5.2).

Normally the second heater overfeed is set as high as possible within the limits of yarn stability, usually in the range 3–12% dependent upon machine configuration and product requirements. If a high second heater overfeed is employed, the tension on the yarn in the heater tube is low allowing the heat available to have its maximum effect. If the second heater overfeed is low, yarn tension is higher restricting the effect of the heat. Note that if the overfeed is too high the yarn can wrap back on the centre shaft of the machine and cause breaks.

The choice of second heater overfeed may also be restricted where an intermingling jet is mounted either above or below the second heater. If the overfeed is too high the yarn tension can be so low as to allow the jet to blow the yarn out of the jet chamber physically, if the jet is of the open type. This is especially true in the case of detorque jets (see Section 5.3.4) which are always mounted below the second heater. With jets of an enclosed or forwarding type, whether mounted above or below the second heater, these restrictions of yarn tension do not apply to the same degree and the main consideration must be that of achieving uniformity of intermingling.

4.3.5 Package build

Building a good package, which means one that meets the manufacturers' standards and that satisfies the customers' needs with regard to off-winding performance, is of crucial importance in order to have a viable product that can compete in the market. There are many factors that have to be taken into account when specifying a yarn package; these will be explored in the following sections.

When winding a package the following factors have to be taken into account and the parameters for building the package adjusted accordingly:

1 the characteristics of the yarn regarding skein shrinkage and intermingling;
2 the end uses of the yarn – weaving warp, weaving weft, warp knitting, weft knitting and, very importantly, package dye.

Factors affecting the form of a package wound on the texturing machine are:

1. yarn skein shrinkage;
2. yarn denier;
3. intermingling level;
4. take-up overfeed;
5. wind angle (traverse speed);
6. cradle damping;
7. taper angle;
8. traverse stroke length;
9. stroke modification;
10. pattern breaking;
11. tree geometry;
12. density requirements – determined by end use (see Sections 4.4.1.1 and 4.4.2).

Each one of the above factors can have a strong influence on the way a package builds on the machine and, in the case of an automatic doffing machine, may influence its doffing performance. They will now be considered separately.

4.3.5.1 Yarn skein shrinkage (effect of setting on the machine)

Yarns with high skein-shrinkage values tend to build denser (harder) packages than yarns with low shrinkage. This is because the yarn tries to shrink while it is on the package particularly high shrinkage nylon yarns and hence tries to force its way both down into the tube and towards the centre of the traverse stroke. Yarns with low skein-shrinkage values tend to build packages where the reversal points are very hard but the package is soft in the middle. This is caused by there being so little shrinkage in the yarn that it tends to remain at the edge of the package where it is laid by the traverse guide and does not try to migrate toward the centre. These low-shrinkage yarns are usually built with a high degree of stroke modification to prevent prominent raised edges on the packages.

4.3.5.2 Yarn denier

The denier of a yarn can be related to its overall diameter or thickness. This has an important bearing on how the package winds. Consider the difference between winding a spool of cotton thread and winding a roll of string. The diameter affects how the layers of yarn on the package lie against each other. For this reason higher denier yarns, i.e. two, three and four plies, are wound at high wind angles, i.e. high traverse speeds. This gives a better opportunity for the yarn to lie side-by-side rather than on top of itself, which in turn can lead to erratic unwinding tensions or to it trapping and not coming off the package at all.

4.3.5.3 Intermingling level (mingle or interlace)

The level of intermingling in yarn has a profound effect on the way a package of yarn is built. Consider two yarns; one with no intermingling, the second with intermingling but in all other respects identical. The non-intermingled yarn winds onto the package like a ribbon due to the effect of the thread-line tension during winding (T_3). With an intermingled yarn, the thread-line tension is prevented from flattening out the yarn, since the intermingling points tend to impart to the yarn a more circular cross-section. The more a yarn is intermingled, the more this effect is apparent (see Section 5.3.3.4).

Where the yarn retains its more circular form, it has more of a tendency to roll over itself as it is being wound on the package. It is for this reason that intermingled yarns are more prone to webbing and overthrows (Section 4.3.6) than non-intermingled yarns. When the yarn is at the reversal points of the traverse, it is subjected to very high forces. The change in direction of the traverse guide puts such force on the yarn that its own momentum tends to throw it on to the outside of the package (hence the term overthrow). The part of the yarn that forms the overthrow is that which is immediately behind the traverse guide at the point at which it changes direction.

To overcome this, intermingled yarns are run when possible with high wind angles and high taper and with a stroke modification programme that is designed to give as hard an edge to the package as possible.

4.3.5.4 Take-up overfeed

The take-up overfeed is the speed of the take-up shaft relative to the centre shaft of the machine. Consequently this has a great effect on the hardness (density) of the package:

1 low take-up overfeed, i.e. 3%, leads to a hard package;
2 high take-up overfeed, i.e. 8%, leads to a soft package.

4.3.5.5 Wind angle (traverse speed)

Over the years, as an understanding of package build and its consequences has grown, the wind angle (or angle of wind) has assumed an increasing importance. Whereas at one time it was used merely to adjust the take-up tension (T_3) for reasons of package density, it is now the predominant factor in building a package of textured yarn.

The angle at which the yarn is laid on the package greatly affects the way the yarn 'packs' or in other words the manner in which successive layers of yarn lie against each other. This in turn has a great effect on the number of package build faults generated on the machine and, very importantly, on how the package will unwind at the customer's plant.

At this point it is worth examining the relationship between wind angle and crossing angle and how these translate to the appearance of specific patterns. Figure 4.5(a) shows these patterns, which are known as 'diamonds' on the surface of the package. It also shows how so-called ribbon phases or pattern points may be found to occur with specific wind angles and package diameters which result in the need for a pattern breaking mechanism as described in Section 4.3.5.10.

The wind angle is defined as half the crossing angle, which as such is determined by the speed of the traverse guide in cycles per minute and the length of the traverse stroke. If the wind angle = α, then:

$$\tan\alpha = \frac{2\times\text{traverse stroke length (m)}\times\text{traverse speed (cycles/min)}}{\text{speed of take-up shaft (m/min)}} \qquad [4.4]$$

e.g. for a process running with a take-up shaft speed of 760 m/min and a traverse speed of 430 cycles/min with a traverse stroke length of 250 mm the wind angle is calculated as:

$$\tan\alpha = \frac{2\times 0.25\times 430}{760} = 0.2829 = 15.8^\circ$$

From this it follows conversely that the traverse speed can be calculated as:

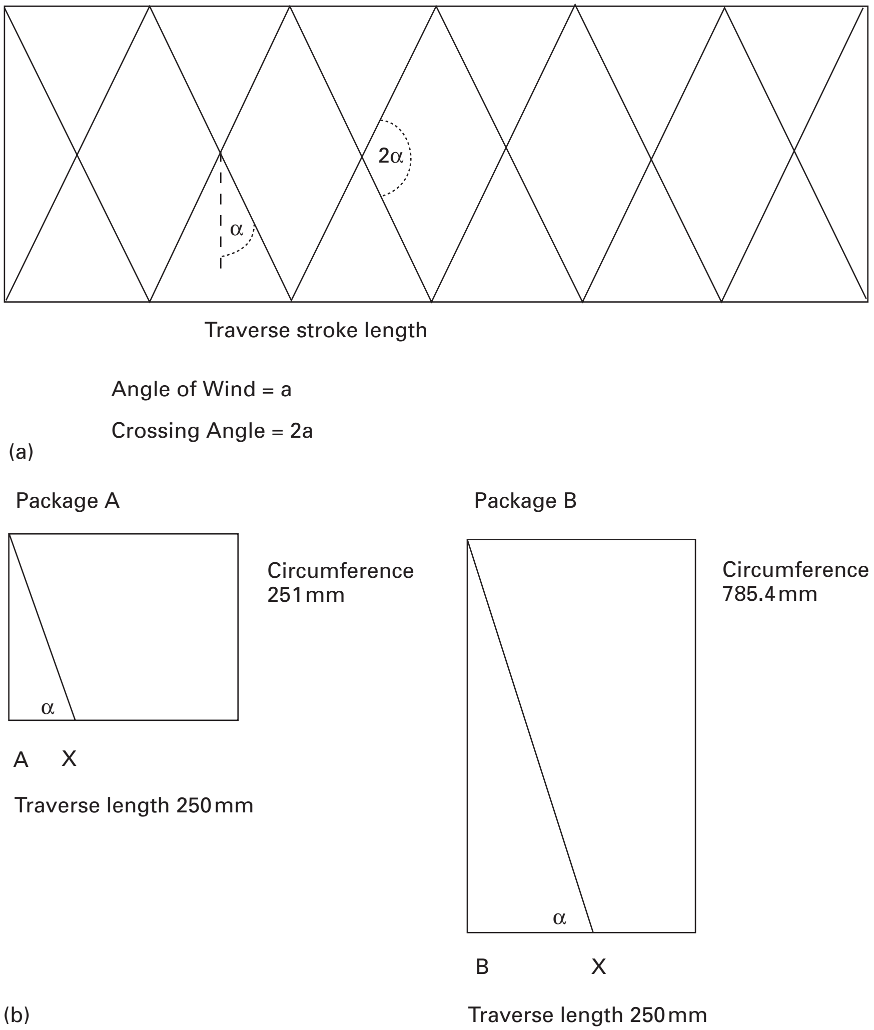
$$\text{traverse speed} = 2\times\tan\alpha\times\text{take-up bowl speed (m/min)} \qquad [4.5]$$

The relationship between α and package diameter will now be described.

As a package builds on the texturing machine a characteristic pattern of 'diamonds' can be seen on the outer surface of the package. The number of 'diamonds' apparent decreases as the diameter of the package increases (Fig. 4.5(b)). As α is fixed, determined by the take-up bowl speed and traverse rate both of which are constant, the number of 'diamonds' apparent is directly related to the circumference of the package. The relationship between these can be calculated as follows.

Consider two packages both built with identical winding specifications but one, package A, of diameter 80 mm and the second, package B, of diameter 250 mm, both using a wind angle of 16.0°. Then:

$$\text{circumference of package A} = \pi d = \pi\times 80 = 251\,\text{mm}$$



4.5 (a) Surface pattern diamonds. (b) Detail of traverse wind.

and

$$\text{circumference of package B} = \pi d = \pi \times 250 = 785.4\,\text{mm}$$

By opening this cylindrical form of the packages out to a rectangular shape, one side of which is fixed by the traverse stroke length, the distances AX and BX can be found by simple trigonometry (see Fig. 4.5(b)). With the wind angle α set at 16.0°:

$$\begin{aligned}\text{AX} &= \tan 16.0^\circ \times 0.5 \times \pi d\\ &= 0.2867 \times 125.5\\ &= 35.98\,\text{mm}\end{aligned}$$

and

$$\begin{aligned}\text{BX} &= \tan 16.0^\circ \times 0.5 \times \pi d\\ &= 0.2867 \times 392.7\\ &= 112.59\,\text{mm}\end{aligned}$$

$$\text{Therefore number of diamonds on package A} = \frac{2 \times \text{stroke length}}{\text{AX}} = 13.89$$

and

$$\text{number of diamonds on package B} = \frac{2 \times \text{stroke length}}{\text{BX}} = 4.44$$

Pattern regions may occur at various diameters throughout the package; these are sometimes known as ribbon phases. These are based on the relationship between the revolutions of the package and the number of complete traverse cycles made. A pattern will occur when this relationship resolves into a whole number integer, since fractional relationships do not result in pattern regions. The diameters at which pattern regions will occur can be calculated as follows.

Let α = the wind angle, N = the observed pattern ratio and D_N = the diameter at which patterning occurs where:

$$N = \frac{\text{take-up speed (m/min)}}{\pi \times D_N\,(\text{m}) \times \text{traverse cycles/min}} \qquad [4.6]$$

It follows that:

$$D_N = \frac{\text{take-up speed (m/min)}}{\pi \times N \times \text{traverse cycles/min}} \qquad [4.7]$$

since D is also related to the winding angle α through:

$$\tan\alpha = \frac{2 \times \text{traverse length}}{\pi \times D} = \frac{\text{traverse cycles/min} \times 2 \times \text{traverse length}}{\text{take-up speed (m/min)}} \qquad [4.8]$$

From this it is apparent that a simple table can be calculated for values of N to determine where patterns are likely to occur (see values in Table 4.5).

Note that the calculated values of diameter for $N = 1$ are exceptionally large, in fact larger than most textured yarn packages will ever become, so that these values can be ignored. Also, some diameter values for $N = 9$ are

Table 4.5 Calculated pattern diameters

	Wind angle														
	11	11.5	12	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18
N	Diameter to nearest whole millimetre														
1	819	782	749	718	689	663	638	615	594	574	555	537	521	505	490
2	409	391	374	359	345	331	319	308	297	287	278	269	260	252	245
3	273	261	250	239	230	221	213	205	198	191	185	179	174	168	163
4	205	196	187	179	172	166	160	154	148	143	139	134	130	126	122
5	164	156	150	144	138	133	128	123	119	115	111	107	104	101	98
6	136	130	125	120	115	110	106	103	99	96	93	90	87	84	82
7	117	112	107	103	98	95	91	88	85	82	79	77	74	72	70
8	102	98	94	90	86	83	80	77	74	72	69	67	65	63	61
9	91	87	83	80	77	74	71	68	66	64	62	60	58	56	54

very small, smaller than most tube diameters, and therefore can also be ignored. If patterning is apparent it is usually found at diameter values corresponding to $N = 3$.

Some guiding principles for the choice of wind angle are as follows:

1 The smaller the angle, the faster the yarn is capable of unwinding from the package.

Logic – with small wind angles, successive wraps of yarn around the package lie closer to one another. Thus, when unwinding the yarn tends to spring off the package rather than have to drag along its length.

2 The bigger the angle of wind the better the package build on highly intermingled yarns.

Logic – because intermingled yarns tend to lie on the package more like a cord than a ribbon they are more prone to roll over layers of yarn already wound on the package. With a high wind angle more space is left between successive layers of yarn as it is wound on the package. This reduces the chance of successive layers being wound directly on top of each other, where they would be prone to roll, and instead gives a greater opportunity for the layers of yarn to lie against each other.

The use of high wind angles brings other factors into play, since the traverse speed and the forces on the yarn at the reversal points of the traverse stroke are very high. These forces have a tendency to try to throw the yarn over the edge of the package (overthrows or webbing). For this reason, when using very high wind angles, a stroke modification setting is used that puts a very hard edge on the package such that it resists the tendency to overthrow.

Some guidelines for wind angles for polyester are:

Process type	Wind angle
Weaving warp	15–17°
Weaving weft	12–16°
Weft knits	12–14°
Raschel	14–17°
Dye pack	16–19°

Hosiery yarns commonly employ smaller wind angles.

Note: Wind angle is of critical importance when building dye packs (see Section 4.4).

4.3.5.6 Cradle damping

Cradle damping is the force on the cradle employed to stabilise the package as it is building to full size. These forces are adjustable and may, dependent on the machine type, be either mechanical or pneumatic. In either case they perform the following functions:

1 Apply a downward force on the tube at the start of package winding:
   - a high down force – more resistance to cradle rising, high density;
   - b low down force – low resistance to cradle rising, low density.

2 As the package increases in size, i.e. weight, the damping system acts to compensate for the increasing weight of the package.

An additional force may be put on the cradle by the application of pressure at each side. This is a relatively weak force that is used purely to give stabilisation to the package and prevent unwanted vibration in the system while the package is building.

Note: Running package dye yarns requires great care in the choice of these forces; these will be mentioned in Section 4.4.1.

4.3.5.7 Taper angle

The taper angle of a package determines the rate at which the stroke length reduces and hence gives the package its final shape. This reduction in stroke length is caused by the taper mechanism controlling the rate at which the gauge screw extends from its set position for the initial stroke. The gauge screw acts through a lever on a cam inside the traverse box, which governs the movement of the sine bar. This in turn controls the movement of the traverse guide. The mechanism controlling the traverse guide is fairly complicated, but it does work.

The simple reason why a taper angle is put on a package of yarn is to improve its winding performance when it reaches the customer. The rule is that the higher the unwinding speed the greater the degree of taper that is put on the package, i.e. the more the package sides slope away from the vertical, as shown below:

Unwinding speed (m/min)	Taper angle (°)
500	90 or 85
1500	75

As a package increases in size the tension on the yarn in the take-up (T_3) area changes, i.e. at initial stroke (start of package) T_3 is at its highest, and at final stroke (at full size) it is at its lowest.

If the package builds at a 90° taper, i.e. straight sided, the wind angle changes as the package diameter increases. This is due to the diameter and hence the circumference of the package increasing. Since it is not possible to reduce the diameter of the package, the reduction in traverse stroke length caused by the taper cam helps maintain the wind angle as its circumference increases (see Section 4.3.5.3).

4.3.5.8 Traverse stroke length

The maximum stroke length that can be set on the machine will vary according to machine type. However, a maximum value of 250 mm is common. Setting the initial stroke length correctly is of importance since it has a fundamental influence on the quality of package build.

It has been found that as the wind angle increases, and therefore the speed of the traverse guide increases, hence the take-up tension (T_3) increases, and stroke length decreases and vice versa. This effect on yarn tension during winding is shown below:

1 high (T_3) – short stroke;
2 low (T_3) – long stroke.

It should be noted that incorrect setting of the stroke length, for example by having it longer than the machine manufacturer's recommendation, can lead to accelerated wear of the components within the winding mechanism and an increase in package build faults.

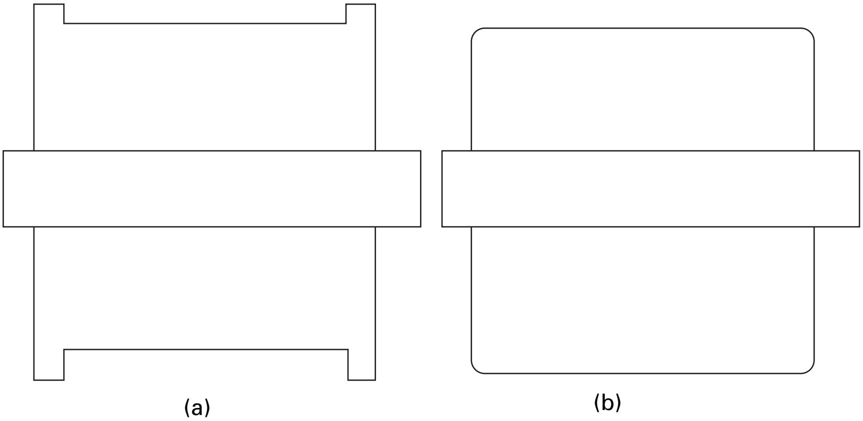
4.3.5.9 Stroke modification

Stroke modification is the name given to the mechanical action of continually varying the traverse stroke length during the formation of a package. This is commonly synchronised to work with variations in traverse speed as part of the cycle known as 'pattern breaking'. This variation in traverse speed is sometimes called the disturbance and is specified as amplitude of percentage variation away from a mean traverse speed (see Section 4.3.5.10).

The stroke modification bar is driven backwards and forwards along the length of each take-up deck by a rotating spindle, which is chain driven from the stroke modification gearbox. An electrical signal usually controls the motion of the spindles, which may be infinitely variable between fixed limits.

Consider the movement of the traverse guide back and forth across the length of the package. If there was no stroke modification, the stroke length would remain constant and hence twice as much yarn would be laid at the edges of the packages as in the centre, due to the length of time the traverse guide spends at the reversal point. The reversal point is the end of one stroke and the start of another. Hence the package would look as shown in Fig. 4.6(a).

To overcome this problem the traverse stroke length is continually varied. The amplitude of the stroke length variation and the speed and frequency at which it is varied have a significant effect on the overall look and shape of the package. More importantly, they affect the package significantly in terms of apparent faults and the unwinding performance. However, if the stroke modification were exaggerated, the package would look like that shown in Fig. 4.6(b). This is just as undesirable, since the edges


(a) (b)

4.6 (a) Yarn package with no stroke modification. (b) Yarn package with excessive stroke modification.

of the package are very soft and prone to both yarn overthrows (see Section 4.3.6.3) and physical damage.

The stroke modification system consists usually of a mechanically driven action whereby the stroke modification chain, driven from a gearbox, drives a threaded spindle, which in turn oscillates the stroke modification bar longitudinally along the length of the machine. Note that there is usually one spindle and one bar for each take-up deck of the machine. In order for the stroke modification bar to perform its function correctly, it must be in exactly the correct position at its start or rest position.

As the stroke modification spindle drives the bar backwards and forwards along the length of the machine, it takes with it a small cam (usually nylon but may be of some other material) which is attached to the bar. This cam acts to move the angle of the lever that controls the movement of the sine bar; this in turn controls the stroke of the traverse guide across the length of the package. As the bar moves to the left it reduces the stroke length. As it moves to the right, it increases the stroke length. It is this variation in stroke length which determines how much yarn is laid by the traverse at the reversal points and hence how soft or hard is the edge of the package.

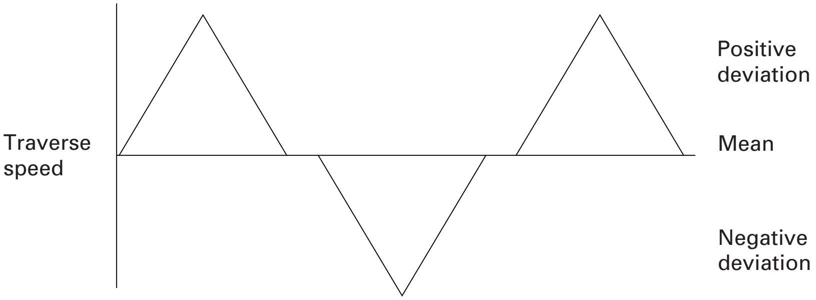
4.3.5.10 Pattern breaking (traverse disturbance)

Rise and fall is also known as traverse disturbance and is sometimes referred to as the pattern or ribbon breaking function on the machine. Usually this works in conjunction with the stroke modification system. The rise and fall feature continuously varies the speed of the traverse guide, within set limits.

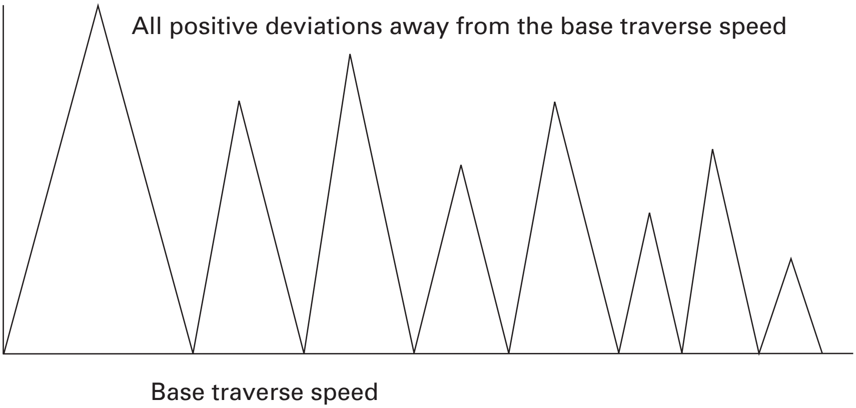
The system of varying the traverse speed is designed to prevent successive layers of yarn being laid upon each other, by continuously changing the traverse speed and thus the wind angle of the yarn. This is designed to prevent ribbon phasing or patterning (see Section 4.3.5.5 on wind angle above). The way in which this variation is generated may vary from machine to machine. On some this variation takes place either side of the average or mean traverse rate, e.g. 3% disturbance and a mean traverse speed of 300 double strokes per minute. A representation of this is shown in Fig. 4.7.

On other machines the traverse disturbance is all positive. In this case it rises from a base level to a maximum and then falls back to the base value (Fig. 4.8). Note that the maximum value of the disturbance may be infinitely varied within limits.

Modern stroke modification systems are often controlled by a microprocessor and are capable of producing a wide variety of disturbance patterns at the reversal points of the traverse stroke. Though complex in



4.7 Traverse disturbance equally distributed either side of the mean speed.



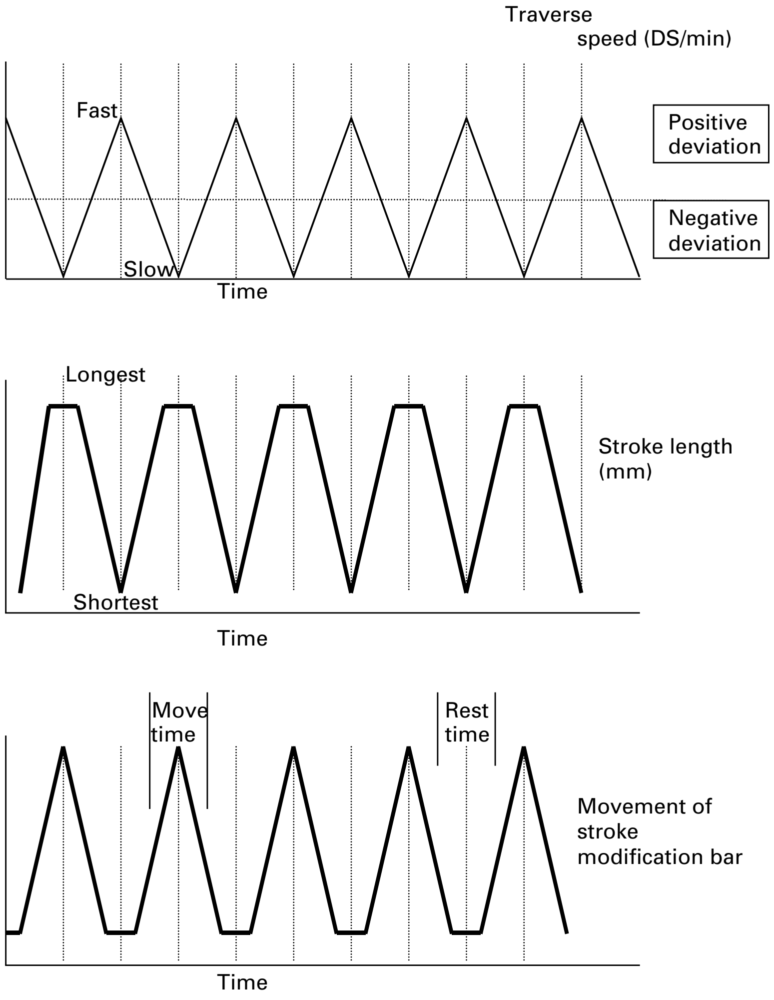
4.8 Traverse disturbance – all positive.

movement, sometimes comprising as many as 16 separate reductions or increases in stroke length to complete one cycle, these complex patterns can be extremely useful when dealing with different yarns, since some are very prone to produce overthrown ends because of their physical properties (see Section 4.3.6).

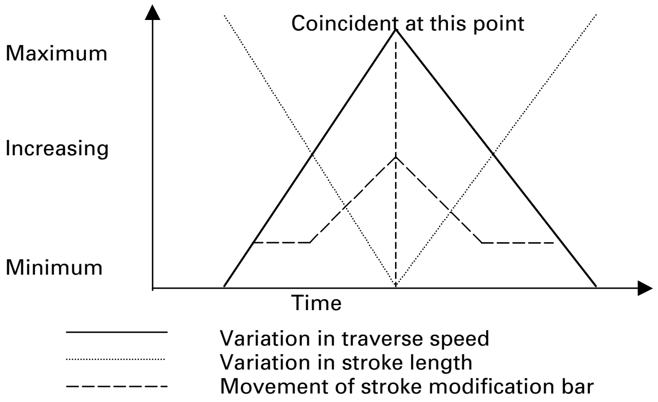
The time taken for the traverse to speed up and slow down must be precise and may be known as either the rise or fall time or ramp-up and ramp-down time. The rise and fall times and the rest and motion times of the stroke modification bar are synchronised. By this synchronisation, the maximum movement of the stroke modification bar occurs when the traverse speed is at its minimum. In other words the shortest stroke occurs when the scroll shaft revolutions are at their peak. The longest stroke coincides with the minimum revolutions of the scroll shaft.

The rest and motion times of the stroke modification are self-explanatory. The motion time is the time in seconds that the stroke modification bar is moving and the rest time is the time in seconds that the bar is stationary. The synchronisation of the traverse disturbance and stroke modification is represented in Fig. 4.9.

By superimposing these diagrams on top of each other it is possible to get a clearer understanding of how the traverse speed variation and the movement of the stroke modification system are synchronised to each other, as shown in Fig. 4.10.



4.9 Stroke modification function. Courtesy of Barmag-Saurer Group.

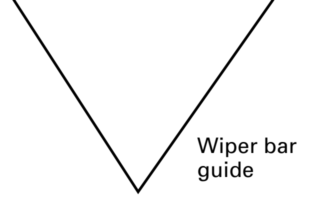


4.10 Stroke modification function superimposed on traverse disturbance.

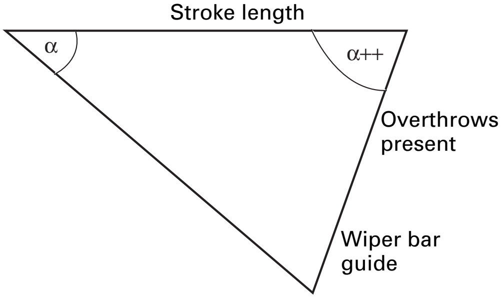
4.3.5.11 Tree geometry

Question: What have trees got to do with texturing machines?

The tree is the name given to the arrangement of the guides that lead the yarn from the oil application roller up to the package take-up roller. The important thing to remember when setting up the wiper bar guides, as they are sometimes known, is that the guides should be exactly centred on the package such that the guide forms the apex of an isosceles triangle of which the initial stroke length is the base (Figs 4.11 and 4.12). If this guide is not centred correctly on the textured yarn package, there will be a tendency for overthrows to be present on the side of the package to which the guide is offset.



4.11 Correct tree geometry.



4.12 Incorrect tree geometry.

4.3.6 Package build faults

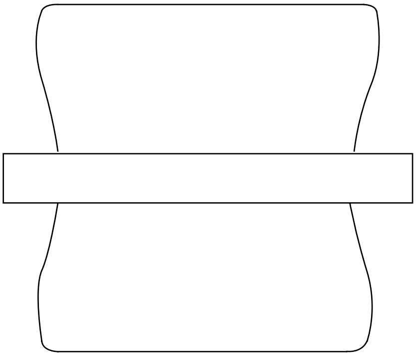
A brief description of some of the more common types of package build faults is included. Where relevant, line drawings of some of the more common types of package build fault are shown (see Figs 4.13–4.18).

4.3.6.1 Bulging

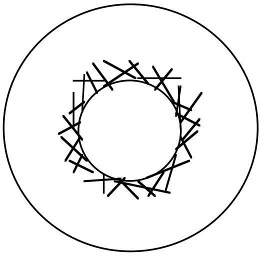
Employing small wind angles, usually of less than 13°, often causes bulging. Though this is sometimes counted as a package build fault, it may also be done as an intentional part of the specification. It helps the yarn to unwind off the package at high speeds and is particularly useful when producing yarns designed for high-speed weft insertion in weaving (see Fig. 4.13).

4.3.6.2 Webbing

Webbing is sometimes confused with overthrows and though some of the causes of this fault can be the same they should be treated differently. There



4.13 Package build – bulging.



4.14 Package build – webbing.

are many reasons why webbing can be apparent on a package some of them machine related and others specification related. These will be discussed separately below. Webbing is characterised by a distinctive 'birds nest' appearance to the package, particularly close to the tube, i.e. within the first half inch of the package (see Fig. 4.14). This not only looks unsightly but will also lead to unwinding problems for the customer.

Webbing is more usually seen with intermingled yarns, especially those, which are built with a high package density. Also to be kept in mind is that the machine design itself may be a factor, depending upon the take-up geometry.

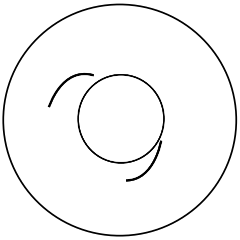
Webbing will occur especially on intermingled products if the wind angle is too small. For this reason intermingled yarns are generally run with wind angles greater than 15°. Webbing is also likely to occur, if the stroke modification programme chosen is one which causes a soft edge on the package at the reversal points.

Some other causes of webbing are poor alignments in the mechanical set up of the take-up system, worn components or even something as simple as a stiff bearing. Uneven damping settings may also result in packages with webbing. The overall density of the wound package is also a big factor. High-density packages produced with correspondingly high take-up tensions will result in webbing.

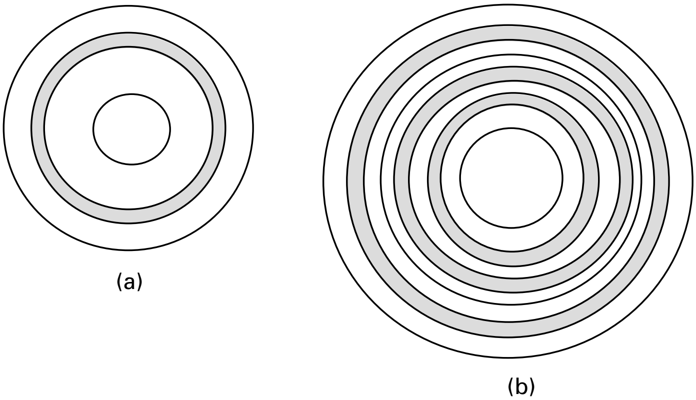
Note: With dye packages a special set of circumstances exists where the edge of the package at the reversal points has to be relatively soft to avoid problems with dye uptake in the dye vessel. When the package is compressed and if the edges are too hard it is not possible to get even dye penetration at the reversal points. Again these will be discussed separately in Section 4.4.

4.3.6.3 Overthrown ends

Overthrown ends or overthrows occur as single, long threads, which are usually observed on the side of tapered packages approximately one inch



4.15 Package build – overthrows.



(a)

(b)

4.16 Package build – (a) ridges, (b) concentric rings.

away from the tube wall (see Fig. 4.15). It is at this point in the package that the anti-bulge feature of the taper cam or other stroke-shortening feature comes into operation. This is designed to prevent the package from bulging too severely at low wind angles. Giving a rapid decrease in stroke length at this point prevents bulging. It is due to this rapid change in stroke that the overthrows are more prone to appear. In this case rapid is a relative term, the actual change in stroke taking place over approximately 15 mm of the package build. This is relatively fast when you take into consideration the overall doff-time.

4.3.6.4 Ridges

These are normally found to be due to incorrect setting of the taper mechanism, particularly when running taper angles of 85 or 90°. The ridge is normally apparent at the very outside of the package, usually within the final 8–10 mm (see Fig. 4.16(a)). It is caused by the taper cam losing contact with the gauge screw thus allowing the stroke to lengthen again and therefore resulting in an apparent ridge on the package. It can also happen that a ridge is seen on intermingled products when a temporary change in air pressure is observed.

The chosen wind angle can also have an effect on the formation of ridges. The exact mechanism of this is not known but it is more likely to happen on yarns with low filament denier. In these cases a wind angle of between 14 and 16° is preferred. It can also happen that ridges, in the form of concentric circles, can be seen on both shoulders of the textured package (see Fig. 4.16(b)). These have been demonstrated to be due either to faulty end caps on the cradle arms or non-concentric tubes, see Section 4.3.7.1. These types of ridges manifest themselves more clearly on high-density products.

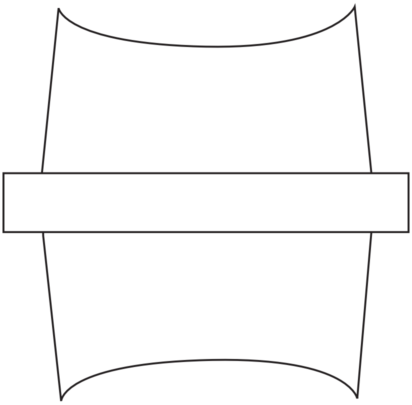
4.3.6.5 Saddling

Saddling is the name given to packages that show pronounced raised edges that are hard (see Fig. 4.17). When this occurs it will usually be seen on every position on the machine and rarely on just one deck. The causes may be:

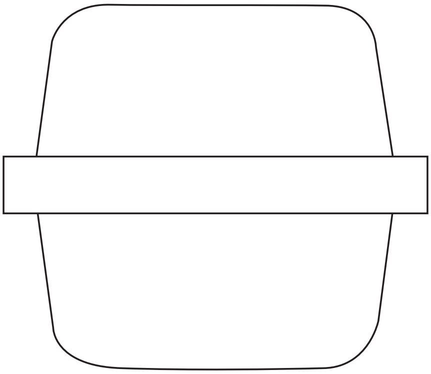
1 take-up tension is (T_3) too high, giving very hard dense packages, or
2 an incorrect setting of the stroke modification system resulting in too much yarn being laid at the extremes of the traverse stroke.

4.3.6.6 Shouldering

Shouldering is the reverse of saddling. It is manifested by the edges of the package being so soft that they have a sloping appearance. Often this will be accompanied by webbing (see Fig. 4.18).



4.17 Package build – saddling.



4.18 Package build – shouldering.

4.3.6.7 No-tail package

A no-tail package, i.e. a package of wound yarn on which there is no reserve of yarn left with which one package may be transferred to another, is sometimes classified as a package build fault. This yarn reserve or transfer tail is formed manually or in the case of automatic doffing machines automatically whenever a new tube is placed in the machine at doff.

4.3.7 Tube design (yarn carrier)

Though often ignored, the type and design of the tube on which the yarn is wound, the materials used and the method of its manufacture can play a very big part in the product behaviour. This may apply not only on the texturing machine, with respect to any package build problems, but also in downstream processing at the customer. Both cardboard and plastic dye tubes are affected but the dye tube is much more critical due to the nature of the process. Dye tubes will be discussed separately in Section 4.4.

4.3.7.1 Cardboard tubes

Cardboard tubes come in two basic designs. These are usually known respectively as either ‘square cut’ or ‘bull-nosed’ tubes, occasionally referred to as ‘roll-nosed’. The difference is that the square cut tube has the same internal and external diameters at either end of the tube, whereas the bull-nosed tube has a smaller inside diameter at one end of the tube, the end opposite to where the transfer tail is placed. This end of the tube being turned in upon itself during the manufacturing process forms the smaller diameter. It is then burnished to form a smooth edge to the tube. This type of tube, though requiring different sizes of end cap at either end of the cradle, does offer the consumer improved unwinding capability since it reduces the incidence of the yarn snagging on the end of tube as it unwinds.

The tubes are made from compressed paper bound together with adhesive. The process of building up the thickness of the tube wall by successive layers is known as lamination and is what gives the tube its final strength. The two most important criteria for a cardboard tube are its concentricity and its 'squareness' at either end. Concentricity refers to how uniformly the circular cross-section is maintained along the length of the tube and by 'squareness' is meant how straight and level the ends of the tube are such that they fit securely and evenly on to the end caps in the cradle.

The final layer in the lamination process is the outer covering of paper, which will designate the tube colour. It is important that this layer is carefully applied to ensure that the overlaps on the wrapping are as smooth as possible. This is to prevent the possibility of yarn snagging and catching on the overlaps when unwinding at the customer. This may result in fabric faults or yarn breaks and is of particular importance on both hosiery yarns and yarns with low filament denier.

If the tube is not concentric this will lead to package build problems. What happens is that at high take-up speeds, i.e. with high tube revolutions, the tube will start to bounce in the end caps; in severe cases the cradle itself can be observed bouncing up and down. As a result of this, a package is built on which a series of concentric rings on the walls of the package can be plainly seen. A similar situation will arise if the ends of the tube are not cut squarely. These problems will manifest themselves more on packages that are built to a high package density than on ones built to a low density.

The crush strength of the tube is also an important consideration. This is particularly so in the case of very tightly wound packages such as those containing nylon yarns destined for use in ladies' hose and especially so-called torque yarns, i.e. yarns with very high twist and little residual shrinkage. If the crush strength of the tube is not sufficient then severe deformation of the tube will occur on the texturing machine leading to growth in the tube length on the machine due to the force exerted on the tube by the wound package. In extreme cases, the tube itself may collapse whilst still in the end caps and result in a forced machine stop.

It is also important to ensure that the tubes are uniform in weight, otherwise information recorded at the weigh scale regarding gross and net weights of yarn packed will be incorrect.

4.3.7.2 Plastic dye tubes

Commonly injection moulded tubes are used for package dye yarns using polypropylene as the base material. A small amount of coloured pigment may be injected into the polymer to give a range of colours available for use in product identification (see Section 9.1.1). Two types of polypropylene may be used, either a homopolymer or a copolymer. In recent times the use of copolymers has found favour; this is because they are more durable and can readily withstand the forces generated during subsequent tube compression in the dye process.

Two types of plastic dye tubes are routinely used for production in the texturing plants: the compressible dye tube and the rigid, non-compressible, perforated tube. Within the category of compressible tubes there are two types. The first compresses along the main axis of the tube. This type is known as an axially or longitudinally compressible tube, i.e. its overall length reduces under compression. The second type are those that allow compression directed towards the centre of the tube such that the diameter decreases. This is known as a radially compressible tube.

4.3.7.3 Axially compressible tubes

The major problem that is apparent with compressible dye tubes is that, as they are intentionally designed to be compressed, conversely they are also prone to expansion on the machine when yarn is being wound on them. This is due to both centrifugal forces and the effect of the increasing weight of yarn placed upon the tube. On a manually doffed machine this does not create a problem but on the automatic doffing machines such as the *Barmag AFK* it can cause a serious problem. Should the tube expand in overall length, then it will not roll out of the cradle properly and as such will result in high doffing failures. This increase in length can also, if great enough, lead to a situation where the tubes are so long that they will no longer fit the cartons for despatch to the customer.

The manufacturer can design different compression capabilities into the tube, in particular by changing the angle of the ribs supporting the length of the open area of the tube. The provision of any longitudinal reinforcement designed to restrict compression and the possible inclusion of stoppers placed between the ribs of the tube are again designed to restrict overall compression.

Plastic dye tubes are manufactured by a process of injection moulding and hence the uniformity of product should be excellent. However, it must be bore in mind when contemplating any changes to the design of a dye tube that this means that modifications (usually irreversible) have to be cut into the mould, a lengthy and expensive process.

4.3.7.4 Radially compressible tubes

The radially compressible tube can be treated in a similar manner to that of the rigid tube, as described in the next section. Tubes of this type are used where the benefits of excellent unwinding capability are required but the tube can absorb the shrinkage apparent in the yarn by a reduction in its diameter.

4.3.7.5 Rigid dye tubes

Rigid dye tubes are, as their name suggests, designed such that they cannot be compressed. This in turn means that they are not prone to the same degree of expansion on the texturing machine. Due to the tube's non-compressible nature the yarn can be wound onto a rigid tube at higher tension leading to higher package densities and increased package weights. To increase the strength and rigidity of these tubes it is common for a small amount of glass fibre to be added to the tube during the moulding process. The same considerations of weight, uniformity and concentricity apply equally to all types of tube for winding textured yarns.

4.3.7.6 Compressible steel springs

For some uses, particularly the production of nylon yarns for package dyeing, the plastic dye tube is eschewed in favour of a compressible steel spring. These steel springs have some advantages over the plastic design, since they are capable of more than one trip through the process, an important economic consideration. They also have a higher compression rate than the plastic tube. Nylon yarns are usually dyed at higher compression rates than polyester and will, due to their nature, shrink on the tube to a greater extent than a polyester product. The steel spring is more able to accommodate this high residual shrinkage than a plastic tube without sustaining physical damage. The greater shrinkage potential of nylon yarns means that the package produced on the texturing machine is wound at a much lower density than a polyester package (see Section 4.4.1.1).

These tubes must be carefully inspected after each journey through the process to ensure that they are free from damage. This is especially important from the points of view of both operator safety and product integrity, and inspection must be carried out before they are re-used on the texturing machine.

4.4 Package dye yarns

Package dye products must be viewed from a different standpoint from normal products wound on cardboard tubes. When building a dye pack it has to be remembered that the package being produced on the texturing machine must perform satisfactorily after it has been dyed, possibly compressed and generally after suffering a lot of abuse. There are certain rules that can be applied depending on whether a yarn is being produced on rigid or compressible tubes. These will be discussed separately below.

4.4.1 Compressible tubes

A compressible-tube product is the most challenging package that can be built on the texturing machine. Almost every rule that would normally apply to building a satisfactory package on cardboard tubes has to be broken when building this type of package. It must be remembered that when winding on to a compressible tube the yarn must unwind satisfactorily after it has been compressed by anything up to 30% within Europe and even more in the USA. This means that the following must be considered when deciding how to specify a dye pack on a compressible tube:

1 The package must be soft, i.e. of low density (see Sections 4.4.1.1 and 8.3.5.3). This is to ensure that when the package has been placed on the spindle in the dye vessel and compressed, it is not so hard or dense that the dye liquor will be prevented from penetrating evenly during the actual dye process.
2 The wind angle used must be large; this is so that the wind angle, which decreases under compression on the package, becomes small enough to enable the package to unwind satisfactorily.
3 A stroke modification setting must be chosen that does not produce a package with hard edges. If the edges of the package on the machine are hard, they will become even harder when the package is compressed and will give rise to uneven dye penetration, hence giving an uneven speckled appearance to the dyed yarn at the package edges.
4 Cradle forces must be chosen such that no undue pressure is put upon the tube, since this may cause distortion of the tube during the winding process.

Also to be bore in mind when producing a dye pack on an automatic doffing machines is how it doffs. Dye packs may be difficult to doff due to two main factors:

1 A very low take-up tension (T_3) is necessary because of the need to produce a soft package.
2 The fact that the tube is designed to compress means conversely that it is far more likely to expand. If the tubes on the machine start to expand

so that they approach the maximum opening length of the cradle, then problems with doffing may occur.

4.4.1.1 Density on compressible tubes

The density of a compressible dye pack must be low, as mentioned above, so that the density of the package after compression is suitable for the even penetration of the dye liquor. Also it has to be remembered that the dye process itself, normally carried out under pressure at 130°C, will also affect the package, since the yarn crimp contraction reduces dramatically during this process, leading to an increase in apparent density. The density to which the package should be wound is heavily dependent on the customer's dye equipment. Some examples of major dye machine manufacturers are *Obem, Krantz, Bellini* and *Longclose*; detail differences exist between the machines produced by these manufacturers.

The *Bellini* and *Longclose* machines are very similar, being what are known as vertical machines, i.e. the packages are stacked vertically in columns one on top of the other. The *Obem* manufactured machine is a horizontal machine, i.e. the packages are laid into the machine in horizontal columns each one of the columns being placed in separate torpedo-shaped tubes. The dye packages designed for use in each type of equipment should be optimised and will be different. However, this is not normally the case in a production environment because it leads to an overcomplexity of product range. As such an all-purpose package must be striven for, one that suits all types of dye machines.

Typical values for the package density on compressible-tube polyester products lie in the range 0.32–0.40 gm/cm^3 (320–400 gm/dl). Occasionally it is necessary to produce packages on a compressible tube to a density outside this range. In this case it would usually be to a lower density. Nylon yarns in particular are wound usually to a significantly lower density (0.13–0.18 gm/cm^3) due to their high shrinkage potential.

As will be appreciated, density is a relative measurement calculated from the overall volume of yarn on the package and its net weight (see Section 8.3.5.3). To ensure the maximum capability of the machine to maintain all packages within a specified density range it is essential that such factors as cradle forces, traverse stroke length and taper angle of the package are set with great care. Every effort should be made to ensure that the winding tension from position to position is as uniform as possible. This applies equally to the physical properties of the yarn, which may affect the way in which the yarn is taken up on to the package. Properties such as crimp level and level of intermingling, where applicable, must also be held within given tolerances.

Note: The lower the density the more difficult it is to build a satisfactory package with respect to overthrows.

4.4.1.2 Package build on compressible tubes

With rare exceptions all compressible-tube products are built with a taper angle of 85–90°, i.e. with a package edge as straight as possible. Why is this important?

When the packages are stacked on top of each other on the dye spindle, they must join together evenly with no gaps or air spaces between them when they are compressed. If there were gaps present it would be possible for the dye liquor to take the easy route when being pumped around the dye vessel system and pass through these gaps in preference to making its way through the coils of yarn on the packages. This fault condition is known as 'blow by' and when present leads to very uneven, streaky dye uptake and blotchy looking packages of yarn.

By making the packages with a straight edge, i.e. taper set at 90°, the top face of the bottom package mates securely with the bottom face of the package above it and so on up the whole length of the spindle. This secure mating of the packages in sequence up the height of the spindle is known as making a good yarn-to-yarn seal.

Normally the total height of the spindle would be equal to between six and eight packages of yarn but it may be more or less than these figures. This is of course dependent upon the type of equipment that the dyer has available, the type of pumping sequence and dye cycle being employed. These have to be chosen carefully by the dyer to ensure good shade uniformity from batch to batch and also to give the most economic use of the equipment.

Owing to the necessity of making a soft edge on the package, dye packs, particularly if interlaced, show a marked tendency towards overthrows. Though the use of high wind angles and low take-up tension help in overcoming this tendency it is always present and can occasionally cause problems.

4.4.2 Rigid (non-compressible) dye packs

Much of what has been written above regarding compressible-tube products can also be applied to a rigid-tube dye pack. However, there are some exceptions that must be noted:

1 It is usual for a rigid dye pack to be produced to a higher package density than a compressible-tube product, usually in the range 0.37–

0.50 g/cm^3 (370–500 g/dl), which after dying closely equates to that of a dyed compressible-tube product. Again these values are chosen to suit the dyers' equipment and process.

2 It is much more common for rigid-tube products to be built with a taper angle of 75 or 80°. This again is to suit both the dyers' process and the unwinding capability of the package. In cases where the packages are produced with a taper, the dyer will use a spacer between each package on the dye spindle to support the packages during the dye process.

3 Owing to the fact that the tube is rigid and cannot be compressed it is possible to build the package in a manner that is much closer to that of a cardboard-tube product. This means winding somewhat harder edges to the package and a wider range of wind angles can be used without giving resulting problems in dyeing or unwinding.

4.5 Machine types and variations

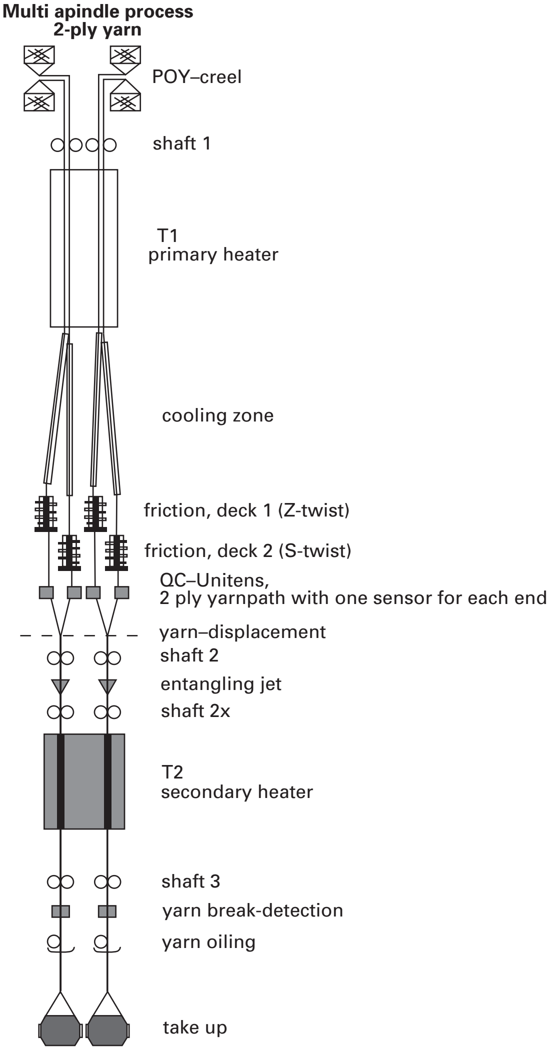
4.5.1 Introduction

At this point it is worth discussing the variety of texturing machines available, though some of these will be discussed in more detail later. Already, mention has been made of contact heater or conventional machines and non-contact or short heater machines. Within these two broad classifications many other variants exist. A standard texturing machine usually consists of individual positions with single thread-lines. This means that if two single ends are combined together to produce a two-ply yarn, effectively half the production capability of the machine is lost, since only half of the available take-up positions can be used. To overcome this, many machine manufacturers produce what are known as double-density machines.

4.5.2 Double-density machine

The double-density machine, shown in Fig. 4.19, is supplied with a doubling of components used to texture the yarn so that all take-up positions on the machine can be used in the manufacture of two-ply products. Thus, the machine is equipped with two creels, two string-up devices, two yarn cutters, two heater tracks, two cooling plates and two friction units (or a single specially manufactured double unit) per take-up position and, where applicable, two on-line sensors and two intermingling jets.

Although these machine types are expensive with regard to both the initial capital cost and the extra amount of floor space required, they can prove to be a sound investment, due to the increased productivity and



4.19 Double density machine. Courtesy of Barmag-Saurer Group.

reduced variable costs per unit weight of yarn produced. In addition to being ideally suited to maximise the production efficiency of the machines when running a two-fold (or two-ply) yarn, this arrangement of shafts opens up other possibilities such as the production of combination yarns. These will be discussed further in Chapter 5.

4.5.3 Multiple-input shaft machine

So-called multiple input shaft machines usually have one, or possibly two, additional feed shafts fitted in the input zone of the machine, though the additional shafts may also be situated at the centre or bottom of the machine dependent upon the type of process (see Section 5.6).

With this arrangement of shafts, each having individual speed control, the possibilities for the manufacture of yarns with properties far removed from those of standard, dyeable, textured yarn become greater than with a conventional machine. There is not only the opportunity to run fibres of different chemical composition side-by-side but also to generate tone-on-tone effects using the same fibre type or to explore the manufacture of core-and-effect-type products. Placing a hotpin or other heating element between the additional feed shafts can further expand the range of possibilities. The addition of these heating elements presents an opportunity to modify the molecular structure of the fibre before it enters the texturing zone. Also it is possible to place an intermingling jet or some other component between these shafts.

Alternative machine arrangements are now finding increased usage for manufacturing yarns which have modified characteristics regarding dye uptake, and both optical and physical effects in fabric. These products are sometimes referred to as novelty or speciality yarn products. Commercially the products have added value, for which a price premium is demanded. These yarn types will be discussed briefly in Chapter 5.

4.6 Plant environment and operating procedures

4.6.1 Plant air conditioning

Ideally both the texturing area and POY storage area should be air conditioned so that temperatures and humidity remain constant all year round. The temperature, and in particular the humidity, has a discernible effect on the efficiency of the texturing process with regard to yarn breaks. This is especially true in the case of nylon yarns, which are extremely sensitive to changes in humidity. Though opinions vary as to exactly what these values should be, those shown below would be typical for the temperature and humidity that the texturing area should be maintained at.

	Temperature (°C)	% Relative humidity
Polyester	21.5 ± 1	52 ± 2
Nylon	22.5 ± 1	58 ± 2

4.6.2 Lighting

Lighting should be maintained to high standards with sufficient light available to allow all operations to be carried out efficiently without the added strain of working in poor lighting. There is no substitute for natural daylight. However, in many instances this is not possible and all areas of the manufacturing plant in which operators are working should be well equipped with overhead lighting, both in the general area and particularly in the machine operating aisles. Operator functions such as splicing POY transfer tails and threading a texturing machine are more easily and successfully accomplished if the lighting is good.

4.6.3 Machine operation and maintenance

4.6.3.1 Machine operation

The operation of a texturing machine requires several different groups of human actions to produce a package of textured yarn:

1 the POY feeder yarn has to be loaded into the creel;
2 the transfer tails of the POY have to be spliced;
3 the yarn has to be threaded manually through the machine;
4 the full-sized textured yarn package has to be doffed.

The performance of these various tasks has to be considered in order to maintain an economic and cost-effective process. The question of whether it is preferred to have specialists for each function or to have each individual operator trained for multitasking needs to be addressed. The solution to this question will obviously differ from location to location dependent on the management philosophy of the operation.

However, no matter which scheme of operation is chosen, there should be a standardised procedure for each of these separate tasks. By having standardised procedures, which are regularly audited to ensure they are being observed, it is possible to maintain consistency from person to person and thus reduce the incidence of operator faults.

4.6.3.2 Machine maintenance

Like all machines, texturing machines will break down and require repair. Also as a matter of necessity they require a certain amount of routine maintenance to keep them in prime order. Again, the manner in which maintenance is planned for the texturing machine will vary from location to location. Dependent on the size of the operation, maintenance may be on an *ad hoc* (as needs) basis or a more formal structured approach may be applied.

It is usually the case that a machine is taken out of service at regular intervals to be cleaned and to receive routine maintenance to ensure maximum efficiency. The exact interval during which a machine is run between these cleaning and servicing procedures will depend not only upon the type of machine but also upon the nature of the product and process. It may be prudent to schedule a thorough maintenance program on the machines for replacement of wear items at longer intervals of possibly one to two years, again dependent on the philosophy of the operation.

As with any routine procedure, it is sensible to have clear standardised methods that are always followed. This not only applies to routine cleaning and servicing of the machine but to all maintenance undertakings ranging from the simple replacement of a fuse to a complete overhaul of the machine. In addition to having standardised methods for carrying out maintenance programs, accurate records should be kept of what work is carried out, the causes of any unplanned machine stops and of high usage of any particular spare parts. By maintaining such records, it is possible to isolate the causes of these stoppages and, armed with this information, to go back to the machine manufacturer or component supplier in order to seek redress or make improvements.

4.7 Safety

As with all machinery that employs high-speed rotating parts the operator working the machine must be made aware of the associated dangers. Unfortunately, owing to the nature of the process it is not always possible to shield these rotating parts adequately and thus ensure freedom from hazards. For this reason high standards of awareness of these dangers must be communicated to anyone working with these machines. Long hair should be safely secured under a hat, rings and other jewellery should be removed and loose clothing, particularly ties, should be avoided.

Many textile processes also involve the use of high temperatures. Here also awareness of the hazards involved should be clearly communicated to everyone involved and appropriate procedures adopted for the maintenance of a safe working environment.

Eye protection should be available for use when working on machines. This is particularly necessary when cleaning machines owing to the possibility of yarn fly and snow deposits being swept into the eyes. Safety shoes are also advisable.

Textile machinery has one other hazard present. It is a source of high-volume, high-frequency noise, especially if equipped with intermingling jets. For this reason ear protection should be mandatory in all textile plants.

Any motorised mobile equipment used should be fitted with both audible and visual warning devices. They should be routinely serviced to ensure maximum safety of the operators in the area.

Safety and the maintenance of an efficient and viable manufacturing plant should be treated as being equally important. Regular safety inspections of all aspects of the plant environment should be actively pursued and accurate records should be kept of any accident or incident. This is particularly relevant in case any litigation should arise.

Should any member of the workforce be found to be infringing safety procedures, no matter at what level, this should be treated as a serious matter and where necessary disciplinary action should be taken.

4.8 Product integrity

Good housekeeping and the maintenance of the manufacturing environment in a clean and well-ordered condition are a necessary part of any textile operation. Not only does it make a more pleasant working environment but also it greatly aids in ensuring that the yarn will reach the consumer in good condition and reduces the number of packages downgraded to a lower quality because of dirt or damage.

All items associated with the handling and transport of the textured yarn should be maintained to a high standard of cleanliness and kept in good repair. This is especially true of any mobile equipment that may be employed. There is no more disheartening sight than packages of yarn, which may have taken many hours to produce, being deposited upon the floor in total disarray, caused by a damaged wheel on a yarn truck. This same philosophy also extends to all kinds of yarn packaging employed (this will be expanded upon further in Chapter 9).

5

False-twist textured yarns

5.1 Introduction

In Chapter 4, the various elements of the machine were considered along with how they influence the final properties of the textured yarn. Here the types of yarn and how their form can be modified on the machine will be explored. Again the work described below will be based upon the production of polyester by the false-twist route but the same general principles can be equally applied to polyamide (nylon) and polyolefin (polypropylene) yarns. Where specific exceptions occur, these will be highlighted. The questions that must be asked are:

1 how is a yarn defined?
2 how are the process conditions on the texturing machine adjusted to make the yarn conform to this definition?

5.2 Definition of yarn type

Some, or all, of the following classifications can define a yarn produced by the false-twist route.

1 **Chemical nature of the yarn** – polyester, sometimes abbreviated to PES or PET, polypropylene abbreviated to PP and nylon (polyamide) abbreviated to PA6 or PA6.6. These are the two most common nylon yarns in textile applications.
2 **Nominal denier and filament number** – i.e. 167/32 or 167 dtex (150 denier**)** f32. Alternative nomenclatures are used, e.g. putting the number of filaments first and then the nominal textured denier, or quoting the POY decitex, then the filament number and then the nominal textured denier are both common, i.e. 290/32/167.
3 **Number of yarns plied together** – (see Section 5.3.2), i.e. 1/167/32 or 2/167/32 or 3/167/32, etc. The first digit represents the total number of plied ends.

4 **Lustre of the product** – i.e. bright, semi-matt, matt (or dull). Thus 1/167/32 semi-matt.
5 **Cross-section of the filament** – i.e. round, trilobal, pentalobal, hexalobal and so forth. Thus 1/167/32 semi-matt, round cross-section.
6 **Degree of stretch in the textured yarn** – i.e. high-elastic (single-heater) or set (double-heater) yarn. Thus 1/167/32 semi-matt, round cross-section set.
7 **Direction in which the twist is inserted in the yarn** – i.e. S or Z and for multi-ply yarns SS, SZ, ZZ, etc. Thus 1/167/32 semi-matt round cross-section, set Z twist.

This final description qualifies the yarn as belonging to a specific type. For most products, but especially polyester, one further classification is possible.

8 Has the polymer itself been modified such that the yarn is now, for example, dyeable with cationic dyestuffs or has flame-retardant properties, etc?

Within these classifications some cannot be altered by the processing conditions on the texturing machine. These are the yarn parameters, which are fixed during either the polymerisation or extrusion phases of the process; these are the filament number, the filament cross-section, the lustre and the dye affinity of the yarn. To some extent the texturing process can enhance or reduce the lustre characteristics of the yarn (see Section 5.3).

Leaving behind the yarn parameters that cannot be altered by the texturing process, those that can be determined by the conditions on the texturing machine are examined below and in Section 5.3 in greater detail. These are:

1 yarn denier by use of draw ratio and effect on tensile properties;
2 production of combined or plied yarns by use of air-jets during texturing;
3 intermingling jets;
4 use of an air-jet to produce torque-free yarn;
5 yarn skein shrinkage;
6 changes in bulk;
7 lustre modification.

Within each of the broad categories there are many variations which can be employed to fit the properties of the yarn exactly to those required for it to perform satisfactorily in terms of process efficiency and in fabric.

5.3 Modification of yarn properties

5.3.1 Yarn denier by use of draw ratio and effect on tensile properties

The denier of the finished yarn can be directly related to the spun denier of the POY and the draw ratio employed on the texturing machine. It should also be noted that the tension at which the yarn is wound on the textured yarn package also has a discernible effect on the apparent denier of the yarn, as does the degree of interlace present in the yarn (due to yarn compaction). An approximation of the finished denier can be found by:

$$\text{approx. finished denier} = \frac{\text{POY denier}}{\text{draw ratio}} \times \%\ \text{take-up overfeed (increase)} \qquad [5.1]$$

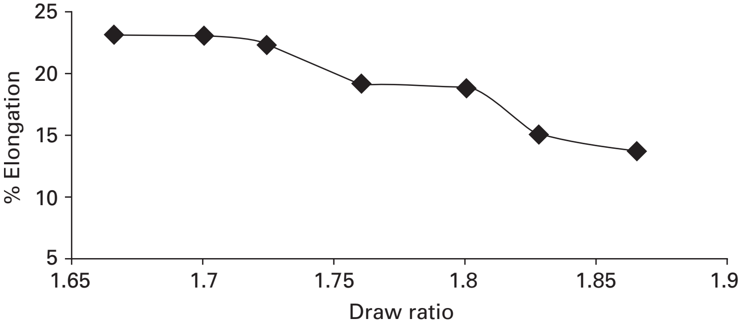
where take-up overfeed is the percentage difference in speed between the centre shaft of the machine and the speed of the shaft driving the wound package.

Obviously the denier of finished yarn can be increased simply by combining two or more running ends of textured yarn together and by joining the separate ends using some form of intermingling. This is discussed separately in Section 5.3.2. Intermingling alone has a discernible effect on denier. The increase is small and is proportionate to the number of intermingled points inserted due to yarn compaction (see also Section 5.3.3.3).

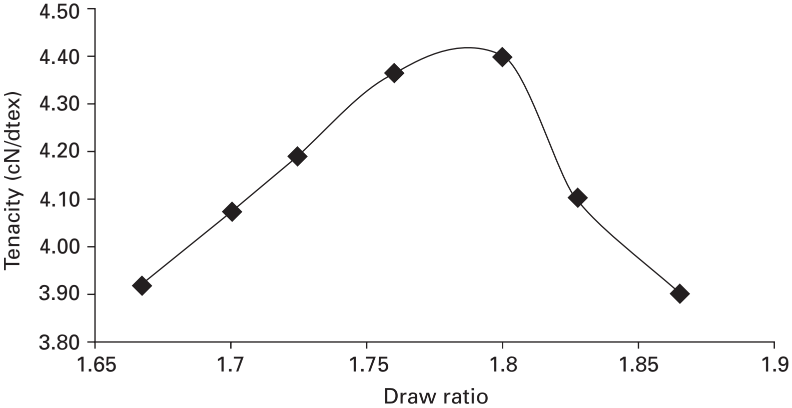
The denier can be altered by changes in draw ratio, but the degree of change that can be applied is governed both by the stability of the process on the texturing machine and other considerations. These are yarn tenacity, elongation, dyeability and textured broken filaments, all of which are influenced by the draw ratio. Table 5.1 illustrates some of the changes observed in both the yarn and process conditions when changing draw ratio.

The graphical representation of some of the data from Table 5.1, shown in Figs 5.1–5.3, gives a clear indication of the effect of draw ratio on the physical properties of the textured yarn. Of particular interest is the graph displaying the measured yarn tenacity plotted against the draw ratio. This clearly shows the effect of extending the yarn above the optimum value to the point where physical damage is incurred, thereby provoking a marked deterioration in its tensile strength. It is shown by a rapid fall off in breaking strength.

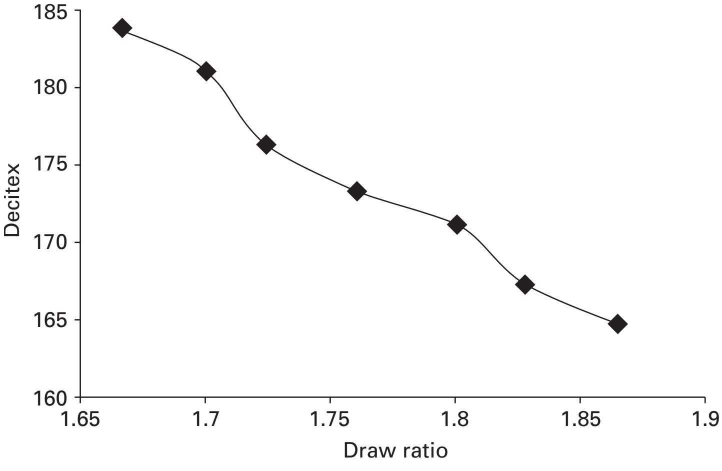
As tenacity is a relative value, calculated from the breaking load and the measured denier, increasing the draw ratio reduces the denier and



5.1 Elongation vs draw ratio. Courtesy of UNIFI Textured Yarns Ltd.



5.2 Tenacity vs draw ratio. Courtesy of UNIFI Textured Yarns Ltd.



5.3 Decitex vs draw ratio. Courtesy of UNIFI Textured Yarns Ltd.

Table 5.1 Effect of changes in draw ratio on process conditions and yarn properties. Courtesy of UNIFI Textured Yarns Ltd

Draw ratio	1.667	1.700	1.724	1.760	1.800	1.828	1.865
Pre-draw tension (T_0) (g)	34.8	39.9	43.5	46.20	57.6	58.3	64.4
Draw zone tension (T_1) (g)	52.1	57	62.7	65.50	77.4	79.5	89.9
Below spindle tension (T_2) (g)	59.8	66.1	68	73.60	78.9	83.3	86.1
Tension ratio (T_2/T_1)	1.15	1.16	1.08	1.12	1.02	1.05	0.96
Winding tension (T_3) (g)	16.5	26.0	22.9	30.00	26.4	26.0	33.2
Breaking load (cN)	720.0	738.0	739.0	757.0	753.0	687.0	643.3
Elongation (%)	23	22.9	22.4	19.2	18.8	15.2	13.8
Denier	183.7	181.1	176.4	173.4	171.2	167.4	164.8
Tenacity (cN/dtex)	3.92	4.08	4.19	4.37	4.40	4.10	3.90
Skein/shrinkage (%)	12.5	11.5	10.6	13.7	8.3	8.5	7.6
Residual torque	3.8	3.3	3.3	2.9	3.4	3.6	2.4

Machine constants
Yarn type (292 Spun dtex) 167/34 nominal round cross-section.
Throughput speed 700 m/min
2 m contact primary heater

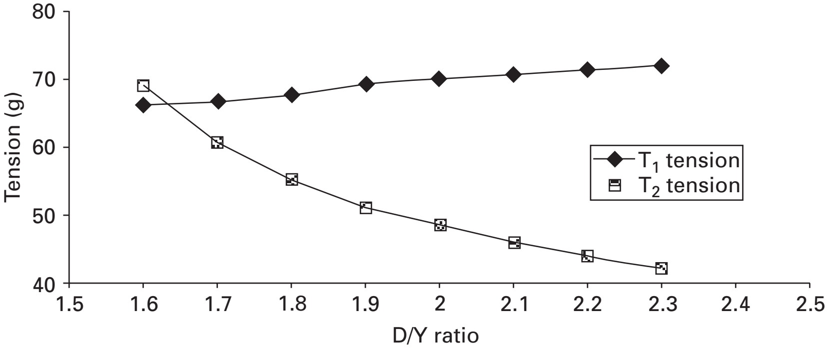
increases the degree of molecular orientation, thereby developing strength in the yarn until the point is reached where it becomes over-extended.

The data above also shows the effect of increasing draw ratio on the skein shrinkage or crimp developed in the yarn. This is a phenomenon associated with the increase in molecular orientation. As the orientation increases, the capability of the polymer chains to buckle and deform under the influence of heat is reduced, thereby restricting the degree of shrinkage that can be developed.

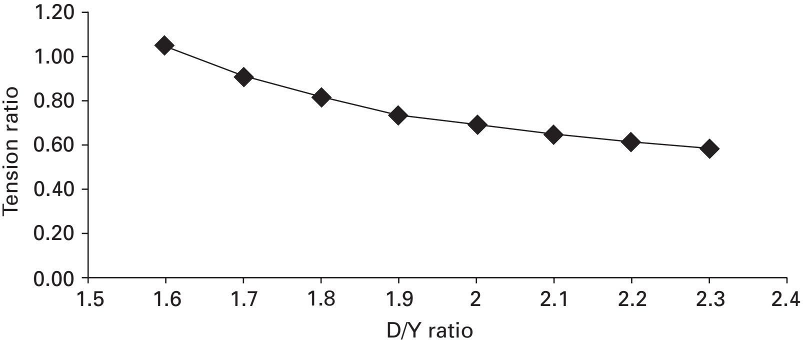
It should also be noted that the D/Y ratio has a discernible effect on the percentage elongation of the textured yarn, and a minor effect on the resultant denier. Increasing the D/Y ratio means that the discs are rotating faster and more twist is inserted into the yarn. This changes the elongation due to the increased twist in the yarn, which is trapped between the input shaft of the machine and the friction unit, and has the effect of shortening the yarn and effectively increasing the draw ratio or stretch (see Table 5.2 and Figs 5.4–5.6). On fine denier hosiery yarns in particular, increases in D/Y ratio can be used as an effective measure to prevent surging due to instability in the thread-path between the input shaft and the twist-insertion device.

Table 5.2 Effect of D/Y ratio on yarn parameters. Courtesy of UNIFI Textured Yarns Ltd

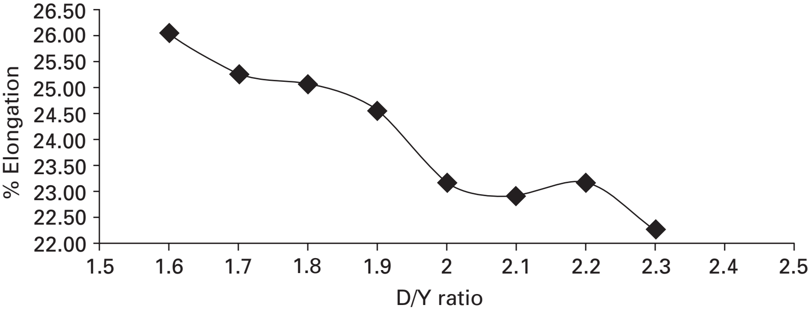
D/Y ratio	T_1 tension	T_2 tension	Tension ratio	Elongation (%)	Bk load (cN)	Denier	Tenacity (cN/dtex)
1.6	66.2	69	1.04	26	759.5	177.6	4.28
1.7	66.6	60.7	0.91	25.25	748.7	177.4	4.22
1.8	67.7	55.4	0.82	25.05	735.3	177.2	4.15
1.9	69.4	51.2	0.74	24.54	737.7	177.3	4.16
2	70.2	48.7	0.69	23.16	734.6	177.3	4.14
2.1	70.8	46.1	0.65	22.91	740.2	176.8	4.19
2.2	71.5	44.1	0.62	23.16	743	176.8	4.20
2.3	72.2	42.3	0.59	22.29	744.6	176.2	4.23



5.4 D/Y ratio vs thread-line tension. Courtesy of UNIFI Textured Yarns Ltd.



5.5 D/Y ratio vs tension ratio. Courtesy of UNIFI Textured Yarns Ltd.



5.6 D/Y ratio vs % elongation. Courtesy of UNIFI Textured Yarns Ltd.

5.3.2 Production of combined or plied yarns by use of air-jets during texturing

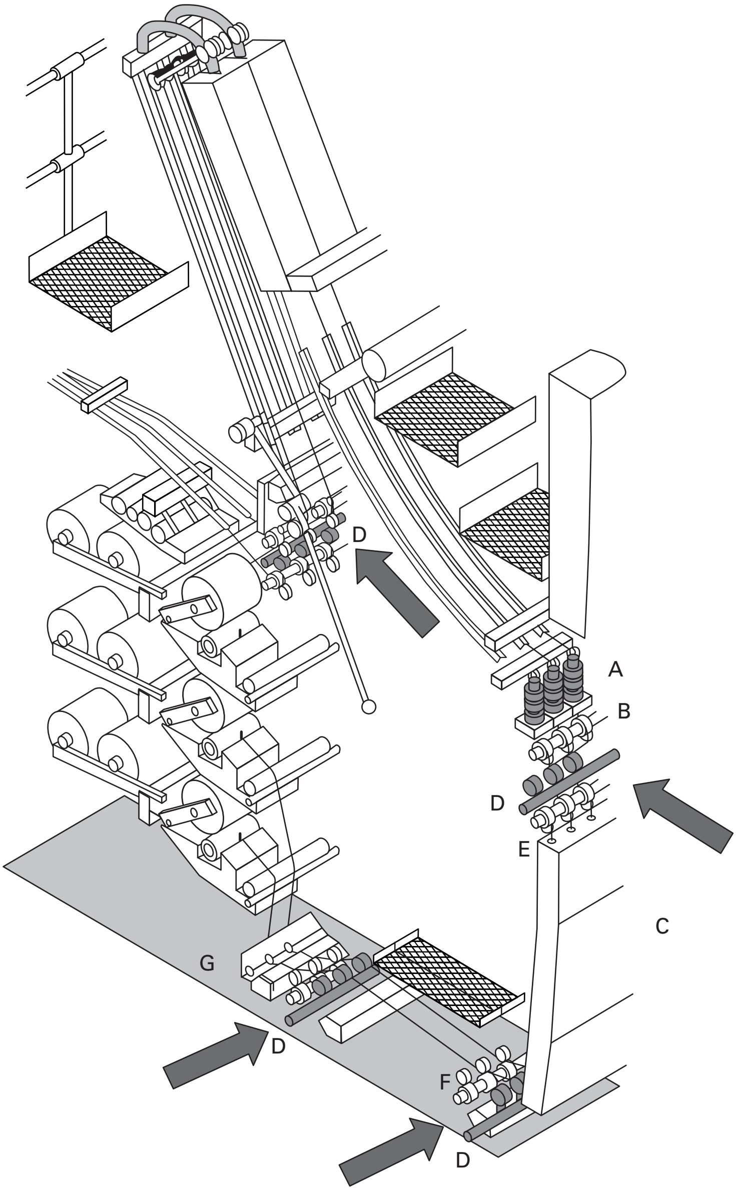
For many end uses the denier available from a single-end or -ply yarn (the older word fold is sometimes used to mean ply) is not sufficient for the fabric construction. In these cases it would be usual to combine or ply two or more ends together on the texturing machine. Such yarns find use in automotive, woven apparel, narrow fabric, upholstery and industrial fabrics.

These yarns usually come in combinations of two-, three- and four-ply, and it is usual for the twist inserted in the yarn to be balanced as far as possible. Indeed the production of two-ply yarns with balanced twist is one route towards the production of a torque-free yarn.

Ply	Twist insertion
2	S + Z
3	S + Z + S or Z + S + Z
4	S + Z + S + Z

There are of course exceptions to these combinations. For example when producing a yarn destined for further processing on a two-for-one twisting machine, all ends that are combined or plied together would be of the same twist. There are other fabric constructions for which yarns of the same twist direction may be combined.

Dependent on the design of the machine the separate ends of yarn may be combined either above or below the second heater of the machine (Fig. 5.7). Intermingling (or interlacing or entangling) jets are used to combine and lock together the yarn ends. The jet may be located before or after the second heater (see Section 5.3.2.1). For some end uses the air-jet may be



5.7 Alternative intermingling jet positions. A) Friction unit. B) Centre shaft of machine. C) Secondary heater. D) Intermingling jet. E) Second intermediate shaft (optional). F) Drive shaft to control second heater overfeed. G) Oil application roll. Courtesy of Barmag-Saurer Group.

omitted. This would be the case for yarns which will go for subsequent twisting operations, where the presence of the intermingled points inserted by the air-jet would be detrimental to the finished fabric appearance. The intermingling stage is also omitted if the yarn is destined for further processing by air-jet (see Chapter 7).

Note: The term 'intermingled yarn' is quoted in *Textile Terms and Definitions*, Tenth Edition, published by the Textile Institute. However, the process of intermingling a yarn by using an air-jet has assumed many different names over the years. They are commonly referred to as intermingled, mingled, interlaced, tangled or entangled yarns. Even the term 'twist substitute' has been used, since from the earliest stages of their development intermingled yarns were indeed used as substitutes for twisted yarns in woven goods. Similarly, the actual points in the yarn at which the filaments are intermingled together have assumed various names. They are commonly known as mingle points, knots, nodes, nips, tack points or simply entanglements.

5.3.2.1 Use of air-jets during the texturing process

Reasons for their use

The basic question that must be asked is why intermingle or interlace a yarn at all? Textured yarns are intermingled for four main reasons:

1 To hold the yarn bundle together in the case of two-, three-, or four-ply yarns. This enables them to be processed at higher efficiencies in weaving or knitting.
2 Single-ply yarn is intermingled, particularly in warp yarns for weaving, in order to hold the individual filaments together as a tight, cohesive bundle. This helps to prevent yarn damage as the yarn passes through the reeds on the loom. Previously these yarns would have been twisted, sized or both before warping.
3 Yarns can be lightly intermingled purely to help the yarn unwind from the package.
4 Lastly, a special type of jet can be used to produce a detorque yarn, i.e. a single-ply yarn with no residual torque.

Range of jets available

The range of intermingling jets commercially available is enormous. Many specialised component manufacturers offer a broad spectrum of intermingling jets within their product ranges, for example *Fibreguide*, *Heberlein*, *Temco*, *Slack*, *Parr* and others. Each one has its own unique geometry which is used in conjunction with various operating tensions and air pressures to impart the required characteristics to the yarn.

When choosing which type of intermingling jet will be used for a product, the following points must be considered:

1. What is the end use of the yarn? Woven, knitted, raschel, etc.
2. What type of fabric will be made from the yarn? Warp or weft faced, cut pile, etc.
3. Will the process be economically viable? Compressed air is very expensive!
4. What fibre type and what filament denier are employed? Generally polyamide is easier to intermingle than polyester due to its lower stiffness and the lower the filament denier the easier it is to intermingle the yarn.

5.3.3 Intermingling jets

5.3.3.1 How is intermingling defined?

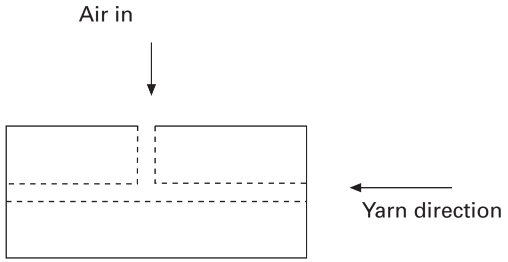
Commonly two criteria are used to define the type of intermingling present in a yarn. These are the number of knots per metre of yarn (kpm) and the strength (stability) of these knots (% retention). Sometimes the number of knots is termed ‘nip intensity’ or even ‘nip density’. As the name suggests, the knots per metre is purely a physical count of the numbers of interlace points inserted in a metre of textured yarn, though to measure them the tension at the point of measurement must also be defined.

The percentage retention is a measure of the strength of the inserted knots, i.e. their resistance to removal, assessed by counting knots before and after the application of a known load or extension to the yarn (see Section 8.3.5.2). This value gives an indication of the ability of the intermingling to survive subsequent yarn processing and to provide the required protection from damage.

Of equal importance when talking of intermingling is to consider the open length of yarn between the intermingled knots. Indeed some would argue that this is the most important criterion, since it is this open length and the consistency of the intermingling that can directly affect how a yarn will process during fabric construction.

5.3.3.2 Mechanics of intermingling

Much has been written about the mechanics of intermingling in various technical journals. It is not the intention here to explore the actual mechanism by which a yarn is intermingled in detail, rather to try to give a brief



5.8 Non-forwarding intermingling jet.

‘users’ guide’, by considering what is required in a yarn and then how this is achieved. However, a basic guide to the principles of intermingling and jet design is included.

The simplest jet comprises no more than a block of metal in which two holes, or channels, are drilled to meet at right angles (see Fig. 5.8). One channel runs the complete length of the block to transport the yarn and the second meets it at right angles for the air supply.

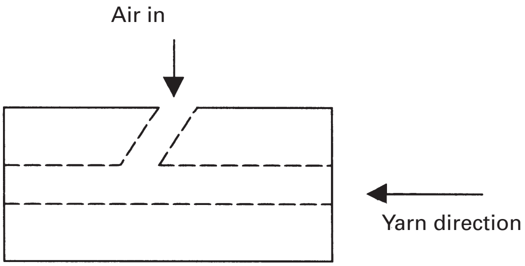
There are jets of this type still being produced but over the years there have been huge advances in the design of jets and many complex designs now exist with wide variations in the cross-sectional shape of both the yarn and air channels.

These changes have been aimed at increasing the efficiency of the jet both by increasing the frequency and strength of the knots and also by reducing the air consumption, so making the jets more cost-effective to operate.

Yarn channels are commonly available in circular, triangular, semicircular and rectangular cross-sections, though other cross-sections are available. The shape of the actual air orifice, where it enters the yarn channel, is usually of circular or elliptical cross-section though some jets have been manufactured with rectangular or trapezoidal air holes.

In a forwarding jet, as the name suggests, the air stream is angled in the direction of the yarn movement such that it imparts a forwarding action to the yarn. This means that this type of jet can operate at a much higher yarn overfeed through the jet than one where the air stream intersects the yarn path at right angles. In this case the tension on the yarn within the jet is reduced. The air inlet channel is usually set at an angle of 8–12° from the perpendicular, in the direction of yarn travel (see Fig. 5.9).

As with all aspects of texturing machines, the design of intermingling jets has become more specialised over the years. The very earliest designs were crude in both engineering design and manufacture. Now they are much more specialised with designs of both yarn and air channels being tailored towards specific processes and end uses. Though this has the advantage of allowing the yarn manufacturer to choose the optimum intermingling jet



5.9 Forwarding intermingling jet (air flow in the same direction as yarn path).

for the process, it has the converse effect of forcing the purchase of a wide range of jet sizes to meet all requirements. No longer is it possible to purchase a universal intermingling jet, one that can cover a wide range of products simply by modifying machine parameters such as yarn speed, yarn tension (overfeed through the jet) and jet pressure employed. This has become a luxury that is no longer available. The consequence of greater specialisation by intermingling jet manufacturers has been to force the yarn producer to spend more and more time in the search for the optimum process. As a result of this increased specialisation by the jet manufacturers, it has become increasingly important for the technologists to specify the production parameters carefully to enable a viable return on investment in both time and equipment to be made.

Some intermingling jets, particularly those designed for use on high-speed processes, are now offered as dual or 'tandem' jets which have two distinct and separate intermingling nozzles mounted upon a common body. A type also exists which has two air inlets into a single body.

Not only has the design of the yarn and air channels been advanced over the years but also the materials and methods of construction have been improved. From the early use of mild or hardened steel, jets are now available made from ceramic or tungsten carbide materials in which the shape of the air orifice, in the case of the latter, may have been formed by spark or wire erosion.

The earlier jets manufactured were of the closed type, i.e. the yarn had to be threaded through the jet before the thread-line could be started to run. It soon became apparent that jets of this type were impractical in a manufacturing environment. Consequently jets of the open type were developed. These jets differed by having a narrow slot cut into the yarn channel into which a running thread could be inserted. There was a small penalty to pay when using jets of this type in that their intermingling efficiency dropped slightly. However, this was tolerated due to the speed and ease with which the running thread could be put into production.

Jets are now available which offer the best of both worlds. The most common is that which can be opened for ease of threading but can then be closed to ensure optimum working efficiency. One example of this type is the *Heberlein SlideJet.* This jet, along with others of this type, also has the advantage that, when opened to allow threading, the air supply to the jet is automatically cut off so further aiding threading and avoiding the waste of compressed air.

5.3.3.3 Factors affecting level of intermingling

Obviously the level of intermingling present in a yarn is not only dependent on the type of jet but also on the process conditions, location of the jet on the machine and the operating pressure of the jet. The two main parameters by which intermingling level is monitored, i.e. knot count and knot retention (or strength), are both affected by these factors. General rules that can be applied to the level of intermingling in false-twist textured yarns are as follows:

1 Increasing the air pressure will increase the number of mingle points inserted into the yarn. This is true to a degree, dependent on which type of jet is being used. There is a point at which increasing the air pressure has no effect, since there is a limit to the rate at which intermingling can take place as well as a lack of sheer physical space to insert any more knots. Should the air pressure be increased further, the degree of intermingling may in fact reduce. This is because so much air is being forced through the jet that the air stream causes too much turbulence within the yarn chamber and instead of intermingling the filaments, it blows them apart.

2 Increasing the size of the air orifice in the jet increases the knot strength but reduces the overall number of knots inserted per metre. This holds true for jets made by every manufacturer and is due to the physical law that the strength comes from the length (as well as the tightness) of the knot. Longer knots mean that there is less in each metre of yarn.

An obvious disadvantage of having too large an air orifice is that the air consumption, at any given pressure, is increased, making the jets more expensive to operate. Also the increase in volume of air at high pressure can cause filament breaks with sensitive products such as cationic dyeable or microfilament yarns.

3 The overfeed of the yarn through the jet determines the yarn tension, which will also influence the number of intermingling knots inserted per metre of yarn. The yarn tension has an optimum value and can be high enough to have a negative effect by preventing the filaments from being

intermingled at all. Conversely, if the tension on the yarn is low enough within the jet, due to an overfeed which is too high, then the air stream can just disrupt the filaments rather than intermingling them.

4 Jet geometry in this instance is taken to mean the input and output angles of the yarn at the jet. This is most relevant when using forwarding jets of the type manufactured by *Heberlein* and *Fibreguide* among others. With this type of jet the air channel is angled so that the air stream imparts a forwarding action to the yarn (see Section 5.3.1).
The ideal input and output angles of the yarn to the jet will vary according to the design of the jet but angles in the region of 20–32° are not unusual with jets of this type. These angles before and after the jet help to stabilise the yarn path by holding the yarn against the side of the air inlet allowing the air stream to work at its maximum efficiency. Because of this, a great deal of thought has to be put into designing a suitable bracket for mounting the jet on the machine, whether the intermingling jet is situated above or below the second heater, so that the jet can work at its maximum efficiency. Some manufacturers supply their jets with input and output guides fixed to the body of the jet such that they are fixed in the optimum position. Even in this case, care must still be exercised in fitting them to the machine.

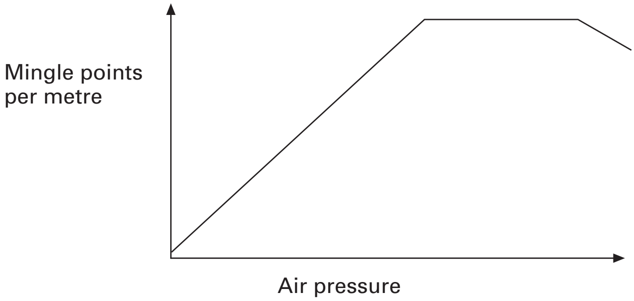
5 Intermingling jets mounted in the centre of the machine, i.e. above the second heater, give a product with a higher degree of retention, or knot strength, than if the same jet is at the bottom of the machine at the same air pressure and overfeed. The reason for this is that as the yarn shrinks in the second heater, the shrinkage effect occurs preferentially in the open yarn lengths between the intermingle points, due to better heat penetration in these areas. This has the effect of giving each individual knot more strength, as yarn shrinkage in the open lengths tends to shorten them locking the intermingling knot more securely into the yarn.

6 Obviously of paramount importance is the correct choice of jet. The overall intermingling characteristics required, the denier of the product and its production speed will all influence the choice of jet type for the process. These factors will help determine which jet is required with respect to air orifice size and yarn channel diameter.

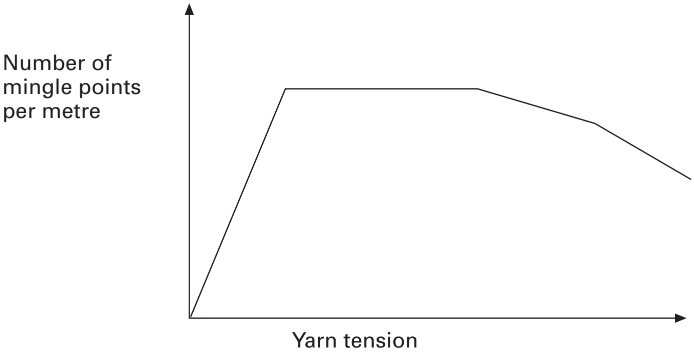
Figures 5.10–5.13 show the type of empirical relationships to be expected as the air pressure (bar) supplied to the intermingling jet and the yarn tension within the jet are increased.

5.3.3.4 Effect of intermingling on yarn characteristics

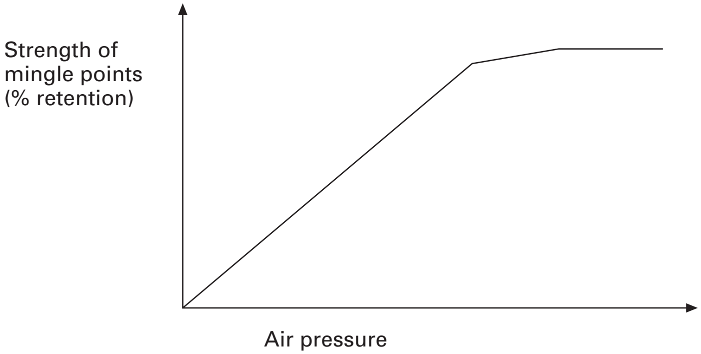
As the yarn is intermingled the action of inserting the mingle points in the yarn has a small but discernible effect upon the physical properties of the yarn. The effects on the different physical properties are shown below.



5.10 Mingle points per metre vs air pressure.



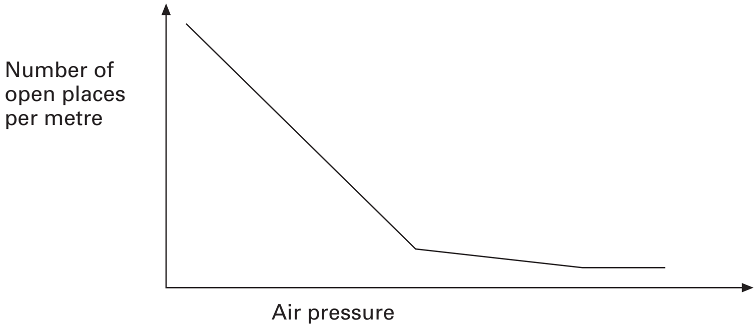
5.11 Mingle points per metre vs yarn tension.



5.12 Strength of mingle points vs air pressure.

Loss in tenacity

Tenacity is a relative value calculated from the breaking load of the yarn and its denier (see Sections 8.2.2.7 and 8.3.2.1). The denier of the yarn increases with the number of intermingling points per meter of yarn



5.13 Number of open places per metre vs air pressure.

inserted due to yarn compaction. This increase in denier has the effect of lowering the calculated values of yarn tenacity (see Figs 5.14 and 5.15).

Loss in percentage elongation at break

Loss in elongation can also be related to yarn compaction and, in particular, to the degree to which the individual filaments are bound to each other by the intermingling action. The tighter the degree of intermingling the more difficult it is for the individual filaments to move relative to each other when subjected to a stretching action (see Fig. 5.16).

Loss in yarn skein shrinkage

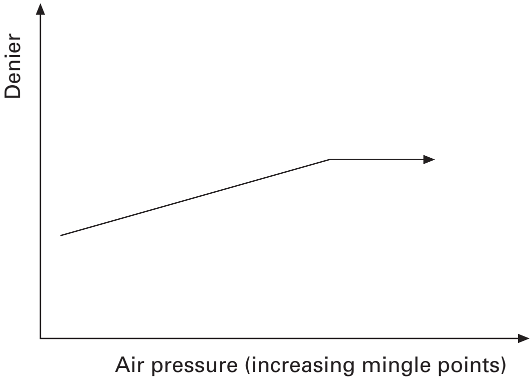
Here again yarn compaction is the cause of the resulting loss in yarn skein shrinkage. The intermingling point effectively acts to restrict the shrinkage or crimp in the yarn, the open lengths of yarn being much more susceptible to the effects of heat than the dense mass of the actual knot (see p. 173 and Fig. 5.17).

Coefficient of friction

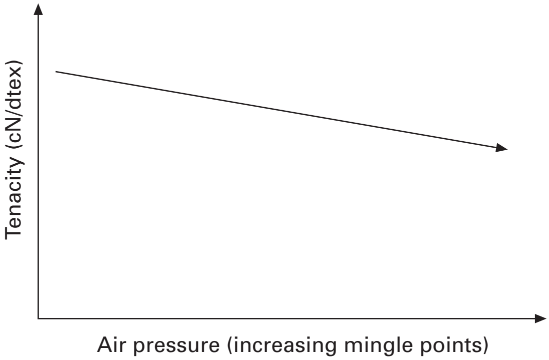
In addition there will be a small reduction in the overall diameter or thickness of the yarn bundle, with the overall cross-section of the filament bundle assuming a more circular form. This is also due to yarn compaction. Correspondingly, a small reduction in the coefficient of friction of the yarn is observed due this reduced surface area (see Fig. 5.18).

5.3.4 Use of an air-jet to produce torque-free yarn

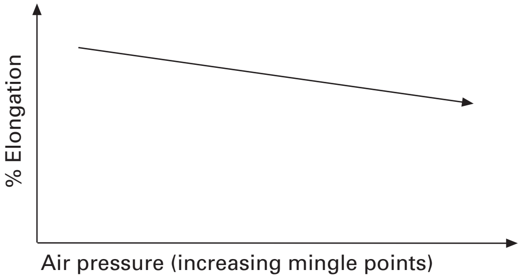
As mentioned above, one route towards the production of a torque-free yarn is the combination of two yarns of opposite twist giving a yarn with



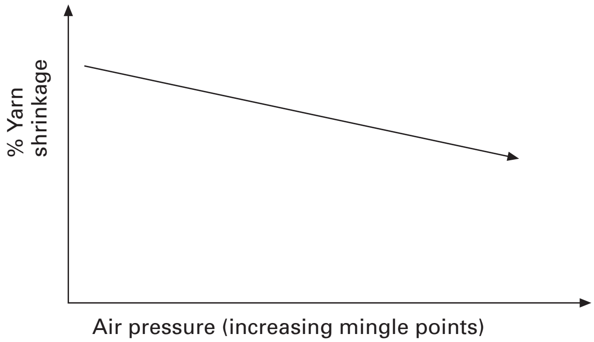
5.14 Denier (decitex) vs air pressure.



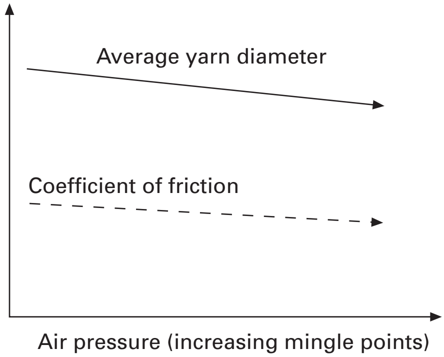
5.15 Tenacity vs air pressure.



5.16 Elongation vs air pressure.



5.17 Yarn shrinkage vs air pressure.

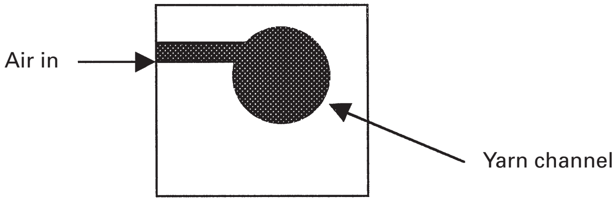


5.18 Yarn diameter and coefficient of friction vs air pressure.

no residual torque. This method has many drawbacks but the most obvious one is the loss of production on the texturing machines by effectively halving the number of packages per doff.

One method of overcoming this is to use an air-jet that inserts a twist into the textured yarn opposite to that imparted by the friction unit. This means that all available ends on the production machine can be employed to produce a single-end yarn. The type of jet used is most commonly referred to as a detorque jet. The twist in the yarn is generated by having the air channel offset from the centreline of the yarn channel, i.e. it no longer intersects at right angles but almost tangentially (see Fig. 5.19).

This offset creates a swirling action inside the jet chamber, which is opposite in direction to the twist previously inserted by the friction unit. It is usual for this type of jet to be reversible so that it can counteract both S and Z twist. These jets are always mounted below the secondary heater, the twist imparted by the jet being set into the yarn by the heat applied in the secondary heater. *Heberlein, Fibreguide* and others manufacture jets of this type.



5.19 Detorque jet.

These detorque jets do not impart any intermingling action on the yarn. This can be a disadvantage in some applications. Thus it is common to operate a detorque jet in tandem with an intermingling jet, usually with separate air supplies as detorque jets would normally operate at significantly lower air pressures than intermingling jets. In this case the detorque jet is usually placed between the exit from the second heater and the intermingling jet so that it can operate to maximum effect by having a more open yarn structure on which the air stream can impact.

5.3.5 Yarn skein shrinkage

5.3.5.1 Double- or single-heater yarns

As mentioned in the previous chapter, textured yarns can be supplied as either single-heater (stretch or high-elastic) yarns or they can be subsequently heat treated on the texturing machine to reduce the amount of shrinkage left in the yarn to produce double-heater (set) yarns. The degree of shrinkage in the textured yarn supplied to the customer is determined by the end use of the finished fabric. Typically woven apparel and knitted goods, both warp and weft knits, are made from double-heater yarns. However, where a degree of stretch is required in the fabric, single-heater yarns would be supplied. These may find uses in upholstery fabrics or in stretch garments. Stretch yarns may also be used in fabrics where a high degree of cover is required. One typical end use where stretch or high elastic yarns are employed is fine denier polyamide yarns for ladies' hose or socks.

5.3.5.2 Factors affecting yarn skein shrinkage

The two major factors that affect the final yarn shrinkage are the amount of heat applied to the yarn on the texturing machine in both the primary and secondary heaters and the overall denier. In addition the filament denier of the yarn itself is also a factor as this affects the ability of the applied heat to penetrate the yarn bundle uniformly.

Heat applied

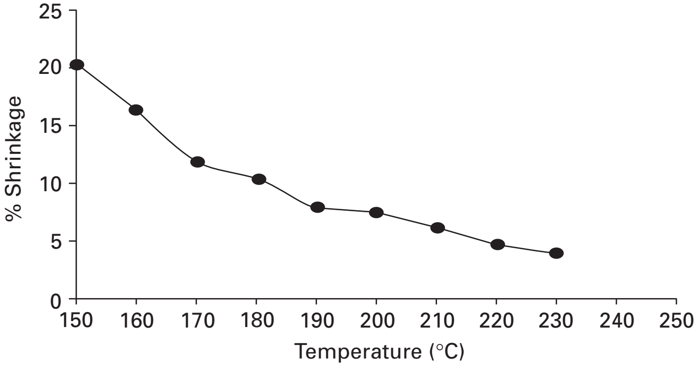
The heat applied by the primary heater to the yarn in the texturing zone has a significant effect on the shrinkage of the textured yarn and could, in isolation, be used to control the level of finished yarn shrinkage. However, it must be remembered that the heat applied in the first heater also has a significant effect on texturing performance with regard to yarn breaks, dye uptake and textured broken filaments. Often, dyed knitted sleeves are produced from yarn made at various first-heater temperatures, and are examined to ensure that the temperature is an optimum for uniform dye uptake. It is usual to find a small range of temperature where dye uptake is more uniform and choosing a process to operate within this heater temperature range results in a less critical situation given the small variations in heater (and hence yarn) temperature that occur in practice. Thus the first-heater temperature is normally set to allow for optimum manufacturing efficiency and uniform dye capability and the shrinkage obtained is accepted at this temperature or, if necessary, adjusted by changing the residence time on the heater, i.e. throughput speed.

The final yarn shrinkage is therefore adjusted to its required value by changes in the temperature of the secondary heater. This heater (see Section 4.3.4) would normally operate in a range of 150–240°C when of the vapour phase type or at higher temperatures if of the short, non-contact type. The residual skein shrinkage of the yarn reduces as the second-heater temperature increases. This is shown in Table 5.3 and Fig. 5.20 for the set of values: yarn type 1/167/34 (150 denier); round cross-section at 700 m/min; first-heater set-point 210°C.

Note that the results gained show not a linear but an exponential type of fall off in yarn shrinkage.

Table 5.3 Effect of changes in second-heater temperature on skein shrinkage value. Courtesy of UNIFI Textured Yarns Ltd

Second heater temperature (°C)	% Skein shrinkage
Ambient (single heater)	34.7
150	20.3
160	16.3
170	11.9
180	10.4
190	7.9
200	7.5
210	6.2
220	4.8
230	4.0



5.20 Yarn shrinkage vs second-heater temperature. Courtesy of UNIFI Textured Yarns Ltd.

Table 5.4 Effect of second-heater overfeed on skein shrinkage. Courtesy of UNIFI Textured Yarns Ltd

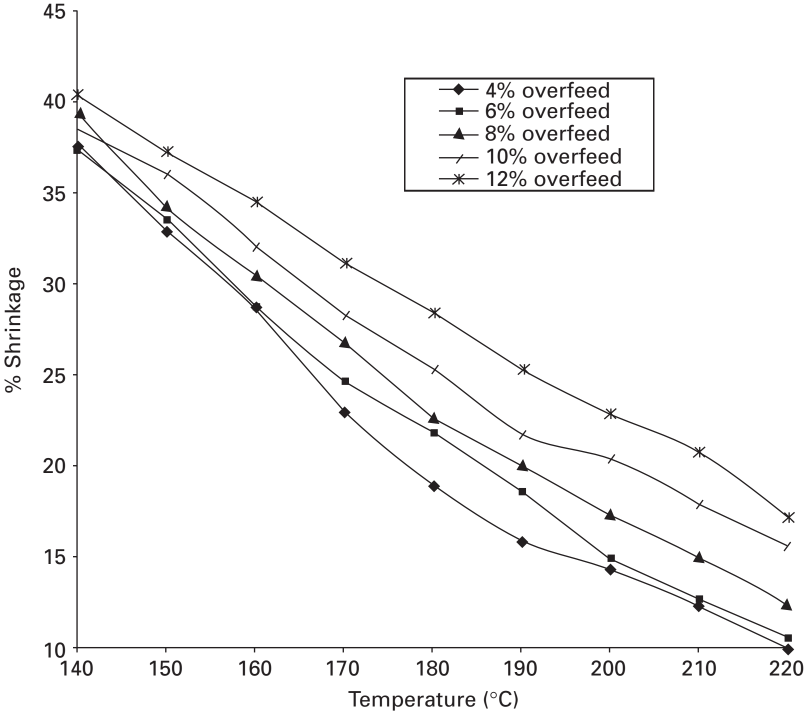
	Second heater temperature (°C)								
% Skein shrinkage	140	150	160	170	180	190	200	210	220
4% overfeed	37.4	32.8	28.6	22.9	18.9	15.9	14.3	12.3	10.0
6% overfeed	37.2	33.4	28.7	24.6	21.8	18.5	15.0	12.7	10.6
8% overfeed	39.3	34.1	30.4	26.7	22.6	20.0	17.3	15.0	12.4
10% overfeed	38.4	35.9	32.0	28.3	25.3	21.7	20.4	17.9	15.6
12% overfeed	40.3	37.1	34.4	31.1	28.4	25.3	22.8	20.7	17.2

Yarn tension through secondary heater

It is not only the heat which affects the degree of measured shrinkage in the finished yarn; the tension at which the heat is applied also has a discernible effect. The tension on the yarn through the second heater is governed by the speed of the drive shaft below the heater relative to that of the shaft immediately above the heater. This relationship is commonly known as the second heater overfeed. The effect of changes in overfeed is illustrated in Table 5.4 and Fig. 5.21 for the set of values shown below: 167/34 (150 denier) polyester yarn produced at 800 m/min.

Secondary heater surface

When considering the effect of the second heater a third variable exists which only applies to those heaters of the enclosed-tube type. This is

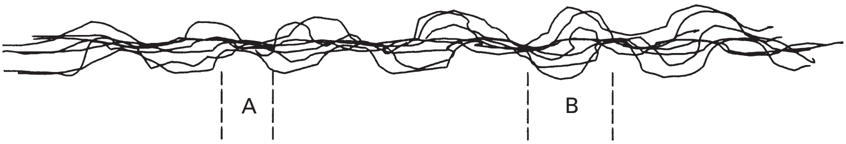


5.21 Skein shrinkage vs second-heater percent overfeed. Courtesy of UNIFI Textured Yarns Ltd.

the internal surface of the second-heater tube. It is possible to purchase machines in which the second-heater tube has three alternative surfaces.

1 **Straight walled** – i.e. having the same internal diameter for the whole of its length.
2 **Pinched** – i.e. the tube has its internal diameter changed at regular intervals along its length by having 'pinch points' in the wall of the tube which reduce its internal diameter at the point at which the pinch is inserted.
3 **Hybrid** – i.e. the tube is constructed such that one half is a straight walled design and the other half is of a pinched type.

Effectively what the pinch point does is to reduce the amount of surface of the tube available for heat transfer into the yarn, thus increasing the residual yarn shrinkage for any given combination of temperature and overfeed. This is particularly apparent in the *Barmag AFK* machine where the second heater is curved, which gives a positive contact between the yarn and the wall of the second-heater tube.



A=Mingle point
B=Open area, more prone to effect of heat on yarn shrinkage

5.22 Mingle yarn structure.

Effect of intermingling

As mentioned previously (see Section 5.3.3.3) the degree of intermingling present in the yarn has a discernible effect on the final, measured yarn shrinkage. As the number of entanglement points per metre increases, so the measured shrinkage of the yarn decreases. The intermingling knot itself binds the individual filaments together so effectively that the ability of the filaments to shrink under the influence of heat is greatly restricted (see Fig. 5.22). The open lengths between the intermingled points are the regions in the yarn where the degree of shrinkage is most apparent.

5.3.5.3 Effect of filament denier

For any given yarn the filament denier decreases as the number of filaments present in the POY increases. This, in turn, leads to a more compacted, denser filament bundle as the yarn passes through the primary heater due to the high level of twist imparted to the yarn. This has two consequences:

1. It is difficult to obtain uniform heat penetration through the yarn bundle, since the filaments on the inside receive less heat than those on the outside.
2. This in turn leads to a decrease in end-to-end uniformity of shrinkage around the machine and possibly to high dye-reject levels.

For these reasons yarns with a low filament denier are usually run at low machine speeds allowing greater residence time on the primary heater and therefore more uniform heat penetration.

5.3.6 Changes in bulk

Inserting more twist into the yarn during its residence time on the primary heater can increase the bulk in the textured yarn. This is commonly accomplished by increasing the number of discs used on the friction unit or by increasing the D/Y ratio, i.e. the rotational speed of the discs. This method works best with fine denier yarns, especially those polyamide yarns employed in the manufacture of ladies' hose. When using this method of generating extra bulk in the yarn to produce improved cover in the fabric, the additional twist inserted is limited by constraints of process stability and the generation of tight spots, i.e. short lengths of yarn that exhibit real twist.

5.3.7 Lustre modification

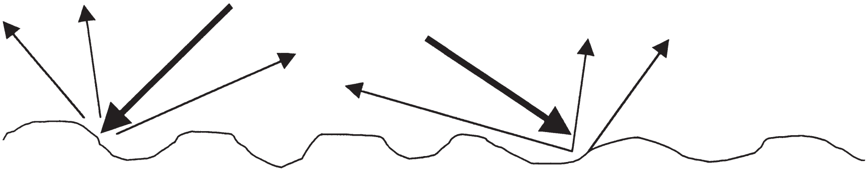
The lustre of the finished yarn is determined by two factors, these being the amount of titanium dioxide (TiO_2), sometimes referred to as a dulling agent, present in the polymer and the filament cross-section to which the POY is spun. The higher the amount of titanium dioxide present, the more matt (or dull) the fibre will appear. Also, the more irregular, i.e. further from a round cross-section, the duller will be the fibre appearance. Hence hexalobal and octalobal spun-filament cross-sections produce a yarn which has flatter, or matt, fabric sheen. This is due to the reduction in light reflected from the surface of the yarn back to the eye. The lustre of a fibre may be enhanced by changing the nature of crimp, or texture, present in the yarn and by doing so altering the manner in which light is reflected from the surface of the fibre. Commonly, there are two methods used to achieve these required changes in crimp character:

1 A lower or leaner crimp can be achieved by means of the friction unit in either of two ways:

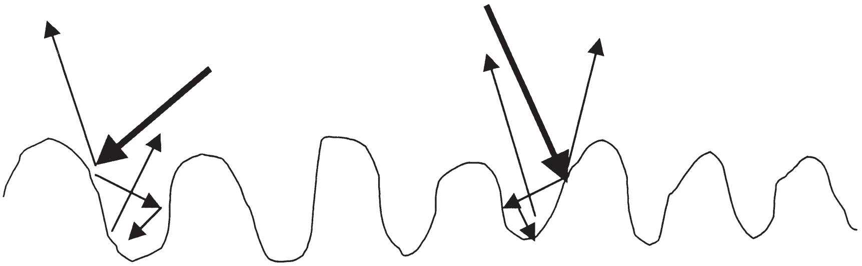
   a by employing a low D/Y ratio, i.e. low friction unit rpm which results in increased tension ratios being observed; or
   b by reducing the number of friction discs employed on the friction unit disc stacking;

   As described respectively in Sections 4.2.9.1 and 4.2.9.3, Both of these methods result in a lower degree of crimp or texture in the yarn (see Fig. 5.23).

2 The yarn may be produced by a more usual method of twist insertion and the resultant crimp or texture in the yarn reduced by using very



5.23 Low crimp light reflectance. The bold arrow indicates incident light and the faint arrow indicates reflected light.



High crimp; low light reflectance; the light tends to bounce around within the wave-like structure of the fibre, instead of reflecting directly back towards the eye

5.24 High crimp light reflectance. The bold arrow indicates incident light and the faint arrow indicates reflected light.

high temperatures in the secondary heater thereby resulting in a very low shrinkage yarn with a correspondingly lean crimp (see Fig. 5.23).

Both of these methods may be used singly or in combination, the final route chosen being dependent upon achieving the required properties in the yarn with an acceptable manufacturing efficiency. By using this type of process it is possible to impart to the yarn a brighter and more lustrous appearance by reflecting more light from the surface of the fibre back towards the eye of the observer.

Conversely the opposite of the above may be desired to achieve a high degree of crimp or texture and high shrinkage. Both of these result in yarn having a more matt appearance by reducing the amount of light reflected back to the eye. However, the effect in achieving a more matt appearance is much less marked than in achieving a more lustrous appearance (see Fig. 5.24).

5.4 Spun-dyed yarns

Spun-dyed yarns, or solution-dyed yarns as they are sometimes called, bring a particular set of problems when being processed on texturing machines. These yarns are produced by injecting metered amounts of pigment, e.g. carbon black for black or grey colours, into the polymer during the spinning process. The amount that is added to the polymer stream determines the depth of shade of the final product. Carbon black is a very aggressive material and this has a detrimental effect on all ceramic surfaces on the texturing machine. These are abraded severely by the yarn, particularly in those areas of the machine where the processing tensions are the highest. This wear is accelerated the greater the amount of carbon present.

Wear on the ceramic guides has a discernible and detrimental effect on the process. High rates of wear on these components are associated with increases in the number of broken filaments and yarn breaks. This means that these guides must be replaced frequently and the associated cost of production increases proportionally. The high rate of attrition on ceramic has another knock-on effect. Where on-line monitoring is employed then obviously the wear on the ceramic sensing head will be high. These are very costly to replace and therefore it may be advisable to replace them with a sapphire surface or to run spun-dyed yarns without any form of on-line monitoring (see Section 8.3.1.2).

If it is decided to dispense with on-line monitoring an increased effort in process control is required if the customer is to be protected from physical faults that may appear in the fabric. This is doubly important when checks on knit sleeves are the only (and expensive) option for checking for physical yarn faults. Moreover any fault that is present may not necessarily be found in the small portion of yarn knitted (see Section 8.3.4).

5.5 Common modified polymers

Possibly the two most common modified polymers encountered during false-twist texturing are used to make the yarn dyeable using cationic dyes or to impart flame-retardant properties. These yarns may be processed as an unmodified polymer with the exception that lower primary-heater temperatures are normally used. This is due to the lower tensile strength of these products and to their susceptibility to textured broken filaments.

5.6 Composite or combination yarns

Composite or combination yarns are usually produced on machines that have been modified by the addition of one or more extra feed shafts. These shafts are usually situated in the input zone between the creel and the first heater on the texturing machine. The creel itself may also be modified to accommodate extra feeder-yarn packages, sometimes of different types. This set-up may be further enhanced by the addition of hotpins or other heating elements between two of the yarn feed shafts in this zone (see Section 4.5.3).

Major texturing machine manufacturers such as *Barmag, Murata, Teijin Seiki, RPR* and others now supply machines with these modifications. When used in conjunction with a double-density machine format the options become increasingly attractive from the point of view of reducing manufacturing costs.

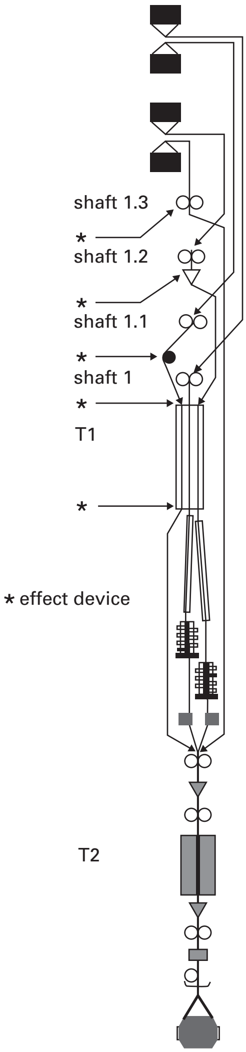
A composite yarn is, as its name suggests, one composed of two different fibre types. These may be of different chemical structure, i.e. a combination of polyester with polyamide yarn, or may be a combination of a disperse with a cationic dyeable polyester. Perhaps more commonly, it is a combination of two yarns having the same chemical structure but which, by being processed under different conditions, can be given tone-on-tone effects, a differential shrinkage, alternate light and dark dye shading or core-and-effect properties. These effects give a fabric appearance that is far removed from one constructed totally from conventional false-twist textured yarn.

Composite yarns are produced by employing various thread-paths in and around the input zone of the machine. There are many feasible combinations. Some of those that are commonly employed are described below.

1 Differential draw ratio. This is where two similar or different fibres are combined by running the input shafts of the machine at different speeds. Therefore two separate draw ratios are applied effectively.
2 Overfeed. This is where the first input shaft of the machine runs at a standard draw ratio for one component of the combination and the second shaft runs at a faster speed than the centre shaft of the machine, thereby overfeeding that component instead of drawing it.
3 Use of a stepping device that can feed one component of the pair into the machine at a variable rate.
4 Use of feed yarns with different levels of molecular orientation; here the effect is similar to running a differential draw ratio but magnified.
5 Use of an intermingling type of jet in the zone between two of the additional feed shafts so that the yarn components are combined before processing on the machine.
6 Using a hotpin or other heating element in the zone between two of the additional feed shafts. One or both ends are wrapped around the hotpin so that changes take place in the crystalline structure of the fibre before processing in the texturing zone of the machine.
7 Use of an additional twisting device such that one or more components are fed into the machine in a highly twisted condition.

There are patented methods (e.g. by *Barmag* and *Wykes*) whereby the use of extra feed shafts on the machine allows *Lycra* to be fed into the machine and combined with textured yarn during the manufacturing process rather than in a separate and costly stage. It is also possible to use these feed shafts either to bypass the twist-insertion device completely or possibly to employ different modes of twist insertion on different thread-lines.

With such an arrangement of shafts and either heating elements or air-jets, it is possible to employ various techniques to generate effects in both yarn and fabric. It may prove that only one or two are viable commercial processes. However, these products may be a useful addition to the port-folio, since not only do they generate income but they also make the customers aware that in the yarn manufacturing plant constant development efforts are being



5.25 Possible layout of multishaft machinery. Courtesy of Barmag-Saurer Group.

made to generate new and improved products; an important commercial consideration. The layout of such a machine is shown in Fig. 5.25.

5.7 Oops! What went wrong?

In this section some of the common problems encountered in a texturing plant will be examined and their possible causes discussed. For ease of use these will be taken in alphabetical order.

5.7.1 Break rate

The break rate, or the numbers of yarn breaks experienced per unit weight of textured yarn produced, is a constant concern in any texturing plant. Yarn breaks cause short packages, lost production and increased labour and packaging costs. The causes of high yarn breaks can be categorised broadly as follows:

1 poor quality POY feed yarn;
2 incorrect processing conditions on the texturing machine;
3 inadequate or poor maintenance on the texturing machine.

Little can be done to compensate for the poor quality of POY feedstock, other than attempt to segregate the affected spinning packages before they reach the texturing machine. If this is not possible, the texturing machine should be run at a slower speed so that the number of breaks in a given time period is lower.

Reasons for poor quality POY that may contribute towards high break rate are:

1 POY broken filaments;
2 incorrect or variable spin-finish level;
3 variation in the POY filament cross-section;
4 package build faults;
5 variation in orientation or denier;
6 handling damage;
7 poor housekeeping in the extrusion plant;
8 yarn packages without tails.

Reasons for high break rates that are process-related can be as follows:

1 excessively high draw ratio;
2 excessively high primary-heater temperature;
3 incorrect D/Y ratio leading to yarn coming out of friction unit;
4 process speed too high, causing instability and surging.

These can be minimised by adjustment to the process specification.

Machine and / or maintenance-related problems might include some or all of the following:

1 worn or damaged ceramic surfaces in the creel or texturing zone of the machine;
2 wear or physical damage apparent on yarn transport systems such as *Casablanca* aprons, nip rolls or any other yarn contact surface;
3 incorrect twist-stop design or material (where applicable);
4 poor thread-path alignment;
5 worn or damaged polyurethane discs (where applicable);

6 incorrect break sensor delay time leading to phantom cuts for no apparent reason;
7 faults with automatic doffing systems, where fitted. These may be related either to machine or process specifications.

Also, it must not be forgotten that the operators can have a discernible effect upon the yarn break rate, particularly when the splicing of the POY packages is not carried out correctly so that breaks occur when the splices pass through the machine.

In some instances there will be no single cause for high yarn break levels. This will often be the case. The way to cure the problem of high yarn break rates is to look at all aspects of the process. Walk the machine, look at what is happening, gather and analyse the data to find the major contributing factors. These must then be addressed. A logical step-by-step approach is the key to success in resolving such problems.

5.7.2 Broken filaments

Textured broken filaments may be related either to the yarn type, POY contributing factors, to mechanical damage within the thread-path or to the settings of the texturing machine on which the yarn is produced. Yarns that are classified as either microfilament or having a low filament denier will be more prone to exhibit this fault that those having coarser filaments. A microfilament yarn is taken as less than one filament denier. Those having filaments between 1.0 and 1.3 filament denier are often classified together with microfilament yarns. Also, in cases where the polymer itself has been modified, such as for cationic dyeable polyester, a higher number of textured broken filaments are likely than with yarn produced from standard polymer.

POY contributing factors may be related to:

1 variation in the uniformity of individual filament cross-sections in the POY bundle;
2 a low spin-finish level;
3 Non-uniform linear density.

Process parameters on the texturing machine that may contribute to high broken filament numbers may be any or all of the following:

1 primary-heater temperature too high;
2 draw ratio too high;
3 throughput speed too high;
4 intermingling jet pressure too high (especially in conjunction with high secondary-heater temperature where the jet is placed at the exit of the second heater).

An examination of the texturing machine itself may reveal a mechanical contribution to the high number of broken filaments. This would be:

1 worn or damaged ceramic surfaces;
2 wear on cooling plates;
3 dirty primary heaters;
4 damaged twist-stops or wrong material used in the design of the twist-stop (where applicable).

Again, the prudent technologist will go and look at the machine and personally assess the situation. Armed with this knowledge and the physical test data of the textured product, the parameters on the texturing machine will be adjusted so that they are at an optimum for the process. If the source of the broken filaments is outside the control of the technologist as far as process parameters are concerned, then all that can be done is to remove the problem by replacing worn machine components or by segregating faulty POY supply packages.

5.7.3 Bulk variation

Variations in the bulk level of the textured yarn may be classified into two separate categories, either end-to-end variation around the texturing machine or along-the-yarn-length variability. In many instances these problems can be attributed to the same cause. The cause may be the throughput speed of the process, which, if it is too high, allows insufficient time for even heat penetration within the primary heater. This is particularly likely to occur on yarns with low filament denier, the twisting action on the yarn creating a very dense yarn bundle. The dense core of the yarn means that it is more difficult to ensure even heat penetration throughout, the filaments in the centre of the bundle receiving less heat than those on the outside.

Other causes of bulk variability may be low draw ratio or incorrect rate of twist insertion for the particular process. This may be remedied by changing either the D/Y ratio or the number of friction discs employed.

5.7.4 Dye variation

Dye variation may be seen in two forms, either an overall drift in shade towards light or dark dye or an increase in end-to-end variation around the machine. A drift in dye shade within a product can usually be attributed to some change in the polymer from which the POY has been spun. More usually seen within a textured product is an increase in end-to-end variability around the machine. This can have several causes, some of which are POY related and others which relate to the texturing process parameters.

Such factors as dirty primary heaters or wear associated with polyurethane discs can contribute to overall changes in dye shade within a product.

End-to-end variation in dye shade around a texturing machine will lead to an increase in the number of packages segregated for light, dark or streaky dye. Light-dyeing yarn is usually associated with either the molecular structure of the POY or with extrusion conditions on the spinning machine. Another cause can be inadequate heat transfer on the texturing machine as a result of an error in threading the machine by the operator so that the yarn is not exposed to the correct primary heat. Or there could be a problem within the heater itself.

Dark dye ends with uneven dye uptake can be attributed to several causes. The affected position on the texturing machine must be examined, as well as possible POY effects, to determine exactly what is the problem. Possible causes of dark dye ends are as follows:

1 disc ejection on the texturing machine (yarn comes out of the friction unit);
2 yarn rolling out of or off the cooling plate;
3 yarn not fully drawn, through a fault with the input or centre feed shaft on the machine;
4 poor heat transference to the yarn caused by dirty heaters or an incorrect specification;
5 surging, incorrect texturing specification or lack of uniformity in the POY.

5.7.5 Intermingling faults

Faults with intermingling can be broadly classified into two groups, those that involve the properties such as the frequency or strength of the intermingling knot and those that are concerned with an irregularity or unevenness of intermingling along the length of the textured yarn.

5.7.5.1 Knot frequency and strength

If problems with the knot frequency and strength are noted, the first question that must be asked concerns the selection of intermingling jet for the particular process being employed. Factors such as the overall denier of the textured yarn, its filament denier and the speed of the process must be taken into account when choosing a jet in combination with a specific product. If these questions have been answered in the affirmative, the process conditions at which the jet is operated must be examined. Trial work is usually necessary to determine the optimum condition of air pressure, yarn tension, speed and jet location for each individual process.

5.7.5.2 Irregularity of intermingling

By irregularity of intermingling is meant the presence of short or long gaps in the textured yarn where no interlace is present. Some of the reasons for this are described above in Section 5.7.5.1 but there are two other possible causes to be taken into account here. One is general housekeeping on the machine. Are the intermingling jets dirty and becoming blocked so that their efficiency is impaired? Secondly is the age of the intermingling jet a factor? Yarn is abrasive and over a period of time wear can be become apparent in the yarn chamber of the jet to such an extent that its efficiency becomes impaired.

5.7.6 Package build faults

Most commonly experienced package build faults have been described previously in Section 4.3.6. Please refer to this. Two other faults are commonly though wrongly described as package build faults, these being dirty or damaged packages caused by poor housekeeping and incorrect handling procedures.

5.7.7 Package density problems

Package density is vitally important in the production of yarn destined for dyeing. There are two common types of problem. In one case the overall package density within a production lot is either too high or too low. Secondly, variation from position to position is experienced around the machine.

Accepting that other yarn parameters such as yarn shrinkage and intermingling are correct, the winding tension must be adjusted to correct the overall package density. This can be done by changing the speed of the take-up shaft or, should other considerations allow, by altering the wind angle.

If the problem is a high degree of variation from position to position around the machine, the following parameters must be compared with the specification:

1 initial stroke length correct;
2 taper angle correct;
3 intermingling correct;
4 cradle damping correct;
5 no drag present in system to increase winding tension;
6 thread-path correct;
7 yarn shrinkage correct.

5.7.8 Surging

Surging can be detected by observation of the yarn running on the machine, by looking at the cooling plate, by seeking the characteristic trace shown by on-line monitoring or, lastly, by examining a knitted sleeve. Surging is a transient instability in the thread-line, which manifests itself in a lean untextured appearance of the yarn. Surging can be caused both by the POY feed yarn and by the actual parameters on the texturing machine. Surging conditions can be overcome by increasing the draw ratio employed. A reduction in the throughput speed of the process and an increase in D/Y ratio, particularly in the case of low-denier yarns, can also help.

These remedies are aimed at stabilising the thread-line as much as possible within the texturing zone, where drawing and twist insertion take place. POY can cause the condition of surging as a result of incorrect or irregular spin-finish application. Irregularity of orientation along the length of the yarn can also cause surging.

5.7.9 Tight spots

A tight spot takes the form of a very short length of untextured yarn and is most easily seen by inspecting long lengths of yarn or by examining a knitted sleeve. They can also be detected by on-line monitoring. The causes of tight spots are those mentioned for surging above and the same remedial action should be taken.

6

BCF processes and yarns

6.1 Introduction

It is still possible to buy and certainly to construct a draw-texturing machine for producing BCF yarns. It could even be an economical proposition for making carpet yarns from a readily available feedstock such as polypropylene or polyester POY.

However, the majority of BCF yarns are produced today in a vertical operation in which nylon or polypropylene granules are melted and spun, or polymer is fed directly from continuous polymerisation to spinning, and then both drawn and textured, all in one continuous sequence. This is partly a result of the development of the original stuffer-box texturing process to become what is now a jet-driven process. The process speeds achievable today are high enough to justify direct integration with spinning. The second factor is that comparatively large volumes or lot sizes are required to produce face yarns for carpets. This favours an integrated process with large packages that can be loaded directly into the creel of the tufting machine.

There is also a need for twisted and heat-set yarns in many carpet qualities. The size of the textured yarn package may have to be restricted to that which fits into a two-for-one twister. Modern direct-cabler twisters do accept large packages but there is still a difference between their capacity and that of the creel in the tufting machine, especially with regard to the maximum diameter of the yarn package.

Originally called stuffer-box texturing, the production of BCF yarns consists of the 'stuffing' of a single yarn into a constricted body, which is part of the machine. This produces a saw-toothed, two-dimensional structure in the yarn. The simultaneous or following application of heat fixes the yarn structure, since we are dealing with thermoplastic or deformable yarns. The resulting yarn has bulk but no torque. The bulk can be removed by the application of a light tension but returns on relaxing this tension. Being wound under a fairly high tension, the yarn in this state is referred to as having latent bulk properties.

During stuffer-box texturing the heat is applied either by means of heated input rolls or by heating the stuffer-box itself. The process suffered from its origin, which was the type of crimper used to produce staple fibres. These crimpers produced fibre with a given and acceptable variability but the subsequent blending of the fibres masked any slight irregularity in the crimp. For carpet yarns with no opportunity to blend, this variability meant that they could not be used in plain constructions without a rigorous testing and sorting of every package of textured yarn.

The breakthrough results from using a jet and an expanding hot fluid that consists of hot air or steam both to open up the filaments by the turbulence created, and to 'stuff' the now hot yarn against the slower moving plug which forms inside the jet. Cooling takes place after the jet by impinging the yarn on to a cooled, slow-moving surface. It is now the hot fluid and yarn plug rather than the stuffer-box that provide the bulk. It is easier to maintain an accurate control of the fluid temperature and this comes into direct contact with the yarn. Furthermore the bulk is characterised as being three-dimensional.

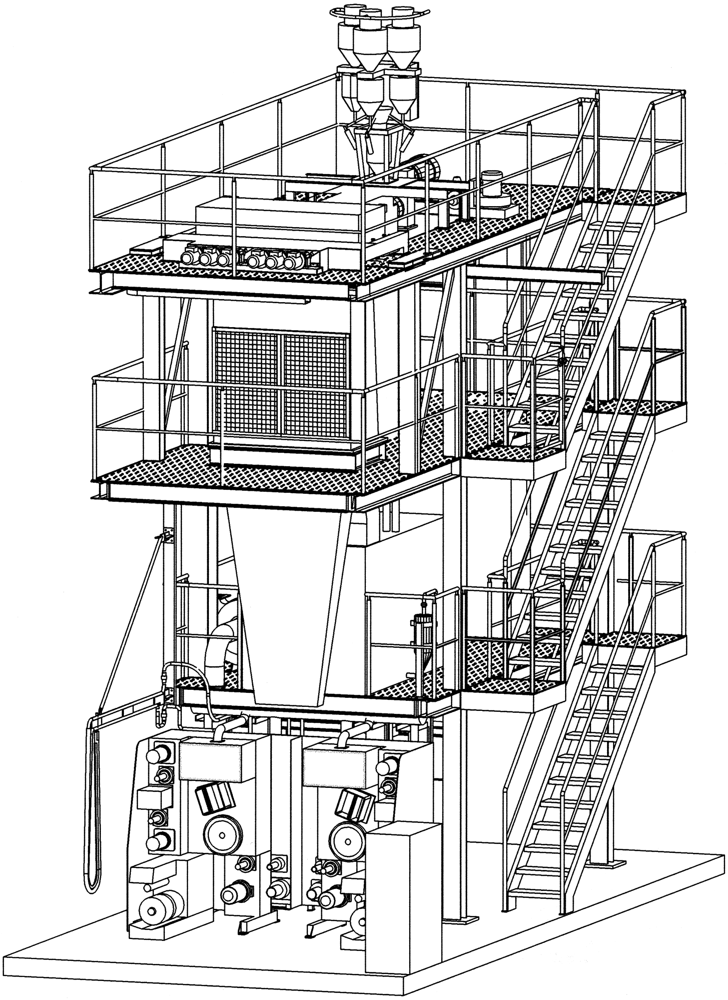
Sequential or predrawing has been a feature of the several generations of stuffer-box machine which were supplied from a creel with undrawn yarn. Even though the newer jet process has been integrated with spinning, it is still necessary to interpose a drawing stage. The heat for drawing is normally provided by heated rolls or godets.

6.2 BCF draw-texturing machine

6.2.1 Layout of the BCF machine

Unlike the false-twist texturing machine the integrated process does not have a yarn creel, since the starting material is polymer in the form of chips (also known as granulate). The polymer chips are normally washed and dried by the polymer supplier. In the spinning plant the chips are kept under an atmosphere of nitrogen to prevent moisture being reabsorbed by the polymer. The dry polymer chips are melted in an extruder and pumped through a spinneret. The number of holes in the spinneret determines the number of filaments in the yarn (or component of the final yarn, since several yarns may be combined at a later stage of the process). After quenching and application of spin finish the 'as-spun' yarn is ready to enter the draw-texturing section. Whereas the blending, extrusion, spinning and quenching take place on various floors of the plant, starting from the top, the draw-texturing machine is located on the ground (first) floor.

Since each position of the draw-texturing section, located as it is below its own spinning head, must be capable of being stopped and started and adjusted in synchronisation with the spinning head, there is no line-shaft drive as in a false-twist texturing machine. Each position consists of driven rolls (also known as godets), mostly being heated, as well as a texturing unit, a yarn entanglement or interlacing section and of course the winding or take-up head. All of these elements will be described below in the order that they occur in the process. The general layout of a typical spin-draw texturing plant for the production of BCF yarns is shown in Fig. 6.1.



6.1 Layout of BCF spin-draw texturing plant. Courtesy of Rieter Textile Systems.

6.2.2 Finish application

Before the freshly spun (extruded) filaments can be handled, i.e. touched in any way, they need to solidify and to be lubricated. The lubricant, which is known as a spin finish, is applied immediately below the quench, either by means of a lick roll or by a ceramic applicator.

Lick rolls comprise slowly rotating rolls with a sintered or porous surface, which both dip in a trough containing the lubricant and touch the passing yarn in order to apply a uniform quantity of spin finish to the filaments. The applicator comprises a metered system, since all of the lubricant applied remains on the yarn unless the level of application is set too high, in which case dripping will be visible. The advantages of the applicator method lie in the metering, which means that the quantity applied is known and that the applied finish is always fresh and not recirculated as with the lick roll.

Both methods rely on an even application to all the filaments. This is not always easy to achieve, especially if a high number of filaments is present. With carpet yarns the number can vary from 34 to 136 per thread-line. Special air-jets can be used which spread the finish evenly over all of the filaments. It should be noted that the filament cross-section also influences the quantity of finish that can be carried by a specific yarn.

6.2.3 Drawing

In common with other jet-texturing processes and in contrast with false-twist texturing, the drawing process must be completed before texturing commences. Nylon can be drawn cold, but in practice the draw forces are reduced considerably by the application of heat. Otherwise larger motors, shafts and bearings would be required and the power consumed by the inverter drives would increase. In any case, the yarn has to be heated as a prerequisite of bulk texturing. The heated rolls are fitted in pairs. They can be both driven and angled towards each other to facilitate the wrapping of the yarn or else one can be a driven heated roll and the other a separator roll, which is neither heated nor driven. The former pairing is often known as a 'duo'. In both cases the objective is to wrap the yarn bundle around the heated roll with several wraps (up to ten), in order to allow time for the heat to penetrate the filaments uniformly. The wraps must not touch each other, in spite of an inevitable slight wandering. Quite obviously the temperature profile of the heated roll must be consistent, not only between rolls, but also along the working surface of each roll.

The drawing takes place in two stages. A roll, which is not usually heated, draws off the yarn from the spinneret, past the quench (cooling) and over the spin-finish applicator. As soon as the filaments start to solidify, the pull exerted by the surface speed of this roll draws the filaments. In other words the weight per unit length of each filament (its denier) is already lower when it reaches this draw-off roll compared with its state at the spinneret. A low stretch of 1–2% is applied between the draw-off roll and the first of the duos in the draw zone, in order to ensure a light but constant input tension.

The main drawing takes place between two duos, each of which consists of a pair of heated rolls. The first pair is heated to between 50 and 90°C. The second pair is heated to a higher temperature. The first application of heat is to assist drawing by locating the draw point where the filaments leave the first duo and by reducing the drawing tension. The stability of drawing is determined by the location of the draw point. The location is the result of a complex relationship between the friction between the now warm filaments and the roll surface and the draw tension exerted by the second duo.

The purpose of the second application of heat is to set the freshly drawn yarn and also to raise its temperature to something close to that of the texturing jet, which it is about to enter. This facilitates the bulking process in the jet, which takes place at a sustained, elevated temperature (see Section 6.2.4 below).

A draw ratio is applied between the two roll duos. This ratio (as well as the applied temperature) depends on the material being processed (see Section 6.4.2 below) but can vary between 1.5 and 4.0. By this means the filament denier is reduced to a level which is fairly close to that which obtains in the final product – the carpet pile or tuft.

Motors drive the rolls and in fact the rotating part of the roll is usually mounted directly on to an extension of the motor shaft. The individual motors are invariably inverter-driven and are of the reluctance type. This allows the speed of rotation and the ratios to be selected and varied with ease. The draw ratio is that between the first and second draw-roll pair or duo in the drawing zone. Too high a draw ratio can lead to filament breaks and sometimes to yarn breaks. These can have a disastrous effect on the efficiency of such a high-production, continuous process. If the draw ratio is too low the yarn physical properties will not be adequate for application in the carpet and may even prevent the bulking jet from performing correctly.

Under normal circumstances the second pair of heated rolls runs at the highest surface speed of any component during the continuous process. The demands both on the accurate control of the speed of rotation and of the temperature of the heater within each roll are high. Various heating methods are used by the machinery manufacturers including vapour phase, high-frequency and induction heating.

Vapour-phase heaters work on the same principle as the conventional contact heaters used in false-twist texturing (see Section 4.2.7). The roll is self-contained and the liquid inside is heated by an induction heater within the roll to produce the vapour. As heat is taken away from the roll surface by the yarn, which is initially colder than the roll, the vapour condenses on the inside surface of the roll to replace the heat loss. Since the temperature of the vapour is controlled very accurately, this system results in the heat being supplied to the roll surface precisely as demanded by the yarn. A very uniform operating temperature is the result.

Induction heaters provide an alternative and very efficient method of heating the roll surface and hence the yarn. This is because they can be so designed that the heat is induced mainly in the outer shell of the roll. For higher temperatures the induction heater core must be of a laminated design to reduce eddy current losses and to prevent an unwanted rise in the core temperature.

Radiant and resistance heaters are also used. The former method is more suitable for rolls of large diameter (>250 mm) and conversely the resistance heater only finds favour for rolls of diameter between 80 and 120 mm.

Depending on the process, the temperature sensors are either embedded in the roll shell or located in a slot at the rear of the roll. To preserve heat and to save energy, the heated roll pairs (duos) are usually housed in an insulated box with doors for access. The rolls used for BCF drawing and processing operate within the range 50–200°C.

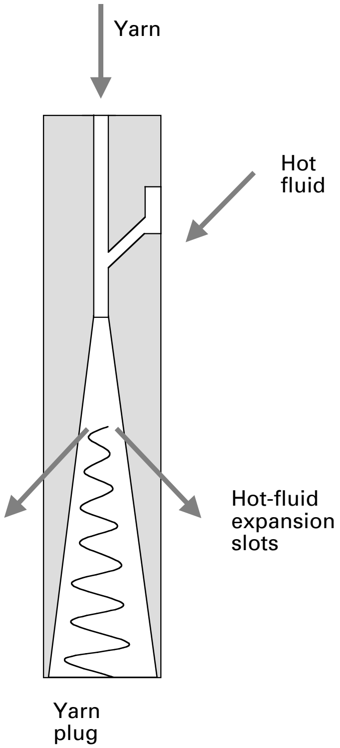
6.2.4 Texturing by hot-fluid jet

The texturing zone follows the drawing and comprises preheating, hot-fluid texturing and cooling sections. The preheating is carried out by means of the second roll duo described in the previous section.

6.2.4.1 Hot-fluid jets

Hot-fluid jets have been the subject of many patents since the early 1970s. These more often than not cover novel methods of generating a hot and turbulent fluid into which the yarn is fed. The jets are so designed that there is a forwarding action on the yarn to assist its passage through the jet. The turbulence within the jet does greatly improve the transfer of heat from the fluid to the yarn. Finally the expansion of the hot fluid within the jet and its escape is an important feature of successful jet design. The principles of a hot-fluid texturing jet are illustrated in Fig. 6.2.

It is the compression of the filaments and the formation into a yarn plug whilst hot which causes the properties of bulk to be imparted to the yarn. Since the yarn is hot, the deformation of the individual filaments results in the well-known, three-dimensional yarn crimp, which is the characteristic of a BCF yarn.

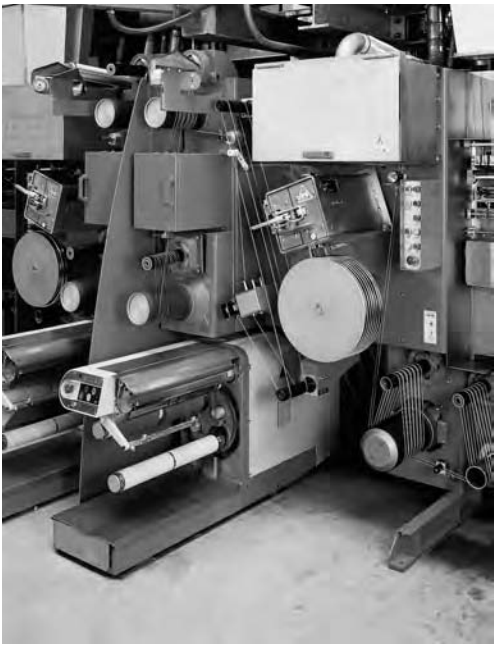


6.2 Principle of hot-fluid texturing jet. Courtesy of Rieter Textile Systems.

In the original stuffer-box it is fibre-to-metal friction and a restricted space which are the prime factors that produce the yarn plug formation. It is the expansion of hot air or steam, and the consequent reduction in its velocity, which slows down the progress of the filaments through the jet and forms the yarn plug in the hot-fluid jet.

When the hot fluid enters the jet its high pressure causes it to enter with a high velocity and degree of turbulence and to carry the filaments forward. However, the design of the jet enables the fluid to expand as it passes through the jet and therefore to slow down. This retards the forward movement of the yarn and causes a plug to form.

Modern jets must have an opening mechanism; otherwise the threading would be impossible in this, a continuous process. Furthermore the jets are usually supplied for two, three or four thread-lines. This is quite a challenge and the hot-fluid jet is a good example of modern precision engineering. It is also necessary to use corrosion-resistant and hardwearing materials. Hot air is commonly used for the jet but there are plants where steam is preferred (see Section 6.3.7).

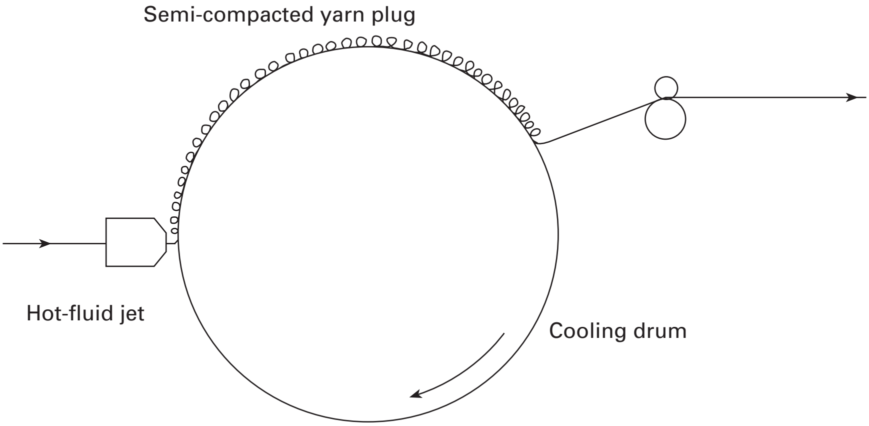


6.3 Close-up of BCF draw-texturing machine. Coutresy of Rieter Textile Systems.

6.2.4.2 Cooling zone

In contrast with cold-fluid or air-texturing jets, it is not the turbulence which causes the bulk formation but rather the constraint on the movement of the hot yarn during its passage through the jet. However, the bulk is not permanent unless it is retained whilst the yarn is cooled. The physical shape of the cooling device varies but most often it consists of a slow-moving, cooled surface on to which the hot yarn plug is impinged.

Figure 6.3 shows a typical cooling drum as well as a hot-fluid jet. Figure 6.4 shows the principle of the cooling drum. Typically it consists of a rotating drum with a mesh surface through which air is drawn. The ambient air passes through the bulked yarn, which is still in the form of a plug though less compressed, and this passage of air provides the required cooling. It is the combination of the flow of fluid in the jet, its regulated temperature, flow and pressure and the action of this cooling drum that determines the uniformity of texture in the yarn. A monomer extraction device may also be provided for fume removal.



6.4 Principle of yarn plug and cooling drum. Courtesy of University of Manchester Institute of Science and Technology.

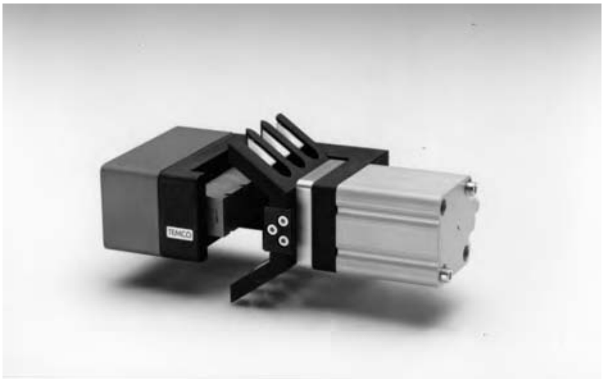
6.2.5 Relaxation and entanglement

A further pair of roll duos is provided after the texturing zone. This allows the freshly textured yarn to be relaxed and entanglement to take place. Entanglement by air-jet is important, especially for yarns which go directly to the tufting process. The jets work on the same principle as those used in the false-twist process (see Section 5.3.2.1). Only the size and therefore the air consumption are greater. For this reason the jets are normally housed in a sound-proof box and are located between the duo pair. The rolls are capable of introducing relaxation by having the first pair running faster than the second (the opposite of drawing). By this means the yarn tension in the jet can be optimised. Thus the efficiency of entanglement is improved with both more frequent and uniform interlacing and lower air consumption.

Figure 6.5 shows the intermingling jet produced by *Temco*. The jet has an opening mechanism to facilitate threading. The version shown is for three thread-lines and has plates designated LD 32 04. The guiding of the yarn through the jet is important especially when three components of different colours are being combined. Other jets for intermingling BCF yarns are produced by *Heberlein.*

6.2.6 Winding

Watching the operation of the automatic winding heads fitted to the *J0/10 Rietex* at work gives a fair indication of the advances in engineering that have taken place during the evolution of the texturing process. Automation



6.5 Entangling jet. Courtesy of Temco Textilmaschinenkomponenten GmbH & Co.

at this stage of the the process not only reduces the demands on labour but also ensures a consistent package build from the start of the package. Waste is reduced to a minimum and the package size is consistent. Furthermore the operators do not have to be present at the precise time of doffing. It is hardly surprising that automatic winding is used so widely in BCF production when production rates of 85–100 kg/head/hour are considered to be normal. The weight of each package is 5–15 kg and two (or even four) yarns are wound side-by-side. The doff-times for each package range from 20 minutes to as low as eight minutes for the smaller packages destined for cabling. Apart from the straight-sided package build and shorter doff-times, much of what has already been written in earlier chapters about package wind quality and variation applies also to BCF yarn production.

The winders are large in size, since they wind up to four packages of yarn on one spindle. They must be capable of up to 5000 m/min and the very high rates of traversing and the resulting high forces as the traverse guide reverses at the edge of the package have led to some unique designs. One of these is the *Birotor* fitted to the *Barmag* range of BCF machines. It consists of a purely rotary action of two vanes that produces the required traversing motion of the yarn from one end of the package to the other. Thus it is only the weight of the yarn and not that of the traversing guide mechanism that is being reversed.

6.3 Process variables

6.3.1 Polymer granulate

In a single-stage process there is considerable scope for influencing the end product before the draw-texturing stage is reached. Quite apart from the type of polymer granulate and the additives for delustring, reducing static and reducing the soiling, the type of spinneret used for extrusion determines the number of filaments and their cross-section. In addition the speed of the spinning pumps alters the as-spun yarn denier. The temperature at extrusion also influences the physical properties of the finished yarn. Some polymer chips, especially polyester, require extensive and controlled drying before reaching the melting stage in the extruder.

6.3.2 Spun-dyed yarns

Perhaps the greatest single variable at this stage is the choice and proportion of masterbatch consisting of pigmented polymer granules. Masterbatch is blended in with the natural polymer by means of dosage equipment and determines the final colour of the yarn. Undesirable variability in colour therefore depends on both the quality (uniformity) of the masterbatch and the accuracy and reliability of the dosing procedure. Natural and masterbatch polymer chips are metered by either volumetric or gravimetric means into the extruder.

Perhaps it seems strange for a process involving coloration to be so dependent on the skills of the masterbatch supplier. Colour matching is a special skill and it is understandable that many of the manufacturers of dyestuffs should also add to their skills by supplying pigmented polymer to match exactly the customers' requirements.

6.3.3 Extrusion (spinning)

The polymer chips having been melted and mixed in the extruder, the melt is distributed to the spinning packs containing the spinnerets via a spinning beam. The main purpose of the spinning beam is to maintain an absolutely uniform temperature of the molten polymer whilst distributing it to the spinning heads. The melt is fed into each spinning pack by a metering pump. The spinning pack contains both a filter and the spinneret. For this reason the spinning pack must be capable of being changed, since filters need replacing at predetermined or monitored intervals. This means that the spinning position must be stopped, however briefly, to allow the changeover to take place.

The pumps are inverter-driven and, together with the first rolls of the draw unit, determine the spun denier of the product. The extruder melts the polymer by means of barrel heaters, which are usually of the induction type. The extruder screw itself performs work on the molten polymer as well as providing a mixing function.

The spinning beam, pumps and spin packs are maintained at a uniform temperature and this is critical for good product quality. The temperature depends upon the polymer material. Nylon is spun at around 260–280°C whereas polypropylene, mostly spun-dyed, is usually extruded with a melt temperature within the range 230–240°C. The temperature uniformity is maintained using the same vapour phase principle as is used with contact heaters in the false-twist process (see Section 4.2.7.1). However, the large volume to be heated necessitates the use of a separate boiler and jacketed pipework.

For polypropylene it is possible to heat the spinning beam, pumps and packs using electrical heating. There is a considerable saving in capital cost but the maintenance of a uniform temperature throughout the process requires very skilful design to ensure even heat flow.

6.3.4 Three-colour spinning

An important development, which is unique to BCF yarn production, is the extrusion of three pigmented yarns in one machine. The three colours are spun from different masterbatch blends in three separate extruders. The spinning beams are so arranged that the spin packs of the three colours are situated side-by-side above the respective draw-texturing machine position. The principle of three-colour spinning machines is shown in Fig. 6.6.

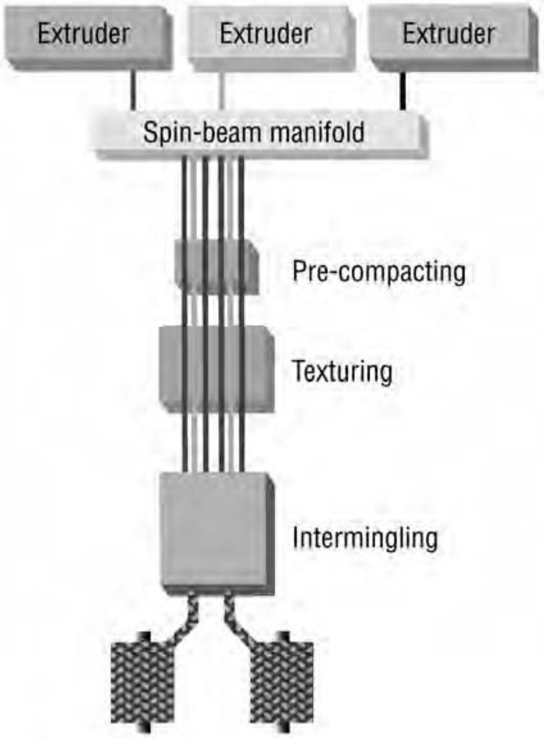
6.3.5 Hot drawing

The effect of increasing draw ratio should be obvious. It reduces the denier of the final product, as with all drawing processes. Although limited by the molecular structure of the as-spun yarn, the yarn strength will also increase and the elongation decrease.

Remembering that the yarn has been partly drawn between the spinneret and the draw-off roll, the temperature of the first duo is adjusted to suit the material being processed. Nylon (which can be drawn cold) is normally drawn with roll temperatures of 50–60°C. Polypropylene requires roll temperatures of 80–90°C.

The second duo is heated to match or come close to the hot fluid applied in the texturing jet. The resultant softening of the filaments reduces the energy required to heat and deform the yarn plug once it is inside the jet. It is also desirable for the yarn to experience a gradual rise in temperature, rather than for it to rise, fall and rise again before it reaches the cooling drum.

Adjustments to speed are made at an operating station using a keyboard with screen to indicate the settings made. The input to the inverter drive is digital. The speeds are given in metres/minute corresponding to the surface speed of the corresponding roll duo.



6.6 Three-colour BCF process. Courtesy of Rieter Textile Systems.

Similarly roll temperatures are set digitally at the keyboard and displayed on the screen. Alarm systems are incorporated to warn of divergences. They can be programmed to operate a visual and acoustic alarm signal and even to cut the yarn at the input to the draw-texturing machine. In this case the yarn is diverted to waste through a suction nozzle, in order to prevent faulty yarn from being wound. Many yarn producers regard this procedure as brutal and wasteful. For this reason on-line monitoring is likely to become the practice of the future. In a fully monitored process, the temperature control system software can 'flag' the yarn package so that it is automatically downgraded during the packing process.

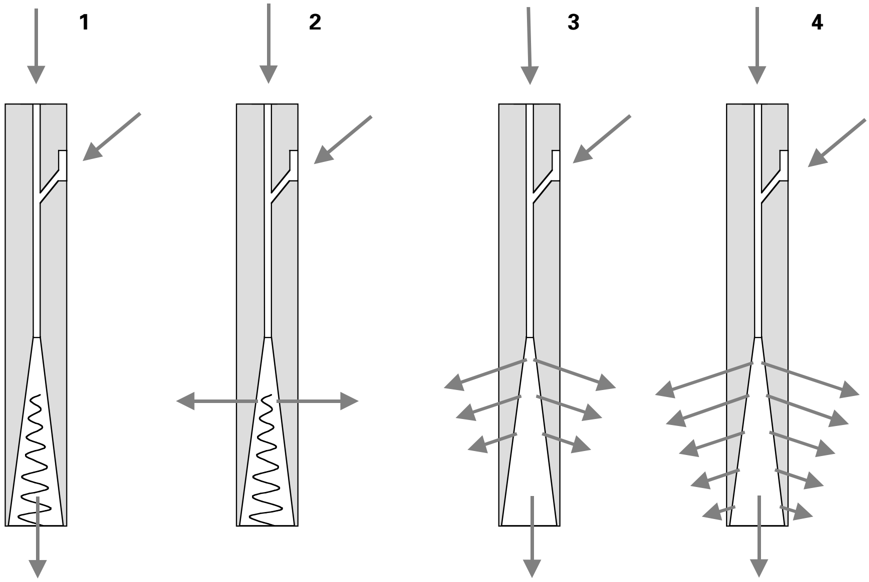
6.3.6 Hot-fluid texturing – Air

The major variable is the air temperature followed by the air pressure. For nylon (specifically nylon 66) temperatures range from 200–220°C whereas polypropylene requires a lower air temperature in the range 140–160°C. An in-line heater system, allowing rapid and accurate adjustment and control of the temperature, heats the air. There is both an indication and an alarm function built into the control software.

The second variable, namely the air pressure, affects the turbulence within the jet. This will influence the heat transfer from air to yarn, although its influence on yarn properties is secondary. The air pressure range is approximately 5–8 bar.

It is important to note that the final bulk in the yarn is influenced not only by the conditions within the jet but also by its whole temperature history from melt to final package ready for tufting or weaving. This applies to all thermoplastic yarns.

The third variable within the jet is the escape of the hot fluid (see Fig. 6.7). This is a design feature of most jets. Though not a process variable it does play an important part in determining the density of the yarn plug and thus influences the bulk characteristics of the yarn. Figure 6.7 shows clearly that a restricted escape of fluid as shown in 1 and 2 causes the formation of the yarn plug and with it the three-dimensional crimp, though this is not permanent at this stage. On the other hand unrestricted escape by the hot fluid as shown in 4 results in no yarn plug and no bulk.



6.7 Flow-controlled plug formation in jet. Courtesy of Rieter Textile Systems.

6.3.7 Hot-fluid texturing – Steam

The use of steam has advantages and disadvantages compared with a hot-air jet process. The infrastructure required to generate steam and to remove condensate is more complex and costly. This does not, however, apply in all cases. There are plants where steam is already available as a piped supply. Examples of the type of plant where steam is consumed include yarn-dyeing operations and also melt-spinning plants for nylon 66.

There is a close correlation between steam pressure and temperature. However, for fluid-texturing the steam is superheated using in-line heaters, in order to attain the elevated temperatures required for good bulking, without the necessity of designing a jet and manifold to operate at very high pressures. For example superheated steam supplied to the texturing jet at 195°C requires a manifold pressure of around 10 bar. Steam usage depends on many factors but a rough guide is that 1 kg of steam is required to process 1 kg of yarn.

6.3.8 Cooling zone

Both the cooling drum and the following duos are rotating at constant speeds. The rate at which fresh, processed yarn emerges from the jet is dependent on its bulk. The length of time that the yarn spends on the drum before it is drawn off is therefore a control measure of its bulk. Photoelectric or infrared sensors are used sometimes to monitor this. The information can be recorded and used to trigger alarms or it can be fed back to control a process variable such as the steam temperature. Closed-loop control is practised with some processes, notably those based on the *Fibre M* principle (see Section 6.3.11).

How often control feedback is applied in industry depends on the stability of the process. Quite clearly a stable process does not require this extra complication and therefore stability should be the prime target for any texturing operation.

The cooling is achieved by means of extraction or suction of air from the inside of the cooling drum, which has a perforated surface. The cooling should be just sufficient to the point where the subsequent handling of the yarn, i.e. relaxation, entanglement and winding, can take place without loss of bulk. The cooling does not have a direct influence upon the final yarn properties unless it is inadequately applied. However, it is only by cooling the yarn plug while it is still in a deformed state that permanent bulk can be imparted to a thermoplastic yarn.

The process variables in this part of the process consist of the surface speed of the cooling drum relative to the output of yarn from the bulking jet and the setting of the extraction fan to increase or decrease the rate of cooling. It should be noted that the yarn leaves the jet and is deposited on the cooling drum in a bulked and partly compacted form (see Fig. 6.3).

6.3.9 Entanglement and relaxation

As with all entanglement or intermingling processes, it is the design of the entanglement jet that has the greatest influence upon the yarn. This means that the yarn channel width and shape and the air inlet must be chosen to suit the yarn being processed. The jet specification must define both the orifice and the air inlet channel dimensions as well as the angle that the air inlet channel makes with the yarn channel.

The yarn channel must bear some relationship to the total yarn count, since jets do not work effectively if the channel is too big or if it is stuffed full of yarn. The air orifice size determines the amount of energy available for entangling from a given air manifold pressure. The formula for calculating the air consumption, q_{vn}, for a jet of known dimensions is as follows:

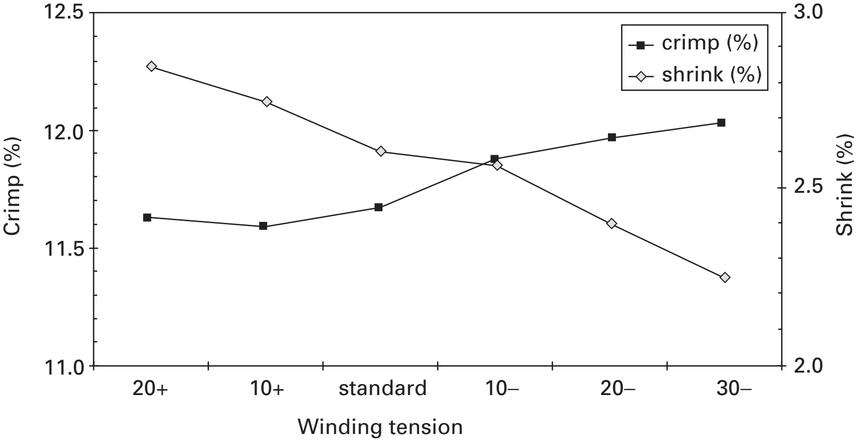
$$q_{\mathrm{vn}} = F(1+p_{\mathrm{e}})\,\mathrm{m}^3/\mathrm{hr} \qquad (\text{or } q_{\mathrm{vn}}/1.58 \text{ in cfm}) \tag{6.1}$$

where F is a factor equal to $0.4648 \times d^2 \times n$, p_{e} is the pressure in bar (1 bar = 100 kPa), d is the diameter of each air hole in mm and n is the number of air holes.

If the jet is located between two independently driven rolls, the yarn tension through the jet can be optimised by adjusting the relative speed of the rolls. If the jets are mounted immediately before the winder some forwarding action from the airflow in the jet is desirable. This is especially helpful in maintaining yarn tension during doffing and thus in reducing yarn breaks or wraps at this point.

Most air-jets have a recommended range of air pressures. Within this range, the higher the pressure the more tightly locked are the knots. Too low a pressure can also lead to irregular knot formation. Some air-jets produce a higher knot frequency with higher air pressures. Others exhibit a flatter curve within the operating range (see Section 5.10). A typical entanglement jet used for BCF yarns was shown in Fig. 6.5. The jet is operated using air pressures in the range 4–10 bar (400–1000 kPa) and the air consumption lies between 20 and 70 m^3/hr per yarn.

If the yarn is destined for tufting without twisting and heat-setting, the entanglement is important for efficient processing of the textured yarn. This can be influenced by a further input of heat under relaxed conditions. In practice this means that one or both of the rolls between the cooling zone and the automatic winder can be heated as a process option. Since the relative speed or overfeed can also be adjusted to give a correspondingly low yarn tension between these relaxation rolls, it is possible to reduce the residual shrinkage of the textured yarn as well as to impart good entanglement



6.8 Influence of winding tension. Courtesy of CENTEXBEL.

properties. However, most carpet yarns are heat-set as part of a following process and not during draw-texturing.

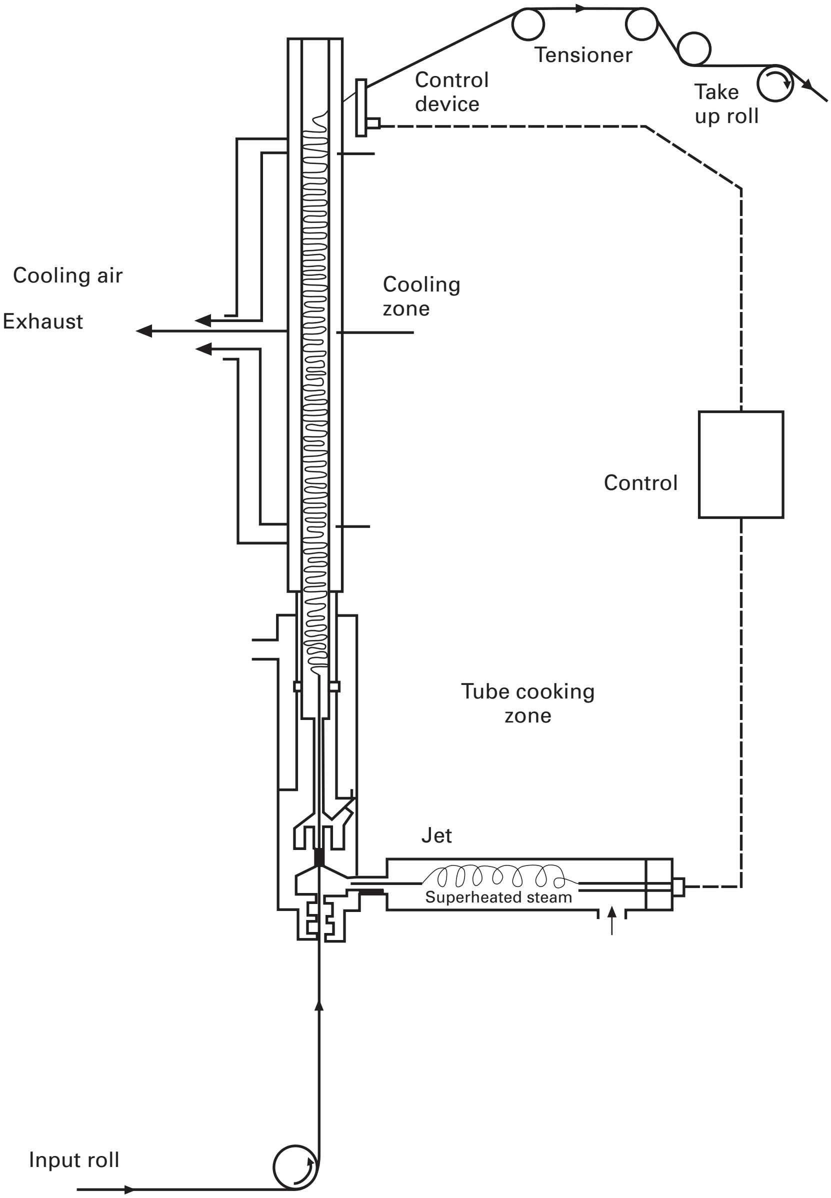
6.3.10 Winding

Although winding is not normally considered to be a process variable, the nature of the latent bulk in a BCF yarn means that winding tension does have some influence on yarn properties. Figure 6.8 shows that an increase in the winding tension will reduce the crimp in the textured yarn but will also result in an increased residual shrinkage. If not monitored closely it therefore follows that an incorrect winding tension can cause visible faults in the finished carpet.

6.3.11 Process control

As we have seen, the process must be very stable in order to produce first-quality carpet yarn. By measuring the yarn bulk and using the measured value as feedback to alter the bulking temperature, the stability of the process can be secured and in some cases improved.

The example shown in Fig. 6.9 demonstrates a principle that can be applied to all hot-fluid jet processes. In this case, it is a steam jet and the yarn plug forms vertically above the jet. Since the yarn enters the jet at a constant rate and is also drawn off with a different, but constant, velocity the height of the yarn plug is proportional to the yarn bulk. Thus the height of the plug is measured by photocell. In order to introduce a more elegant proportional control, four cells are in fact used. This system is used in



6.9 Fibre M process – control loop. Courtesy of UMIST.

production and it has been shown that a more uniform steam bulk results from its use. The level appearance of a carpet yarn is due both to the dye uptake and the uniform reflectance of light as a result of its controlled level of bulk. The same control principle can be applied to the deposition of the yarn plug on to the cooling drum and to the point at which it leaves the drum, remembering that it is being withdrawn at a constant rate.

6.4 BCF yarns

6.4.1 Yarn form

Since all the yarns described in this chapter are destined for furnishing fabrics, in most cases specifically for carpets, the final form of the yarn is the same or similar, whether the starting material is nylon, polypropylene or polyester. The requirements for woven and tufted carpets do differ. Tufting machines are fed usually from spacious creels. Large, textured yarn packages are needed to allow a maximum run time during tufting. The size is limited by the winder or by the size of the creel on the tufting machine.

Very few BCF yarns are dyed after texturing. Coloration is most commonly achieved either by using pigment dyes in the polymer in the form of masterbatch or by dyeing or printing the finished carpet. There is a process by which yarns are printed, which is known as space dyeing. In this process the BCF yarn is passed through a printing head with several colours. It is a package-to-package process.

The major factor which affects the choice of yarn package size is the requirement of many cut-pile carpet constructions that the BCF yarn is first twisted and heat-set. Since the twisting is often combined with plying, special machines have been developed. One of these, is a direct-cabling machine made by *Volkmann* of the *Saurer Group* and known as the *VTS-05 Carpet Cabler*, based on the two-for-one twisting principle with the additional feature of being able to twist and ply in one stage. However, the two-for-one spindle into which the BCF textured yarn package has to be placed imposes a size limitation. Typically direct-cabling machines can accept packages with an outside diameter of 285 mm compared with a maximum of 400 mm on many automatic package winders.

Following this the yarn is heat-set using steam or hot air. The fact that the yarn is heat-set after twisting affects the post-texturing conditions in the BCF draw-texturing machine. The principles by which heat-setting machines for carpet yarn operate do differ but they all allow heat to be applied to the yarn in a relaxed state. The time that the yarn is subjected to heat is also adjustable. After passing through the process the yarn is wound and is ready for tufting or weaving. *Superba* and *Suessen* make the most commonly used machines for heat-setting carpet yarns. The former employs pressurised steam heat and the latter dry heat.

The designation of BCF yarns is similar to that employed for false-twist textured yarns (see Section 5.2). An additional category is provided by the description of a twist-set yarn.

6.4.2 Fibre materials

6.4.2.1 Nylon

The most commonly used continuous-filament material for carpet-face yarns is polyamide, which is known as nylon (6 and 66) throughout most of the world. For pile applications the filaments are coarser than those used in other texturing processes, notably >10 dtex/filament, since tuft and loop resilience is an important property of the yarn in a carpet. The total range of yarns produced lies between 600 and 3000 denier (660–3300 dtex). The subsequent twisting and plying (cabling) process often used results in a carpet-pile yarn with up to three times the count of the as-textured product.

Filament cross-sections vary but trilobal is by far the most common. This is because a BCF yarn made from filaments having a trilobal cross-section has the desired light reflectance and soil-hiding properties. The trilobal-filament cross-section is chosen not only because of the light reflectance properties but also because the shape effectively increases the bulk of the yarn and hence the cover in the carpet. In addition a delustrant is usually added to the polymer.

Although spun-dyed nylon carpet yarns are growing in importance and have been available for a long time in one or two basic colours, mainly black, most nylon carpet yarn is still spun, drawn and textured as écru (undyed). The carpet is produced as a greige fabric before dyeing or printing to order.

Dyed carpets are not necessarily plain. Cross-dyed effects are common as a result of a combination of nylon filaments having different dye affinities or by using a spun-dyed combined with an écru yarn. There are also effective carpet printing processes. Printed carpets are often seen in airports and hotels, since the very large pattern areas that are possible with this process are highly visible and can be produced by this method.

Spun-dyed yarns in carpets offer several advantages. First, the achievable colours are brighter. The whole of the filament cross-section has a uniform colour whereas many dyestuffs only react with the skin of the filament surface. The trilobal cross-section enhances the colour, especially when the whole filament is coloured. Furthermore the colourfastness including the resistance to bleaching is greater with a spun-dyed product.

The properties of carpet yarns made from BCF nylon are very good in terms of resistance to wear and tear in the carpet. Nylon carpet yarns have the outstanding property of high resilience, which is important for a carpet tuft. If suitably treated, carpets made from BCF nylon retain good anti-soiling characteristics and can be treated also to reduce static.

6.4.2.2 *Polypropylene*

One major difference between nylon and polypropylene is that the vast majority of polypropylene BCF carpet yarns are spun-dyed. That is to say masterbatches of polypropylene chips having a specific colour are blended accurately with the naturally-coloured chips before extrusion (see Section 6.3.2 above). There are, however, disperse-dyeable grades of polypropylene and new variants are appearing on the market all the time.

Polypropylene BCF is available in a wide range but most commonly from 600–5000 denier (660–5500 dtex). The filaments are similar in shape to those used in nylon carpet yarns with trilobal predominant and for the same reasons.

Because the application depends on the gauge of the tufting machine and resilience is a premium property, textured yarns made from polypropylene resemble those from nylon. The resilience of polypropylene BCF yarn being somewhat lower than nylon, it may be that a slightly thicker filament will be used, in order to achieve the desired carpet quality.

The carpet yarn produced from polypropylene is characterised by its chemical inert properties, its freedom from static and its volume, which arises from its low density. The yarns should cost less to produce as a result of the raw material price (the main raw material is propylene, which is a by-product of oil refining). Also the low density means that higher yields can be expected during the production of carpets.

Since temperatures applied for drawing and heat-relaxing polypropylene are lower than those required for nylon, the machines that are produced solely for processing this fibre may be simpler in concept and therefore supplied at lower cost than those that are capable of processing nylon as well as polypropylene. Processing speeds may also be lower, though the gap is narrowing.

Many machines are capable of producing carpet yarns from both the major fibres. But at least two machines, the *Rieter Pathfinder* and the *Austrofil BCF* by *SML*, have been introduced which are specifically designed for polypropylene fibre.

6.4.2.3 *Polyester*

Polyester BCF yarns are the ones least commonly found in the carpet business. The properties of polyester BCF are similar to those of polypropylene and it is of course a dyeable fibre. However, the main reason for its production is the existence of polyester variants with excellent flame-retardant properties. The range of yarns available is similar to the other two materials, though the total weight actually produced is quite small.

A different approach to the process technology can be made because polyester yarns are so widely available as POY. It is therefore common practice to operate the draw-texturing process in a second stage separated from spinning. There are no carpet yarn machines marketed in Europe which are designed specifically for producing polyester BCF yarns in a single stage. However, the specification of such a machine would not differ greatly from that designed for nylon. Temperatures and speeds would be similar to those used for nylon (nylon 66).

6.4.2.4 Starting materials

Since this book is dedicated to yarn texturing, the starting material for the process covered here is a freshly spun, quenched and lubricated yarn, which may in some cases be coloured. Alternatively three different coloured yarns may have been extruded and combined before, during or after texturing. The three coloured yarns are presented usually to the draw-texturing stage of the process side-by-side. The side-by-side layout is retained at least until after spin-finish application to ensure a more even application of finish to each yarn.

6.5 Modification of yarn properties during draw-texturing

6.5.1 Yarn denier

The denier of the finished yarn is determined by the requirements of carpet tufting or weaving. Furthermore the final denier may be reached by plying, either during spinning and texturing (two or three ends combined at the entanglement jet) or during twisting by cabling and plying.

A second important aspect is the number of ends that are processed through one fluid jet. Quite clearly it makes economic sense to process as much material as possible through a texturing jet up to its maximum capacity. Schellenberg (1984) was one of the first people to report that up to four ends can be processed when finer yarns are being produced. It is necessary to split the ends from the spinneret so that they both enter and leave the jet with separation.

The as-spun denier is a function of the speed of the metering pumps and the draw-off rolls, which in turn provide the input to the drawing section. Since the metering pump and draw-off roll speeds also affect the molecular orientation of the yarn, the relationship is complex and cannot be decided by a simple formula.

Whatever compromises have been made during spinning the relationship for calculating the draw ratio after spinning is simple, namely:

$$\text{denier before texturing} = \text{as-spun denier} \times \frac{\text{output draw-roll surface speed (m/min)}}{\text{input draw roll surface speed (m/min)}} \qquad [6.2]$$

By and large the influence of this draw ratio on the yarn properties is the same as indicated in Section 5.3.1.

6.5.2 Yarn bulk

Miller and Southern (1991) have shown that both yarn bulk (also known as fibre crimp) and dyeability of the finished yarn can cause streaks in carpets, especially in the case of nylon 66. From this it is clear that the property of yarn bulk is very important. Since the tuft sits vertically in the carpet, yarn bulk is related directly to cover. If the yarn is too thin the light reflectance will change and a visible streak will be apparent.

This also means that the bulk must be entirely uniform for the carpet appearance to be acceptable. There are no blending stages after texturing, unless heat-setting is applied. Here Miller (1994) has shown that heat-setting, when skilfully applied, can level out some yarn bulk variation (see Section 6.4.1).

Translated into process variables, uniform bulk means impeccable control of temperatures, fluid flow (volume and pressure) and cooling conditions. The ability to control these parameters accurately lies firstly in the machine design but also in the plant discipline applied to this complex process, where only a few minutes out of control spills out large volumes of waste yarn.

The process know-how and conditions which lead to good-quality BCF yarn are the property of the large carpet fibre and yarn manufacturers. Here it is sufficient to state that yarn temperatures should be similar throughout the process from spinning to the hot-fluid jet and again during post-texturing treatment. One thing to avoid is subjecting the yarn to widely fluctuating temperatures during the successive process stages. It should also be remembered that thermoplastic yarns have a memory. If a nylon yarn is heated to a temperature that is higher than that during the previous process (stage) then its properties, including bulk and shrinkage, can change. This applies during subsequent processing, especially during heat-setting or when the carpet is being finished. In contrast to nylon, polypropylene and polyester respond to reheating, even if the temperature is lower than that experienced previously during processing.

Temperatures, air pressure, and cooling drum settings must be determined by experiment. This may not be as difficult as it sounds, since the suppliers of the polymer chips, the masterbatch and the machinery maker will be able to advise about the best starting point for these trials.

6.5.3 Entanglement

For single-end yarn destined for tufting without twisting, plying or heat-setting the specification of the air-entanglement jet is a most important factor. As we have seen (in Section 6.3.9) the air-jet size must be matched to the yarn, though each size of jet is capable of processing yarns in quite a wide range.

Entanglement jets for BCF yarns are provided for single-, two-, three- and four-ply yarns. When three yarns of different colours are being combined at the jet, the guiding arrangement before the jet is critical, since any imbalance in the yarn tensions can cause a variable appearance in the yarn. This is in the hands of both the machine and jet manufacturers.

Compared with these aspects, the possibility of variation in entanglement properties by changing air pressure and yarn tension is limited. It is sufficient to state that the yarn tension must be kept as low as possible, compatible with a stable thread-line. Too high a yarn tension will necessitate higher air pressures (i.e. consumption of air) and will ultimately lead to a situation where entanglement becomes impossible.

A well-entangled BCF carpet yarn does not exhibit the visible knots that are seen in an intermingled, false-twist textured yarn. In fact the structure of the entanglement knot is quite subtle and can be seen most easily when two or three spun-dyed yarns are combined and entangled in one jet.

6.5.4 Yarn shrinkage

Much of what has been written about false-twist textured yarns applies also to BCF yarns (see Section 5.3). Only here the temperatures used during spinning, drawing and texturing determine the bulk in the BCF process. Post-texturing heat treatment is usually a separate process after twisting, since the applied twist needs to be set into the yarn by the application of heat. Yarns for tufting only are not normally heat-set after texturing as part of the BCF process. That is to say, the last roll before the winder is unheated or, if a heater is provided, it is switched off.

As we have seen, both polyester and polypropylene respond in a direct way to the application of heat. The more that is applied, the lower is the residual shrinkage. The relationship is slightly more complex because the yarn tension that is present during the application of heat also influences the residual shrinkage. So does the time during which the heat is applied, especially if there follows a rapid cooling of the yarn. This means that the residual shrinkage of the final product is influenced directly by the processing conditions at all stages from extrusion to final heat-setting.

The relationship between the time of heat treatment and the yarn residual shrinkage is more complex in the case of nylon. One additional factor is the presence or otherwise of moisture. For this reason, the final heat-setting stage, after twisting and cabling, is the point at which the final shrinkage of a nylon BCF yarn can be influenced significantly. The use of steam means that nylon can be set at almost 100°C lower than when dry heat is applied (see Section 2.2.7).

Uniformity of treatment during spinning, drawing and texturing has a direct influence on the yarn shrinkage. If it is uneven, then the tuft height may be variable leading to a carpet with a poor appearance. Furthermore variable heat treatment can always cause differences in dye uptake with nylon yarns.

6.5.5 Yarn lubrication

If a BCF yarn is to be tufted without intermediate processing, the only opportunity to apply lubrication is between quenching and drawing. In other words, the conventional spin-finish application must be designed so that the yarn friction properties are suitable for texturing, winding and tufting. This is quite a tall order.

Modern plants use applicators for the addition of spin finish. Because BCF yarns have at least 30, and sometimes over 100, filaments the applicator must apply the finish evenly across all the filaments. The level of application varies from under 1% in the case of nylon yarns to between 1 and 5% for spun-dyed polypropylene yarns. It is adjusted by the metering of the finish to the applicator. One disadvantage of the old lick-roll system is that the correlation between lick-roll speed and the pick-up of spin finish is not so good. Changing the depth of lubricant in the lick-roll trough also has a marginal effect on the level of spin finish applied to the yarn. This is the reason why applicators rather than lick rolls are seen commonly in a modern BCF yarn texturing plant.

6.5.6 Yarn appearance

When a yarn is destined for a carpet there are many properties which determine its appearance. It is not the only concern of the yarn producer that the yarns dye evenly. Just as important are the properties of light reflectance. In fact, two yarns, which have been spun from the same polymer, may appear to have different shades in the carpet, because of an optical effect caused by bulk or other physical variations.

As we have seen previously (see Section 5.3.7) light reflectance is influenced by many properties, including fibre cross-section, the amount of delustrant applied to the polymer and the level and type of bulk. Two yarns may have the same overall level of bulk (see Section 8.3.3.2) but the first may have a finer crimp than the second. This will have a dramatic effect upon the appearance of the yarn in carpet.

The BCF process is therefore one in which control is vital at all stages. To repeat, the productivity of the process is so high that even a few minutes with the process out of control will result in a large quantity of downgraded product.

7

Air-jet texturing and yarns

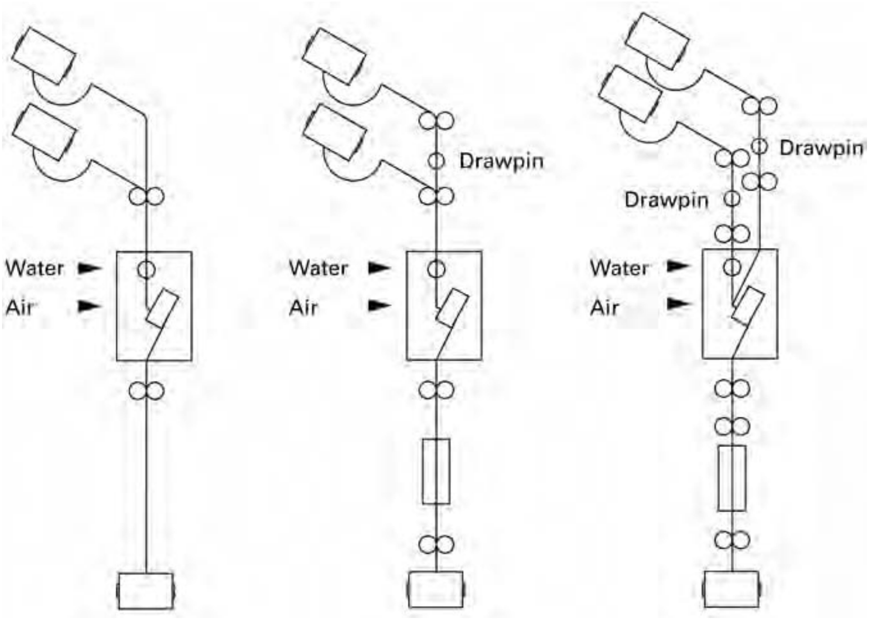
7.1 Introduction

Air-jet textured yarns are produced from thermoplastic, cellulosic or non-organic filament yarns using a turbulent fluid, which is usually compressed air. Loops are formed on the surface of the filament yarn, giving it a voluminous character. Depending upon the material used, the loop structure results in a yarn with characteristics which resemble those of the conventional staple-fibre product. At one time the yarns were known as spun-like yarns.

Thus, in its simplest form, the air-jet texturing machine consists of no more than a supply of yarn (in a creel), a suitable winding head fitted with yarn transport including an extra pair of feed rolls and an air-jet interposed. Since the loop formation results from a shortening of the yarn, the feed rolls before the air-jet are operating at a higher rate of feed than those drawing the yarn out of the air-jet. This is known as overfeeding. The process is illustrated in Fig. 7.1.

When processing certain thermoplastic yarns, chiefly those that are readily available as POY, it is common for the machine to be fitted with a predraw zone, which consists of at least one extra set of feed rolls and a draw-pin. If the machine is to be used for processing polyester POY then the draw-pin will be heated, in order to raise the temperature of the yarn to above the second glass transition temperature T_g (see Section 2.2.3).

Similarly, thermoplastic yarns are often subjected to a heat-setting process, in order to reduce the residual shrinkage of the textured yarn and (it is claimed) reduce the size of some or all of the surface loops. The addition of a heater and at least one further set of yarn feed rolls situated after the air-jet allows this heat-setting to be carried out in-line. Two further pairs of rolls are preferred if the textured yarn can be shown to benefit from a so-called 'mechanical stabilisation', which is nothing more than the tightening of knots by pulling on each end of the yarn, i.e. by stretching. This results in a yarn which is more stable, meaning



7.1 Air-jet texturing processes – single, parallel and core-effect (left to right). Courtesy of Heberlein Fiber Technology Inc.

that its structure cannot be altered by the application of further tension such as would be encountered during weaving.

Many air-jet textured yarns are produced from two or more feeder yarns and these may well be processed using different levels of overfeed through the jet. Add to this the need for predrawing each of the feeder yarns and it is apparent that what was originally a simple process can become quite complex. This is illustrated by comparing the first and third examples in Fig. 7.1.

7.2 Air-jet texturing machine

Air-jet texturing machines come with many different profiles and configurations. However, there are two main groups: the first consists of machines with individual drives and the second resembles the false-twist, draw-texturing machine in having a headstock with motors, drives and shafts at each position. The latter may be called lineshaft machines.

Machines with individual drives are characterised by the very wide range of yarns that can be produced and by the fact that each machine position can be set up to produce a different yarn. Components can be added to the machine, either at the time of assembly or as part of a conversion, so that all of the process technologies described in the previous section can be achieved. Individual winding heads mean that doffing is on a random basis, an essential when yarns of high denier are being produced. These are now available with automatic doffing of the textured-yarn packages.

Lineshaft machines have winding heads of similar specification to those used for false-twist processing and are therefore commonly doffed in groups by machine side. Winding heads fitted to these machines are usually limited to about 1500 denier and so this type of machine is only used for finer yarns. They are available with automatic doffing, which makes random doffing a feasible alternative. They are fitted with a short setting heater that is identical to that fitted to the false-twist texturing machine to which the lineshaft-driven, air-texturing machine is closely related.

The thread-path components are the same, though several are optional:

1 two shafts (yarn transport), between which the yarn is drawn, often fitted with a heated pin;
2 two shafts between which the yarn is textured. The texturing jet is housed in a sound-proof box, which also contains a device for wetting the yarn before it enters the jet;
3 two shafts between which the yarn can be stretched;
4 two shafts between which the yarn can be heated and relaxed;
5 an oil application device;
6 a yarn collection and winding head.

Most air-jet texturing machines are equipped for two different feed yarns. This means that 1 is represented twice and in parallel on the machine. On the other hand the simplest form of air-jet texturing involves only 2 and 6. However, if two feeder yarns are to be handled, then the input feed unit of 2 has to be present twice.

Summarising, the simplest machine has three shafts and a winder and the most complex (in common use) possesses seven shafts and a winder. The *Stähle* (*SSM*) *RMT-D* air-jet texturing machine represents the individual drive machine here as shown in Fig. 7.2. Lineshaft, air-jet texturing machines made by *Giudici*, *ICBT* and *RPR* are to be found operating in European plants.

7.2.1 Creels

In most respects the creel of the air-jet texturing machine is similar to that of the false-twist machine (see Section 4.2.2). However, because a greater number of feeder yarn ends are provided for each texturing position, the creels are larger and require more floorspace.

Even with lineshaft machines the single-package, magazine creeling of the false-twist machine is replaced by two feeder yarn packages, the first

7.2 SSM Eltex Stahle RMT-D air-jet texturing machine. Courtesy of SSM.

for the core and the second for the effect yarn. This means that the creel must provide for at least four POY packages at each winding position, since magazine creeling is practised.

In the case of individual drive machines, there may be up to eight supply packages plus eight in reserve for each texturing position. Although the gauge of these machines is around 600 mm (though reduced to 440 mm in the latest *SSM* model *DP2-T*), the number of feeder yarn packages provided means that the creels for air-jet texturing machines require considerable floor space. It is necessary for missing feeder yarn ends to be detected, which means that the creel is considerably more complex than that on the false-twist texturing machine.

7.2.2 Yarn cutter or stop motion

A yarn cutter is provided on lineshaft machines that operates in the same way as on false-twist machines (see Section 4.2.3). A stop motion is preferred on machines with individual drives, so that the missing end may be repaired and the position restarted. This is an advantage of the process, although the extensive use of yarn heaters may render stopping and starting an undesirable practice. This is because yarn that is resting on a heater may be overcooked and this results in a length of textured yarn with a faulty appearance.

7.2.3 Yarn transport system

The same yarn transport systems are used on all lineshaft machines, whether for false-twist or air-jet texturing; namely nip rolls or apron feeds (see Section 4.2.4). The *SSM-Stähle RMT-D* machine (illustrated in Fig. 7.2) will be described throughout this chapter, since it is the most widely used air-jet texturing machine with individual drives in Europe. It also contains many of the same components as its predecessor – the *Eltex Model AT*.

This individual-drive machine is fitted with two kinds of yarn transport system. The first and most common consists of a rubber-covered feed roll with a separator to achieve several yarn wraps and thus to ensure adequate grip. The separator consists of either a fixed ceramic or rotating roll guide. Alternatively the machine may be equipped with ceramic-coated metal rolls and rotating separator rolls. The latter have the advantage of longer life but more yarn wraps are required.

The rubber rolls are supplied with a range of diameters. This enables finer adjustments to be made to the overfeed (or draw ratio) than would be possible by gearing alone. Colour-coded roll covers have been available in the past to simplify the process of checking that the machine (position) is set up correctly.

In all but the most recent versions of the individual-drive machine, the rolls are driven by belt drive. This means that pulleys must be changed on each head when making step changes to the process. The latest machines have rolls that have independent, inverter-driven motors. This means that speeds and ratios can be changed quickly from the central machine-control panel. The latest machine from *SSM-Stähle* is the model *DP2-T* and this incorporates independent, motor-driven rolls (see Fig. 7.3).

7.2.4 Yarn displacement system

As with most of the drive and feed equipment, a yarn displacement mechanism is fitted to line-shaft machines as part of the standard equipment (see Section 4.2.5). The *SSM Stähle RMT-D* machine has forward-facing rolls. The provision of yarn displacement systems on this type of machine was restricted initially to the draw roll where yarn tensions are highest.

7.3 SSM Stahle DP2-T air-jet texturing machine. Courtesy of SSM.

7.2.5 Heated draw-pins

By far the most common method for providing heat in the draw zone is by using a static-heated pin (often known simply as a hotpin). Rotating hotpins of 80–100 mm diameter have also been used, as have driven-heated rolls of 130 mm diameter.

For the hotpin to work effectively there must be a frictional force which retards the yarn as it is pulled over the surface. Experience shows that the ratio of yarn tension before and after the hotpin should be approximately 5:1. Of course the choice of hotpin surface will vary depending upon the type of yarn to be processed and its frictional characteristics. There is often a need to compromise between a hardwearing hotpin surface and one that has the required frictional characteristics. In practice either an orange peel surface in ceramic or a knurled, matt chrome surface is used.

Machines have been available for some time which feature the use of heated rolls for drawing. When used in place of the input feed unit they have the advantage of avoiding the problem of wear. That they work should not be doubted, since they are used extensively on draw-winding machines. The extra cost and higher power consumption have left them as an expensive alternative, so far. Now they are gaining in popularity not only because there is little or no wear but also because their greater heat input makes them ideal for producing yarn with a low residual shrinkage without resorting to the autoclave batch process (see Section 7.3.7).

7.2.6 Yarn wetting system

Most air-jet texturing machines employ a water applicator before the jet. This is because the efficiency of the process is greatly improved if one of the yarns being fed into the air-jet is wet. The introduction of yarn wetting enabled an increase in production rates from 150 to 450 m/min to be realised. This is because the application of water brings about a beneficial reduction in interfilament friction, since the filaments are required to travel through the jet with different velocities and therefore need to be able to slide alongside each other.

Water is applied by an applicator, which is similar to that used for spin finish or for applying coning oil on false-twist texturing machines (see Section 4.2.11). The water must be supplied to each position of the machine in a well-regulated quantity and quality. Metering pumps at each position would be regarded as too expensive and unnecessary, but some system of metering needs to be provided for each row of positions. This is achieved usually by a combination of flow and pressure control.

By water quality is meant a clean, filtered and reliable supply. Hard water should be treated to soften it and demineralised water should be avoided if metal jets are used, since there is a small risk of corrosion.

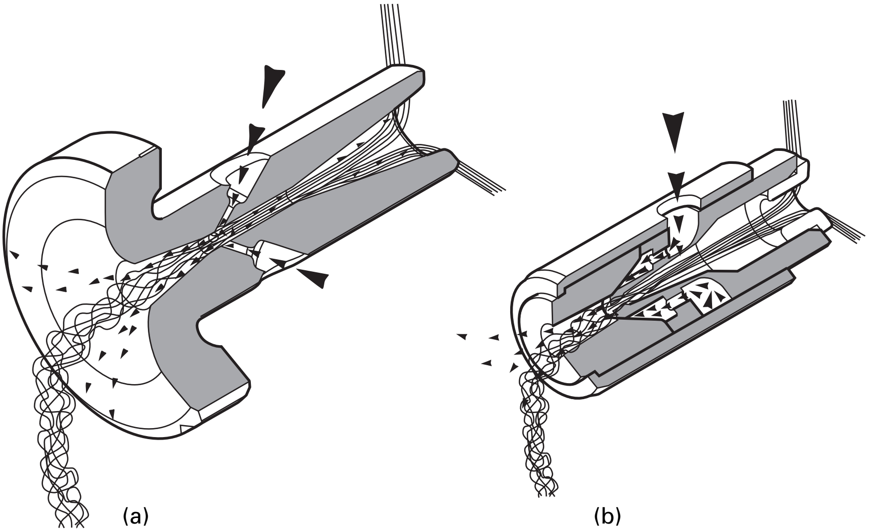
7.2.7 Air-texturing jet

The air-jet is the heart of the process but modern jets require little or no adjustment in use. Most important is the selection of the correct jet, since the *Stähle RMT-D* machine is capable of processing yarns from 50–5000 denier (55–5500 dtex) but individual jets are limited to a narrower range. Furthermore the choice of jet is determined by the material to be processed and by the end-use and characteristics of the yarn to be produced.

There are two basic types of texturing jet, the axial and the radial. Figure 7.4 shows these two types side by side. The first is the axial jet (see Fig. 7.4 (b)). This was the first type of jet to be developed for air-jet texturing, initially by the *DuPont Company* (*DuPont*), using the trademark *Taslan* ®. The principle of the jet has remained the same for many years, but there have been many detailed improvements. There are still many *Taslan* ® jets in use from Mark XIV onwards and there is also the equivalent made by *Heberlein*, which has the designation *EO52*. *Heberlein* became the owner of the *Taslan* ® trade name and patents when *DuPont* decided to cease licensing air-jet texturing technology.

The second generic type is known as the radial jet (see Fig. 7.4 (a)). This jet was developed originally in Czechoslovakia using the *Mirlan* name but has been manufactured by *Heberlein* since 1977. Again, what was originally a single model has developed into a wide range for different yarns and production rates. Radial jets are made from both ceramic and tungsten carbide materials.

Whereas the axial jet was developed initially to be adjusted during production, in order to obtain the optimum yarn processing tension, the radial jets have always been fixed. They require only cleaning, and the replacement of seals and damaged surfaces during their lifetime. Both the axial



7.4 (a) Radial and (b) axial jet. Courtesy of Heberlein Fiber Technology Inc.

and radial jets are fitted with a form of baffle device at the point where the yarn leaves the jet. These have been given various names such as baffles or coanda bars. Baffle devices are described in more detail in Section 7.3.5.4.

7.2.8 Jet box

Both the air-jet and the water applicator are enclosed in a sound-proof box. Eyelets are provided where both the input yarns and the textured yarn enter and leave the jet box. There is also provision for the water to drain to a central point (for treatment) and an air extract. The air extract is connected to a central fan and maintains the jet box under a slightly negative pressure, even when the air-jet is working. This reduces the escape of air and mist into the plant environment.

Of course, the jet box must be opened for access and especially when threading the machine. Although the wearing of ear protection is recommended (and in many plants compulsory) when working close to the machine, the noise level close to an air-jet texturing machine is quite acceptable when the jet boxes are designed correctly and all are closed.

7.2.9 Mechanical stabilisation

Just as a shoe knot must be tightened after formation, so must an air-textured yarn be stretched slightly, in order to anchor the loops in the core of the yarn. On most machines this is achieved by having two extra feed-roll units after the jet. By setting the speed of the second typically 2–3% higher than the feed roll immediately after the jet, this can be achieved simply.

7.2.10 Heat-setting

All manner of heaters have been fitted to air-jet texturing machines in attempts to produce a textured yarn with a very low residual shrinkage (see Section 7.3.7 below). Lineshaft machines are often fitted with secondary heaters taken from the 'sister' false-twist machine (see Section 4.2.10). However, the core of an air-jet textured yarn is much denser than the equivalent false-twist yarn and it is acknowledged that heat-setting in-line is not as effective. Much has been written about shrinking so-called wild loops but there has been little published evidence that this actually occurs.

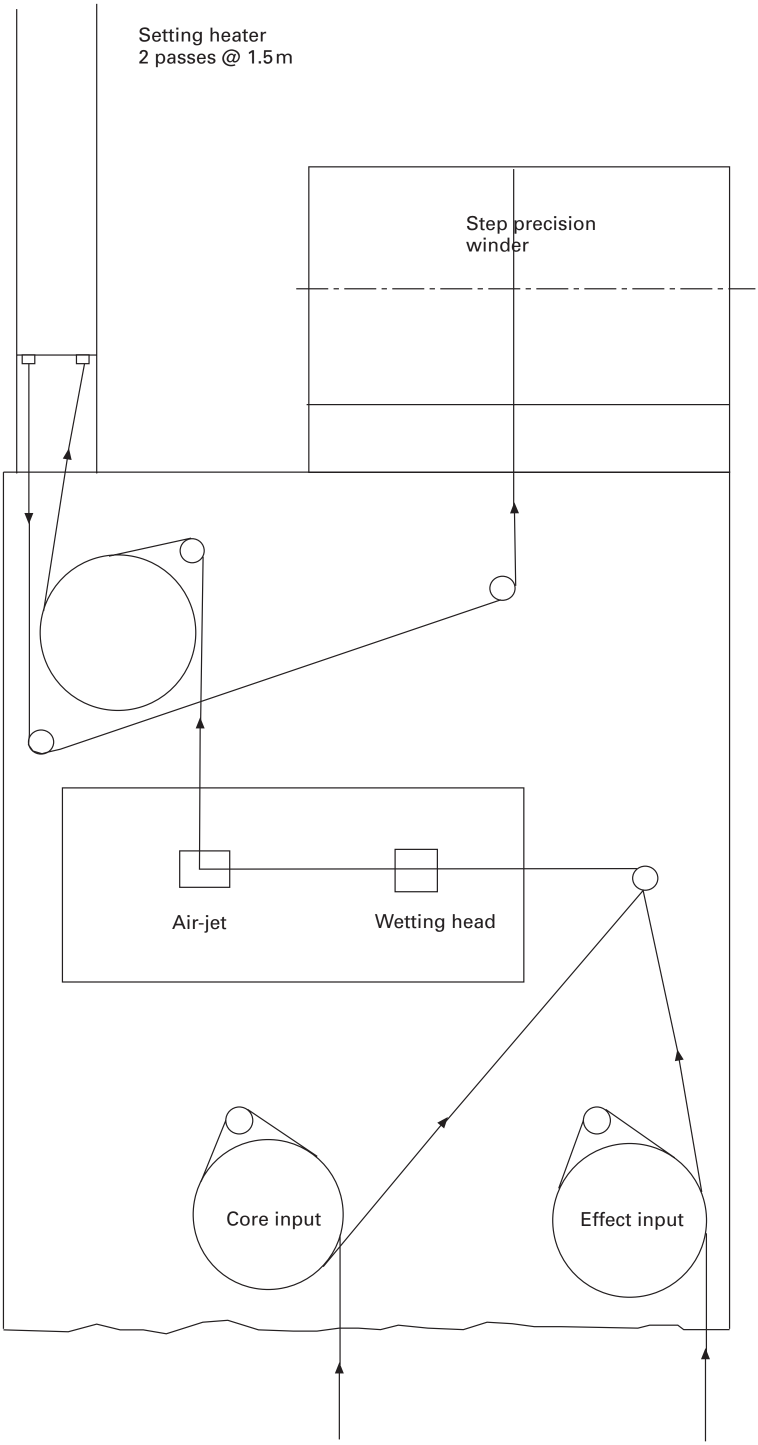
Machines such as the *SSM Stähle RMT-D* allow scope for fitting different optional heaters. Perhaps the two most common are long non-contact heaters and heated rolls. The long heater is placed above the machine as shown in Fig. 7.5 and this allows a double pass, thus effectively doubling its length. Heated rolls having 130mm diameter are also effective, though sometimes up to 20 yarn wraps are specified, which must make operating procedures a nightmare to check.

7.2.11 Coning oil application

The same techniques are used here as with false-twist texturing machines (see Section 4.2.11).

7.2.12 Take-up/package build

A lineshaft-driven, air-jet texturing machine is fitted with the same type of winding head as that fitted to the false-twist machine (see Sections 4.2.12 and 4.3.5). Automatic doffing is now generally available as an option. The individual-drive machine has been fitted with relatively simple winding heads in the past. The compensation for package build-up was by weights and the random wind combined with a slight variation built into the traverse cam was sufficient to avoid serious patterning. A major variation was the modification to allow the winding of conical packages. This is important for good unwinding of heavier furnishing yarns. Of course it requires a compromise, since the yarn is being textured at a constant speed and no cone winder with a friction drive can match this. It works, because the yarn (usually polypropylene) is textured with high



7.5 Air-jet texturing machine with setting heater. Courtesy of SSM.

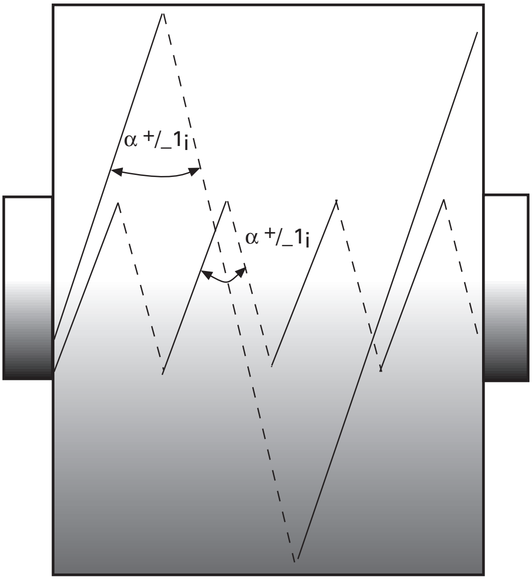
overfeeds and has a residual elasticity or stretch. Whatever the theory, very acceptable cones are produced for this segment of the industry with few problems.

Since the introduction of the *SSM Stähle RMT-D* with individual heads, a step precision-winder has been offered as an alternative (see Figs 7.2 and 7.3). The fact that each head is separate with its own winder and traversing mechanism means that the advantages offered by a precision-winder can be contemplated. The problem is that a conventional precision-winder maintains a constant wind angle, but not a constant winding speed, since the package is driven directly through the spindle.

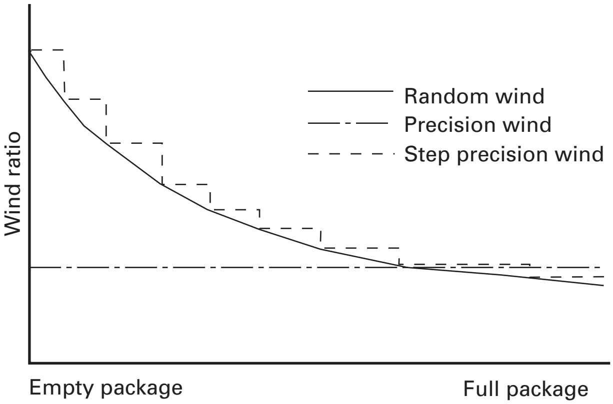
A step precision-winder is a compromise between a random but constant speed friction-drive winder and a precision-winder. Instead of the ratio between the winding and the traverse being fixed throughout the package build, it is varied in predetermined steps, as the name implies.

First, by changing the speed of the traverse relative to the constant winding speed, the number of windings per traverse length decreases whereas the crossing angle is the same at the end of the package wind as at the beginning (see Fig. 7.6). The reason why these changes take place stepwise rather than continuously is so that the regions where patterning is likely to occur, i.e. where the traverse lays each layer of yarn exactly on top of the previous one, can be avoided.

The advantages of this mechanism are:



7.6 Stepped precision wind – crossing angles. Courtesy of SSM.



7.7 Wind ratios – empty to full yarn package. Courtesy of SSM.

1 no patterning or ribbon zones;
2 higher and homogenous package density;
3 crossing angle can be optimised to give best unwinding characteristics;
4 unwinding tension variations at a minimum;
5 little or no danger of sloughing during unwinding;
6 leading to higher unwinding speeds.

The crossing angles at the start and finish of the package are shown in Fig. 7.6 and the variation of winds per revolution compared with the package diameter is shown graphically in Fig. 7.7.

Newer versions of the *Digicone* winder are fitted with the *Preciflex* traversing system. A stepper motor drives the traversing guide now. This not only eliminates the changing of gears or pulleys according to the package required but also facilitates the programming of the package build for any individual or collective winding position from the machine console. It also means that open or closed winding, straight or tapered packages and even unusual package shapes can be programmed and set at will. The only moving parts are the stepper motor and the drive belt and the only part that needs changing is the traverse guide itself. Even this change only occurs if there is a requirement for the winding of many heavier or finer yarns.

7.3 Process variables

7.3.1 Draw ratio

The draw ratio is the amount by which the yarn is stretched before entering the texturing zone. Therefore:

$$\text{draw ratio} = \frac{\text{shaft speed after draw-pin (m/min)}}{\text{imput shaft speed before draw-pin (m/min)}} \qquad [7.1]$$

This can be seen in Fig. 7.1. When two yarns are being processed the calculation has to be made separately for each input yarn.

Unlike the false-twist, draw-texturing process, the draw ratio is not the only parameter that influences the denier of the textured yarn, since this is also affected by the overfeed through the texturing jet and by subsequent stretching and relaxing.

The formation of loops during texturing means that the strength and elongation of the filaments, which both result from the draw ratio, have only a secondary influence on the properties of the textured yarn. Stretching and applying a load to an air-jet textured yarn initially will cause the loops to be pulled out. Only when the filaments have returned to the original untextured structure do they start to extend so that their properties show up in the load–extension diagram.

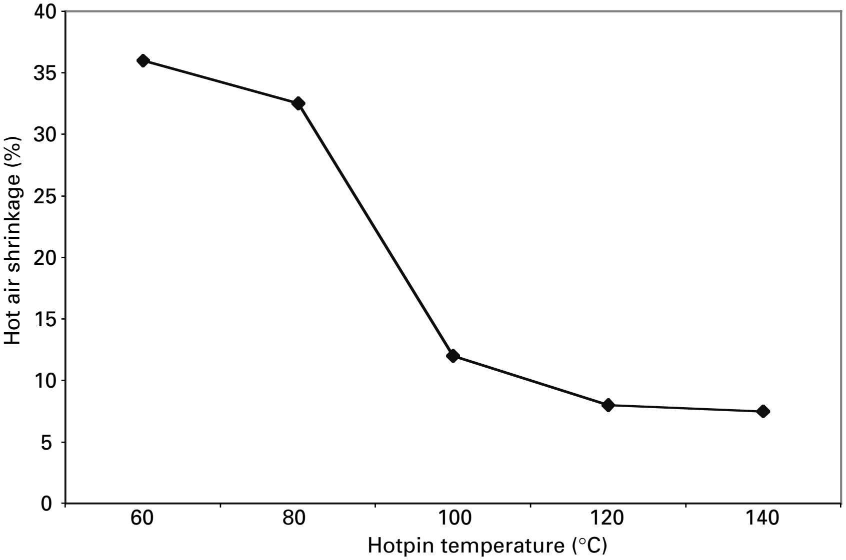
Draw ratio does affect levels of faults such as numbers of broken filaments (caused by a ratio that is too high). Underdrawing will produce a yarn that exhibits some plastic, i.e. non-elastic, stretch under load. This is sometimes done intentionally to produce a fabric which can be stretched into the shape of the seat for which it is intended.

The draw ratio has an influence upon the molecular orientation and hence the dye-uptake of the textured yarn. This influence is magnified if heat is applied during the drawing process. This is the case when hotpins are used for drawing polyester (as described in the following section).

7.3.2 Hotpin or draw-pin

Since the largest single market for air-jet textured yarns in Europe consists of yarns for car seat fabrics made from polyester, the process for making such yarn will be used as the basis for the following description of process variables. Polyester is widely available in the form of POY and therefore any texturing process suitable for this market has to include the means for drawing POY. The common practice is for a heated draw-pin or hotpin to be used when processing polyester. The pin is located between the first two rolls and provides a fixed draw point and a means of heating the POY to above its second-order glass transition temperature T_g which ranges from 70–100°C for polyethylene terephthalate (PET) (see Section 2.2.3).

Typical hotpin temperatures range from 135–160°C. This is higher than would be necessary to exceed the second-order transition temperature. However, air-jet texturing is basically a process that does not require heat. Sometimes the hotpin is the only source of heat and so is used to reduce the residual shrinkage of the textured polyester yarn by running at a higher



7.8 Variation of yarn shrinkage with hotpin temperature. Courtesy of Chemical Fibers International.

than normal temperature. The effect of hotpin temperature on the hot-air shrinkage of a drawn yarn is shown in Fig. 7.8.

Where hotpins are fitted, they can be used for other fibres such as nylon and polypropylene. Although nylon can be drawn cold, the use of a hotpin reduces the yarn tension during drawing from approximately 4 to 1 g/denier (dtex). Also if a coldpin is used it takes time for the pin to heat up as a result of the friction and the natural heat of drawing. Provision of a pin that is already heated will stabilise this situation and ensure that the same processing conditions apply immediately after a 'cold' start. If a heated draw-pin is provided on the machine, then it is usual for it to be used for nylon with a set-point of typically 80–100°C.

Polypropylene requires heat to assist the drawing process and a hotpin can be used to provide this. However, the heat generated by friction can both raise the yarn temperature too much and cause damage to it. Therefore, heated rolls are preferred for drawing polypropylene. This is not yet seen much in practice, since most continuous-filament polypropylene for texturing is produced by the spin-draw process and requires no further drawing. This may change as more polypropylene POY becomes available.

In general the blind application of draw ratios as specified by the feeder yarn supplier should be avoided. It is always preferable to establish the elongation properties of the POY by producing a load–extension diagram in the laboratory. This will enable a more appropriate draw ratio for the specific yarn to be determined and applied.

7.3.3 Yarn overfeed

7.3.3.1 Single and parallel yarn processing

The overfeed through the jet, which is approximately the same as the difference between the input feed and the speed at which the yarn is being removed from the jet, has a direct influence upon the bulk or specific volume of the yarn. The word approximate is used here, because the heat that may have been applied during the previous drawing process often leads to a delayed shrinkage or shortening of the yarn.

Since overfeeds applied during the air-jet texturing of single yarns are higher than those that were used in false-twist texturing (even before the advent of draw-texturing), there is also a direct and proportional increase in denier, which cannot be ignored. The formula that is used to calculate the final denier during air-jet texturing does not, unfortunately, take into account the possible shrinkage of the yarn as a result of heating during drawing and rapid cooling on reaching the expanding, and therefore cold air, inside the air-jet.

The formula is:

$$\text{Rdtex} = \text{core}(\text{dtex} \times n_\text{C} \times Of_\text{C}) + \text{effect}(\text{dtex} \times n_\text{E} \times Of_\text{E}) \qquad [7.2]$$

where Rdtex = final denier of the textured yarn, n_C = number of ends in core, Of_C = core overfeed expressed as an integer, n_E = number of ends in effect and Of_E = effect overfeed expressed as an integer.

As an example, if we are processing four ends of 300 denier (330 dtex) polypropylene, two each in the core and effect, the former with 15% overfeed and the latter with 80% overfeed:

$$\text{Rdtex} = (330 \times 2 \times 1.15) + (330 \times 2 \times 1.80) = \text{approx. } 1750 \text{ denier} (1950\,\text{dtex})$$

It must be remembered that this is an approximation. One reason for this has been given already. But polyester is usually drawn as part of the texturing process. Therefore the POY denier must be taken and be divided by the draw ratio (again, as an integer, see Section 4.3.1) to obtain the core and effect denier used in the above formula. Even with a drawn feeder yarn such as polypropylene, care must be taken to use the overall overfeed, taking into account the fact that some stretch is applied to the yarn after texturing. The gearing charts in most machine manuals enable the overall overfeed to be calculated, once the settings on the machine are known.

7.3.3.2 Core and effect yarn processing

Since two different yarns are being fed into the air-jet at the same time, the result of varying the overfeed when processing under core and effect conditions is more complex. By definition the core yarn overfeed is lower than that of the effect yarn. This means that the majority (but not all) of the filaments that comprise the 'core' yarn find themselves in the centre (core) of the textured yarn and those of the effect form the surface loops. Of course this distinction is not complete, since there is a considerable interchange or migration of position between the filaments. Indeed the textured yarn would not hold together, if this were not the case.

Changing the core yarn overfeed has a direct influence on the strength of the textured yarn, i.e. the breaking load, and also on the so-called stability. By stability is meant the resistance to removal of the loop structure under load. Since the core overfeed affects the length of the textured yarn, it has a major influence on the denier of the yarn. Core overfeeds usually range from 2–15%. The effect yarn overfeed determines the size of the loops. It also has an indirect influence upon the number of loops per unit length and also on the denier.

Perhaps the most important influence of the effect yarn overfeed is to be seen in the structure and appearance of the yarn, not only as an entity but also in the fabric. This is because loops are seen on the surface of the yarn in the same way that hairs are visible in a spun yarn of similar filament or fibre fineness. The loop structure together with the filament fineness also affects the frictional properties of the yarn (see below).

Effect yarn overfeed ranges from 15–150% and in exceptional cases can exceed 150%. The maximum overfeed is usually determined by the type of air-jet in use, the number of filaments present and the fact that a yarn with frequent large loops can be very difficult to process in certain fabric constructions.

7.3.4 Yarn wetting

The amount of water that is required has been shown to be very small. However, minimum practical levels of application range from 0.5–2.5 l/hr per jet. Of course the heavier the yarn, the more water is applied. These levels used to be approximately ten times higher until the introduction of reliable methods of metering small quantities of clean water to each head without the risk of the jet running dry. Many machines are still supplied from a header tank. Using a header tank alone makes the accurate adjustment of the water supply to each jet very difficult, both to set and to reproduce.

Water and spray is collected in the jet box and removed by means of a gravity drainage system. It should be remembered that this water contains pollutants washed from the yarn during processing, mostly of the oil-based type used in the spin finishes that are applied to the feeder yarns during the spinning process. Thus suitable precautions are required before this water can be reused or passed into the plant's effluent disposal system.

7.3.5 Air-texturing jet

7.3.5.1 Selection of jet

The first choice that has to be made concerns whether an axial or radial jet is more suitable for the process under development. Although radial jets were introduced for finer yarns than the original axial jets (largely for reasons of economy, since they were designed to consume less air), there is now a considerable range of yarns which can be produced using either type of jet. This range is from 500–5000 denier (550–5500 dtex).

The axial jet can be operated with considerably higher net overfeeds. The practice is to use core overfeeds in the range 4–20% to impart stability to the textured yarn. This enables the effect yarn to be overfed at up to, and in some cases over, 100%. Since the increase in denier is proportional to the average overfeed, it can be understood that yarns made using the axial jet are often bulky and voluminous. More will be written later about applications but in general it can be said that these bulky yarns are most suitable for furnishing fabrics including some of those used to cover car seats.

A typical example would be a yarn used widely for flat-woven, car seat fabrics and having a final textured denier of 1215 (1350 dtex) when prepared for weaving. This product is usually made from feeder yarns, which have a combined denier of only 750 (835 dtex) at the point of entry into the jet. This means that the total increase in denier is 60%.

However, caution should be used when deciding which overfeeds to set on the machine. Polyester yarns of this type are often wound as soft cheeses in preparation for package dyeing. Before dyeing they are steam-set in an autoclave. In the autoclave the yarn is allowed to shrink and this contributes around 10% to the increase in denier.

Radial jets are used where lower total overfeeds are required and where high processing speeds are desirable. This would be the case where the input and final yarns are closer in denier, when the total denier is below 700 (<770 dtex) or where a smooth yarn with small regular loops is required. Not only must the total overfeed through the radial type of jet be kept below 40% but also the difference between the core-and-effect overfeeds should not exceed 30%.

7.3.5.2 Jet material

The jet cores of a radial jet are made from sintered material. This material is either high-grade ceramic or tungsten carbide. Sintered titanium carbide has also been used. There is no easy way of determining which material to choose. Because the yarn is lubricated during spinning and wetted before entering the jet, the friction between the wall of the jet and the yarn does not appear to exert a great influence upon texturing performance. However, there does seem to be a link between water quality, i.e. hardness and constituency, and the texturing performance. Furthermore the spin finish applied and the water quality interact and can have a strong influence on jet cleaning cycles. All things being equal the jet material that has the greatest resistance to wear should be chosen. This would be a high-grade ceramic material in most cases. It may be necessary either to conduct trials with different materials or to ask the yarn and/or the jet supplier whether experience of the yarns to be processed in the chosen locality indicates a preference for a specific jet material.

Axial jets have not hitherto been offered in alternative materials to the same extent as radial jets. Nevertheless there is a variety of materials in different jets. The venturi can be made from either sintered metal or ceramic material. Also the needles are supplied with both ceramic and sapphire inserts at the tip and even without any insert at all for yarn materials such as glass fibre.

These choices need to be made when the type and size of jet is specified. If problems arise which appear to be related to the material used in the jet it is necessary to discuss alternatives with the jet supplier.

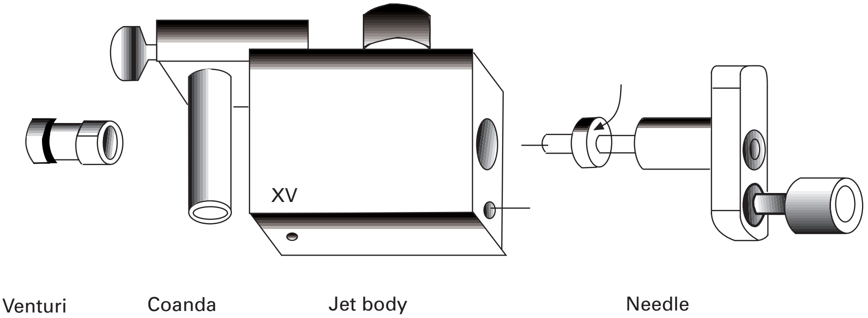
7.3.5.3 Size of jet

Since most types of jet have no adjustment, selection of the correct size is important. However, the ranges given in the jet manufacturers' data sheets must be treated only as a guide. Whereas it is obvious that a yarn with a total denier which is too high for a given size of jet cannot be forced through it, there are circumstances when the use of a larger than normal jet can be beneficial. An example is a yarn which has particularly stiff filaments, due either to the material or the diameter or cross-section of the filament. In this case the extra energy which can be generated in a larger jet may help to achieve a stable and well-integrated textured yarn.

In determining which size of jet to use, it is important to note the large differences in specific volume of different yarn materials. The highest volume and therefore the largest yarn channels are required for polypropylene. Glass fibre yarns have the highest density. Table 7.1 shows the densities of the yarns which are most commonly processed using air

Table 7.1 Density of fibre materials for air-jet texturing. Courtesy of British Textile Technology Group (BTTG)

Material	Density (g/cm^3)
Glass Fibre	2.50
Cellulosics	1.53–1.32
Polyester	1.38
Polyamides	1.18–1.17
Polyolefins	0.93–0.90



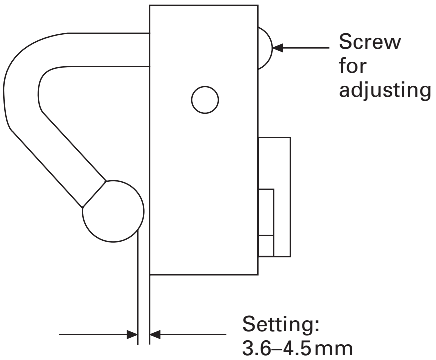
7.9 Type XV axial jet components. Courtesy of Heberlein Fiber Technology Inc.

jets. Some jet data sheets clearly specify different jet sizes for different materials.

7.3.5.4 Jet Baffles

Although most types of jet offer no adjustments during production, there are two factors, which need to be considered:

1 First, the distance or size of the jet baffle does vary with the yarn to be processed. *Taslan* ® jets employ a baffle device known as a coanda bar at the point where the yarn leaves the jet (this can be seen in Fig. 7.9). Coanda bars are available with two different diameters, namely 3/8″ (9.5 mm) and 15/32″ (12.0 mm). The *Heberlein* axial jet baffle comes in only one size and with one setting. Radial jets can be supplied with or without baffles but are fitted with them for all but the coarsest yarns. These baffles have three settings, which depend upon quite wide ranges of yarn and are preset in the user's workshop using feeler gauges. The



7.10 Setting of baffle on air-texturing jet. Courtesy of Heberlein Fiber Technology Inc.

method of setting using the adjusting screw and feeler gauges can be seen in Fig. 7.10.

2 The second factor is the orientation of the jet with respect to the yarns, both entering and leaving the jet. Both types of texturing jet function in part as a result of the yarn being drawn out of the jet at 90° to the main yarn axis through the jet. It is this fact, combined with the yarn overfeed through the jet, that facilitates loop formation.

However, the angles at which the yarns enter the jet are also important. This is especially relevant when core and effect yarn overfeeds differ greatly. The net effect is that the core and effect yarns enter the jet with different velocities (observe the surface speeds of the respective input feed rolls). It is therefore desirable to keep them separate for as long as possible, even after they enter the yarn channel within the jet. Guides located either in the jet box or on the jet housing facilitate this. Both these input and output angles were shown clearly in Fig. 7.4.

Jet manufacturers and the suppliers of machines collaborate to ensure that these angles are correct. However, the manuals should be consulted when changing jet type, in order to find out whether any changes to the yarn guiding and jet orientation are necessary.

7.3.6 Mechanical stabilisation

Rather like tightening a knot in shoelaces by pulling, the stability of an air-jet textured yarn is improved considerably by stretching after the texturing zone. Incorporating at least two yarn feed units after the jet box does this. The ratio is set to suit the yarn. The higher the (core) overfeed the greater will be the effect of stretching upon the yarn stability. In practice the stretch will range between 2 and 10%. Heat may be applied within the mechanical stabilisation zone as a means of inducing tension in the yarn.

7.3.7 Heat-setting

Air-jet textured yarns are much denser than false-twist textured yarns of the same denier and therefore the effect of heat-setting is not so noticeable in the end product. Nevertheless the effect of applying heat means that overfeeds of up to 10% are used, depending upon the residual shrinkage of the textured yarn. The applied overfeed has to be 'absorbed' by the shrinkage of the yarn or else the process would break down. Apart from this, much of the information contained in Section 5.3.5 applies here.

The alternative heaters available for the *SSM-Stähle* machine are described above in Section 7.2.10. The choice between these different heaters and no heater depends upon the purpose for which the textured yarn is intended. In many cases polyester is dyed as a yarn on the package. To ensure even dye penetration it is important that no further yarn shrinkage takes place during dyeing. This is achieved by steaming the textured yarn in an autoclave for approximately 20 minutes at about 130°C. Since this is extremely effective in reducing the residual shrinkage of the yarn to below 1% (measured in hot air at 180°C) there has been no rush to complicate the texturing machine by adding optional heaters and consuming an extra 1–2 kW of power. However, newer machines are being fitted with heated rolls immediately before the jet for both the core and effect yarns. These do reduce the residual shrinkage of polyester yarns significantly. Furthermore they can be used in place of hotpins provided that the draw zone is capable of withstanding the higher tensions that result from cold drawing.

Polypropylene is rarely heat-set on the texturing machine, though for different reasons. There has simply been no perceived benefit for a yarn which usually goes directly from texturing to weaving. Polypropylene has a low melting-point of around 160°C which means that severe heat treatment is impossible.

Sewing threads based on air-jet textured yarns present a different problem. Although these yarns are also dyed, there is no opportunity to build a softly wound package suitable for autoclaving during the texturing process, because of the need to twist the yarn. Therefore it is desirable to reduce the shrinkage of the yarn to below 1% by some other means, preferably during the draw-texturing process. It is here that the heated roll or godet has been applied successfully, in conjunction with the use of hotpins and sometimes also hotplates before texturing. This is because the residual shrinkage of polyester yarns can be reduced step by step. In other words the effect is cumulative.

7.3.8 Yarn lubrication and package build

Most of the information contained in Section 4.3.5 applies equally to air-jet textured yarns. Since the yarn has a much lower stretch (elongation) the take-up overfeeds applied are lower. Methods of applying lubricant to the yarn and varying the quantity are identical to those for false-twist textured yarns.

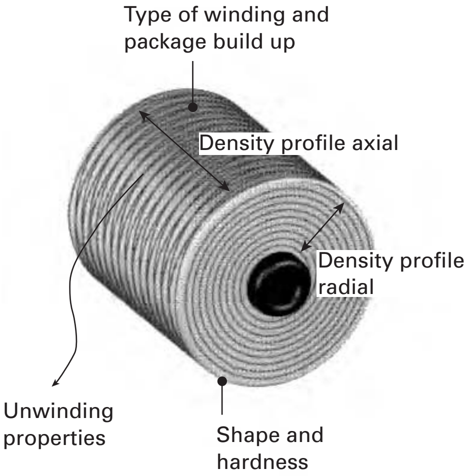
The winding of soft packages of air-jet textured yarns prepared for the autoclave and for package dyeing presents a different set of challenges. If the residual shrinkage is high at the point of winding the yarn coils within the package are compressed during the steaming process. This causes density variation from the inside to the outside of the textured yarn package that can cause unacceptable differences in dye-uptake.

In earlier times the only countermeasure which was found to be effective was to even out the winding tension variation as far as possible by using a long thread-path from the last yarn feed unit to the winding head. An element of tension compensation has also been added, bringing with it a marginal improvement. This step has been taken to its ultimate limit on some machines by using a yarn storage feeder placed between the last driven yarn feed unit and the winder. This effectively ensures a constant winding tension apart from some variation caused by the traversing motion.

Another effective countermeasure has been the employment of a step precision-winding head (see Section 7.2.12). Since precision winding can produce an open or closed type of wind, it is obviously the former that is selected. The setting of the winding parameters has been greatly simplified since the introduction of the *Preciflex* winding head. The selection of these settings and the principle of the *Preciflex* winding head can be seen in Fig. 7.11.

Apart from the use of step precision winding most of what has been written about package dye yarns in Chapter 5 applies to air-jet textured yarns. Compressible tubes are usually employed. However, air-jet textured yarns for package dyeing are normally wound with a zero taper angle, i.e. as a cylindrical package (straight-sided cheese).

Some air-jet texturing machines are provided with winding heads which produce random-wind, conical packages. This applies especially to textured polypropylene yarns destined for woven furnishing fabrics. Such yarns are produced using high effect overfeeds of up to 100%. This can present unwinding problems especially from cylindrical packages. On the other hand these yarns are also produced with sufficiently high core overfeeds to allow the winding of conical packages. This is because the resulting textured yarn has a higher degree of stretch or elasticity compared with other air-jet textured yarns.



7.11 Preciflex – setting parameters. Courtesy of SSM.

7.4 Air-jet textured yarns

7.4.1 Yarn form

Whereas false-twist textured yarns fall into two main groups, namely textured polyester and nylon (with polypropylene as an outsider) and BCF yarns are made either from nylon or polypropylene, but destined for one market, air-jet textured yarns are very diverse. To quote from the respective catalogues, one can buy an *SSM-Stähle* air-jet texturing machine (the latest model being the *DP2-T*) capable of use with a wide range of yarns from 50–5000 dtex (even coarser, as far as glass fibre yarns are concerned). From the *Heberlein* jet data sheets it is possible to select five jets (four of these are radial and fit into the same housing) and the whole of this range of yarns can be covered from one installation.

To cover this wide range in one chapter, it is necessary to look at three groups, with a fourth as an extra:

1 fine air-jet textured nylon for woven and knitted fabrics;
2 medium air-jet textured polyester for woven and knitted fabrics (automotive applications);
3 medium to coarse air-jet textured polypropylene for woven furnishing fabrics;
4 polyester air-jet textured sewing threads.

Table 7.2 shows the range of end uses for which air-jet textured yarns are produced. It also shows the characteristics of the air-jet textured yarn which

Table 7.2 Air-jet textured yarn properties and applications. Courtesy of Heberlein Fiber Technology Inc.

Property	Application	Remarks
Low friction character	Sewing thread	By means of protruding loops: * cooler needle * lower needle friction * good cover
Spun yarn	Sports and leisurewear	* mainly nylon and polyester
	Car seat cover	* from polyester POY
	Interior furnishing	* mainly polypropylene
	Outerwear	* mainly nylon *with* polyester * with raised surface
High friction	Skiwear, tablecloth Bed sheeting Belts and straps Luggage, rucksacks	* slip resistance
Dimensional stability	Tarpaulin Coated fabric Tyre fabric chafer Printed circuit	
Blended yarns	Composites comprising: * different fibre materials * coarse and fine filaments * yarns with different properties * heather effects (spun-dyed) * combinations of these	
Structural effects	Curtains Wall coverings	* variable texture * flame resistant i.e. glass fibre
Functional wear	Rain and sportswear Leisurewear Sports underwear	* microfilament * double layer fabric from wicking yarns

make it suitable for each of the applications. These desirable characteristics should be borne in mind when deciding the specification of the yarn to be produced.

7.4.2 Yarn designation

The fact that many air-jet textured yarns are made from core and effect feeder yarns that are not necessarily the same, slightly complicates the search for a clear and agreed method of designating the yarns. *Heberlein* suggest the following in their jet manuals:

1 a single yarn has no symbol or × 1
e.g. PES (for polyester) 167 dtex 64 fils;
2 a parallel yarn (which means two or more yarns with the same speed into the jet, e.g. PP (for polypropylene) 330 dtex 47 fils × 3 (ends);
3 a core/effect yarn (which means that the core yarn and the effect yarn are fed into the jet at different speeds), e.g. PA 66 (for nylon 66) 78 dtex 34 fils + PA 66 78 dtex 51 fils.

Clearly the other designations mentioned in Section 5.2 can also be used. The main point is to use the + sign to separate the core yarn from the effect yarn, when designating the make-up of the yarn.

There is as yet no agreed method of describing whether a yarn has been stabilised or heat-set after texturing. Nor is the drawing process (if used) indicated in the product designation. Add to this the facts that polypropylene is still often referred to in terms of denier and that glass fibre yarns and finished sewing threads both have their own 'count systems' and the problems of achieving clarity multiply. One can only recommend that yarn conversion tables are kept handy!

7.4.3 Air-jet textured nylon for weaving

Textured nylon for skiwear was the first market for weft yarns made by the air-jet texturing process. Previously the process economics made it economical only for yarns over 300 denier (350 dtex) destined for furnishing fabrics. The breakthrough came as a result of new jets and machines which enabled processing speeds of over 300 m/min to be reached. That the yarns were still limited to weft applications was a result of the tendency of the loops of adjacent yarns to cling to each other. This is known as the *Velcro*™ effect. This effect caused problems during unwinding, which caused some limitation of weft insertion rates and also made the use of these yarns in warps problematical without sizing or twisting.

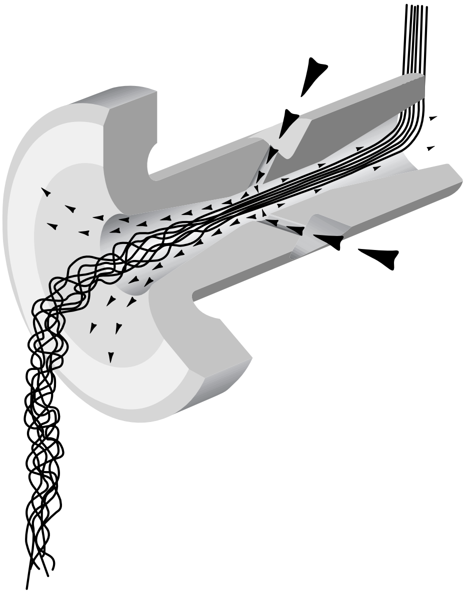
These limitations no longer exist. First, the yarn manufacturers have contributed by introducing nylon yarns with lower filament denier. Whereas originally the finest nylon yarns had a filament denier of around two, now the average is lower with filaments of one denier and even finer being available. Secondly, the use of storage feeders such as the unit made by *Memminger-IRO* on the weaving or knitting machine, has enabled the unwinding problems to be overcome. Last but not least, the modern air-jet texturing machine is fitted with step precision winders, as we have seen (see Section 7.2.12) and these enable packages with much improved unwinding characteristics to be produced.

This has not only enabled woven fabrics to be made from 100% air-jet textured yarns, but also that the breakthrough into knitting has been achieved. Spun-like characteristics are desirable but so also is the ability to blend easily yarns with different properties, including dye uptake, during texturing.

Modern machines are fitted with hotpins or heated godets for drawing POY. This is used to advantage when processing nylon. Not only are lower draw tensions obtained, but also a better, more uniform yarn results from the consistency of the draw-pin temperature.

For producing a typical, air-jet textured nylon yarn with a final count of 190 dtex either a lineshaft (*ICBT*) or individual drive machine (*Stähle*) can be used. A step precision or similarly adjustable winding head is an advantage. Drawing zones fitted with draw-pins are required with the addition of a hotpin considered as a bonus. The air-jet should be of the radial type, typically a jet designated *S 315* from *Heberlein* (see Fig. 7.12).

Two different nylon yarns or even a combination of nylon with polyester will be processed under conditions of core and effect. The yarn component with the finer filament denier would normally be processed as the effect component, so that the loops have a softer feel with a significantly reduced tendency to snag. An example of the set-up is given in Table 7.3.



7.12 Air-jet – 'S'–core for high speed processing. Courtesy of Heberlein Fiber Technology Inc.

Table 7.3 Set-up for air-jet textured polyamide for woven fabric. Courtesy of Heberlein Fiber Technology Inc

Texturing	Units	
Jet type		Heberlein radial
Jet size		S315
Pressure	bar	9.0
Yarn wetting	l/hr	1.0
Drawing		
Draw roll – core	m/min	896
Input roll	m/min	728
Draw ratio		1.23
Hotpin	°C	100
Draw roll – effect	m/min	1040
Input roll	m/min	845
Draw ratio		1.23
Hotpin	°C	100
Texturing zone		
Core overfeed	%	12
Core input	m/min	896
Effect overfeed	%	30
Effect input	m/min	1040
Roll after jet	m/min	800
Stabilisation		
Second roll after jet	m/min	816
	%	2
Heat-setting zone		
Roll before take up	m/min	808
	%	−1
Heater type/temperature	°C	200
Take-up		
Winder	m/min	816
	%	1
End product		
Core	Material/dtex	PA66/96/66 × 1
Effect	Material/dtex	PA66/96/66 × 1
Final	Material/dtex	PA66/185/132

7.4.4 Air-jet textured polyester for automotive products

As far as the interior furnishing of the car is concerned (seat covers, seat backs, door and roof liners) polyester predominates in the medium price category of vehicle. Although air-jet textured yarns have been used in all of these areas, it is the seat cover for which the properties of textured polyester are ideal. Although not the subject of this textbook it is first and foremost the dyeing of the polyester combined with the abrasion resistance of the fabric that make the product very suitable for this application. Car seats are subject to heat, intensely bright sunlight (in some parts of the world) and a lot of wear and tear. Air-jet textured yarns, especially made from polyester, have been shown to meet these demands and at a competitive price. They form by far the largest single market for air-jet textured yarns in Europe (Bösch, 2000).

What is more, the process shows its versatility in that yarns are made for flat woven, warp and circular knit fabrics. Both parallel and core/effect texturing processes are used. Which type of machine will depend mainly on the product denier range. Above all, most of the yarns are dyed on the package, in order to meet the demand. This brings its own problems:

1. A step precision winder is essential in order to ensure the open windings required for good dye penetration (see Fig. 7.11).
2. Tension variations during winding will affect the package build, since air-jet textured yarns do not have much stretch.
3. Any residual shrinkage after texturing will lead to actual shrinkage during steaming in the autoclave. This can affect the density from the inside to the outside of the package and lead to variable dye uptake.
4. The loops can cause yarns on adjacent packages to snag, leading to damaged filaments.

Some of these problems are overcome by choosing the correct machine specification, namely 1 and 2. The residual shrinkage can be reduced by using a higher hotpin temperature in the draw zone (see Section 7.3.2) or by using a heated roll before the jet. Although attempts have been made to heat-set the yarn after texturing but before autoclaving, this is not yet widely practised. Depending on the type of post-texturing heater chosen, the reasons for this are different. If a non-contact heater is chosen, this needs to have a length of 1.5 m and should incorporate two passes of the heater. It adds as much as 1.5–2.0 m to the height of what is otherwise a compact and accessible machine (see Fig. 7.5). Furthermore it may still not provide a significant reduction in the residual shrinkage of the yarn. Using a heated roll after the jet requires between 10 and 20 wraps and tends to iron the yarn flat. It then has a ribbon-like structure, which does not always have the desired appearance in fabric.

Wrapping each cheese in a muslin or plastic sleeve with perforations can prevent snagging of the yarn on different packages. This holds in the loops whilst allowing the dye to penetrate fully.

Perhaps the best example of the process is the one that is used to make yarn for flat woven fabrics. The yarn is produced from POY and processed under core/effect conditions, although sometimes parallel processing is used for yarn under 700 denier (800 dtex). One or more ends of POY may be spun-dyed to enhance the colour effect produced. An example of the set-up for polyester with a resultant denier of 1235 (1350 dtex) is given in Table 7.4.

7.4.5 Polypropylene for furnishing fabric

Of the air-jet texturing processes described here, this is the simplest, since most polypropylene for furnishing end uses is produced using the spin-draw process and requires no further drawing before texturing. The problems arise from other sources. First, the feeder yarn is inevitably dyed in the melt (see Section 6.3.2). Up to six ends may be placed in the creel at one time, which means that detection of broken or lost ends in the creel is essential. For a process that depends so much on interfilament friction within the jet, the fact that the pigments used to produce a range of colours impart different frictional characteristics to the filaments causes some problems that are unique to this process.

Many of these problems are manifest in the jet itself. Earlier jets of the axial type were adjustable, in that the distance between the needle tip and the cone of the venturi could be varied (see Fig. 7.9). It is no coincidence that this type of jet, epitomised by the *Taslan ® Mark XV* jet, is still in widespread use in this segment of the yarn processing industry. Putting it another way, those that do use the fixed jet, usually of the radial type and for finer yarns of less than 700 denier (<770 dtex), have a struggle to produce yarns with the same characteristics from feeder yarns of all colours and combinations. Furthermore the mixture of pigment, polymer and spin finish that is deposited rapidly inside the jet means that cleaning must be more frequent and thorough.

Polypropylene yarns used in furnishing fabrics have a filament denier in the range from four to six. Since the effect overfeeds can be very high, snagging problems can occur. It is for this reason that the texturing machines used are fitted with a conical wind attachment. An example of the machine settings that can be used for producing a yarn of 1500 denier (1650 dtex) from spun-dyed polypropylene is given in Table 7.5.

Table 7.4 Set-up for air-jet textured polyester for automotive fabric. Courtesy of Heberlein Fiber Technology Inc.

Texturing	Units	
Jet type		Heberlein EO52
Jet size		N70/V180
Pressure	bar	9
Yarn wetting	l/hr	1.5
Drawing		
Draw roll – core	m/min	339
Input roll	m/min	199
Draw ratio		1.7
Hotpin	°C	140
Draw roll – effect	m/min	600
Input roll	m/min	353
Draw ratio		1.7
Hotpin	°C	140
Texturing zone		
Core overfeed	%	13
	m/min	339
Effect overfeed	%	100
	m/min	600
Jet input roll	m/min	300
Stabilisation		
Roll after jet	m/min	324
	%	8
Heat-setting zone		
Roll before take up	m/min	317.5
	%	–2
Heater type/temperature	°C	1.5 M/220
Take-up		
Winder	m/min	333
	%	5
End product		
Core	Material/dtex	PET (POY) 285/30 × 2
Effect	Material/dtex	PET (POY) 285/72 × 3
Final	Material/dtex	1235/276

Table 7.5 Set-up for air-jet textured polypropylene for furnishings. Courtesy of Heberlein Fiber Technology Inc.

Texturing	Units	
Jet type		*Taslan*™ Mk XV
Jet size		Needle 40C Venturi 78
Pressure	bar	9.5
Yarn wetting	l/hr	2.0
Texturing zone		
Core overfeed	%	14
	m/min	285
Effect overfeed	%	36
	m/min	340
Jet input roll	m/min	250
Heat-setting zone		
Roll before take up	m/min	252
	%	1
Heater type/temperature	°C	150
Take up		
Winder	m/min	273
	%	8
End product		
Core	Material/dtex	PP 330/74 × 2 spun dyed
Effect	Material/dtex	PP 330/74 × 2 spun dyed
Final	Material/dtex	PP 1500/296 heather effect

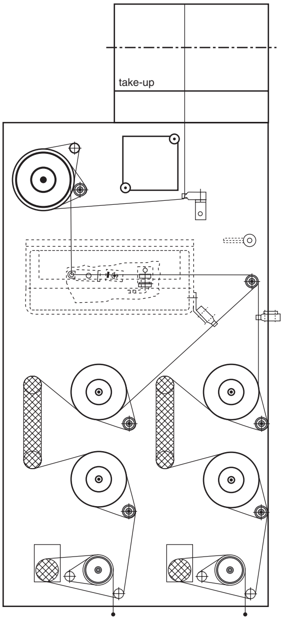
7.4.6 Polyester sewing threads

This is a very specialised area of yarn production where air-jet textured yarns and the thread resulting from them have shown considerable promise if not yet success on a large scale. When ranking sewing threads for performance air-jet textured products are ranked probably second or third with core-spun polyester/cotton at the top. In fact the air-jet textured product has superior tensile strength, when measured as specific strength or tenacity. It also has an excellent abrasion resistance and because of the surface loop structure it allows sewing at over 6000 stitches/min without melting or breaking.

Two things have probably hindered their large-scale acceptance so far. The textured yarn still requires the addition of real twist before dyeing and spooling. Thus the large package size potential of a texturing process starting from POY is spoiled by the need to restrict the textured yarn package to that which fits into the two-for-one twister. This means that the potential cost savings are reduced and perhaps are no longer sufficient, when considering the whole process chain from raw material to finished thread. However, this problem will be overcome and then a real cost saving will have been achieved as well as a reduction in labour cost by the application of automation. This is important where it is hard to find people willing to work shifts or weekends.

An interesting factor that warrants a study of the air-jet texturing of yarns is that almost all the methods of applying heat to the process are utilised. In order to retain yarn strength at the same time as to reduce the residual yarn shrinkage to below 1%, heat is applied in a different way to the core and to the effect thread:

1 The core yarn denier should comprise well over two thirds of the total and the core overfeed into the jet must be as low as is practicable. Both



7.13 Air-jet texturing machine for making sewing threads. Courtesy of SSM.

these steps contribute to minimising the loss of tenacity between the feeder and the final textured yarn.

2 The effect yarn is there only to provide a very subdued loop structure. Thus it comprises a feeder yarn of lower total and filament denier. Although the overfeed through the jet may be >25% the yarn is not preshrunk. Instead a heated roll is used after the jet. The temperature used combined with the dwell time on the heated roll (determined by the number of wraps) are sufficient to cause the loops to shrink into the core of the yarn, leaving what the *Coats* patent describes as 'bud-like projections' on the surface. These are sufficient to impart an enhanced sewing performance to the finished product.

The thread-path of a machine suitable for producing these yarns is shown in Fig. 7.13. The processes involved are the subject of several patents of which the most important by *Coats* (1981) is still valid at the time of writing. So it is a question of 'user beware'!

8

Quality assurance

8.1 Introduction

In any manufacturing environment it is essential that there should be some form of quality assurance system in place, not only to protect the customer from receiving faulty goods, but also of equal importance to protect the manufacturer from spurious claims against his produce.

As a prerequisite to any worthwhile quality assurance testing schedule it is essential that all methods of testing have clear written standards. Equally, if not more important, is that all operatives engaged in the testing and measurement of these parameters are adequately trained and that all are of a comparable standard.

In a complete quality management system this would ensure that all incoming goods as well as outgoing goods have some form of documented quality procedure and records of tests determined by these procedures maintained. Some checks that may form part of the testing regime are described below.

8.2 Raw materials

The term ‘raw materials’ is very broad. In a manufacturing environment it must be taken to mean more than just the properties of the POY used as feedstock for the texturing process. The various machine components that are wear items and on whose quality the maintenance of the machine in good order depends, must also be considered. Ancillary items such as tubes, interlace jets, coning oil and packaging should be routinely inspected. The quality of the services provided at the manufacturing plant such as water, compressed air and electrical power supply should also be considered as raw materials and reviewed as such.

8.2.1 Machine components and ancillaries

In the majority of cases replacement machine components may be purchased from the original manufacturer. However, in today’s economic climate more and more items are being purchased from specialist component suppliers at reduced cost. Though these are usually reputable, the prudent textile technologist will have a system whereby an objective measure of the supplier's performance can be made. This can take the form of a simple assessment of the ability to supply components on time and at economic cost. Alternatively the incoming goods themselves may be tested against a standard previously agreed between supplier and consumer. It may not be possible to perform any meaningful testing on some components delivered owing to limited time and resources. In this case some arrangement for the return of and compensation for faulty goods must be agreed.

One item that can be simply checked and is of vital importance to the viability of the product is the tube on which the textured yarn is wound (see Section 4.3.7). It is very easy to set up a system whereby tubes can be checked for weight, dimensions and concentricity. All of these are important for reasons of correct shipping weights and elimination of package build problems caused by poor tube manufacturing tolerances.

8.2.2 POY feedstock

The quality of the feedstock employed in the draw-texturing process is of fundamental importance; if this is not of first-rate quality then no amount of changes to the parameters at which the textured yarn is produced can compensate.

All of the following are prime requirements of the POY and must be both within specification and consistent:

1. yarn denier (linear density);
2. uniform linear density (U%);
3. number of filaments present;
4. lustre (titanium dioxide content);
5. spin finish level;
6. molecular orientation;
7. tensile properties;
8. filament cross-section uniformity;
9. freedom from package build faults;
10. Package identification.

With the exception of 2, 5, 6 and 7, all of these can be simply and cheaply tested with a reasonable degree of accuracy in a moderately well-equipped laboratory, or in some cases in the POY marshalling area. Tests for the uniformity of linear density ('*Uster*' value, known universally as the U%), molecular orientation and tensile properties require the use of more sophisticated and expensive equipment.

Though this book is not intended as a reference on testing of materials, it is worthwhile briefly considering how these test procedures can be carried out. Guidelines for the testing of and tolerances for these parameters are discussed below.

8.2.2.1 Denier

Denier is defined as the weight in grams of 9000 m of fibre or filament and is a unit of linear density or mass per unit length. The standard unit of denier is the tex; this is the unit that should be used for all yarns. The tex is the mass in grams of one kilometre of the product. The decitex (dtex) unit is more convenient and avoids the use of the decimal point for the finer-filament yarns. It is the tex count multiplied by ten. In fact there is widespread use of both decitex and denier throughout the texturing industries. Denier is more commonly used in the USA and Japan and for polypropylene yarns in wide areas of the world.

The decitex of a yarn can be easily and routinely checked with the use of a wrap reel having a circumference of 1 m and a balance capable of weighing accurately to four decimal places. The decitex of the POY is calculated by wrapping a skein of 100 m of yarn and weighing it. To obtain the result in units of decitex the weight in grams is multiplied by 1000. For end uses in apparel, upholstery and automotive markets denier tolerances of not greater than ±1% are desirable.

8.2.2.2 Uniformity of denier

This is a measure of the mass variability per unit length of yarn. The unit of measure is U%, which is a unit in use throughout the textile industry and is statistically equivalent to the percentage mean deviation. The test is based upon a system whereby yarn is passed at constant speed through a capacitance cell. The changes in capacitance seen are represented on a chart as the U% value. The change in capacitance, recorded by the tester, can be directly related to the mass of the fibre within the measuring cell. For textile operations the U% value of the POY should ideally be <0.8%.

8.2.2.3 Number of filaments

The number of filaments present is directly related to the denier of the yarn. If filaments are missing due to problems during extrusion, it may be possible to determine this from a low denier measurement. However, if this method is not available there is no alternative but to count the number of filaments in the yarn bundle. POY with low filament count may also be detected on the texturing machine by use of on-line monitoring (see Section 8.3.1.2). The yarn tension will be lower than expected.

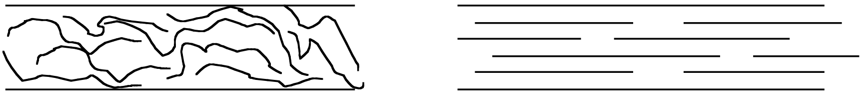
8.2.2.4 Lustre

The consistency of the lustre of the POY is determined by the homogeneity of the polymer. If the polymerisation and extrusion processes are carefully controlled and sufficient blending and mixing has taken place, this should not be an issue. If, however, there is a problem during these stages of the process, it may sometimes be seen on the sides of the POY package, either as a mottled appearance or as discrete bands of varying lustre. These visual checks are the only ones that can be made without the use of sophisticated and expensive test equipment, but they may nonetheless be sufficient for a problem to be identified. Obviously such an occurrence will lead to apparent shade differences when dyed, and as such, any packages found must be segregated before being placed in the texturing machine creel.

8.2.2.5 Spin finish level

Spin finish is the lubricant applied to the POY during the extrusion process. The lubricant is usually applied as an emulsion in water by a metered system. The spin finish has two important roles to play. Not only must it impart the correct frictional properties to allow for the formation of a POY package free from winding faults, but it must also offer sufficient protection to the filaments to allow them to survive the draw-texturing process without sustaining damage. As these two requirements are to an extent contradictory, the choice of lubricant and its uniform application at the correct level are of vital importance for the efficient processing of the yarn on the texturing machine.

Spin finish level may be determined by traditional soxhlet extraction using a suitable solvent such as petroleum ether or it may be determined by the infrared analysis of specific carbon groupings. In this case a calibration must first be carried out with samples of known concentration. Both of these methods will give an accurate determination of the overall level of spin finish applied to the filaments. Levels of the order of 0.2–0.5% by weight of yarn are usual for texturing applications. The measurement of the uniformity of application along the length of the yarn is more difficult. However, it may be determined by examination of U% charts (see above) Since these are capacitance based the level of moisture present from the applied emulsion will have a discernible effect. Alternatively, non-uniform application can be determined from the tension traces generated by on-line monitoring systems on the texturing machine itself (see Section 8.3.1.2).



Orientation in POY as spun

Orientation in fully drawn yarn

8.1. Orientation in POY and drawn yarn.

During the production of BCF yarns the level of finish applied is measured using a technique called nuclear magnetic resonance. By this means the level can be measured either in-line using a hand-held instrument or in the laboratory. Both require calibration and the former is used mainly for comparative checking.

8.2.2.6 Molecular orientation

The orientation of the molecules in the POY is a measure of the degree to which the individual polymer chains are aligned along the main axis of the filament. When spun as POY this alignment of the polymer chains is somewhat haphazard. The action of drawing brings the polymer chains into greater alignment (see Fig. 8.1).

The degree of orientation, sometimes referred to as draw-force, a reference to the degree of force applied to the POY to extend it by a predetermined amount, has a significant effect upon how the POY will process on the texturing machine. In particular it will greatly affect the processing tensions and dye uptake of the yarn. The degree of orientation in the fibre is influenced by conditions during the extrusion process; in particular the temperature at which the filaments are extruded, the draw-down of the filaments from the extrusion head to the winder and the quench conditions applied to the extruded filaments to cool them.

One instrument that can be used to measure the degree of orientation present in POY is the *Dynafil* manufactured by *Textechno*. The orientation can be measured by a system whereby heated POY is drawn at constant rate between two rolls and the tension generated in the yarn by this drawing action is measured. The resulting tension may be represented as a number or, alternatively, a chart may be generated which represents graphically the uniformity of orientation along the length of the yarn.

To avoid downstream problems with dye shade variation it is advisable to maintain the variation from package to package within limits of ±5% of the target mean. The test instrument can also be fitted with an electronic balance, which calculates the denier of the yarn from the weight of the drawn test length used to evaluate the orientation of the yarn.

Another type of device consists of a standard laboratory knitting machine to which a heater and a set of drawing rolls have been attached. The POY is heated and subjected to constant drawing, subsequently being fed directly into the knitting machine at constant tension. This has the advantage that the measure of orientation used is the dyeing process itself. By using this method it is possible to remove any POY packages that show light, dark or uneven dye uptake before they are placed on the creel of the texturing machine. A variety of knitting head sizes is available to accommodate a wide range of spun-yarn counts. This kind of test can be carried out on a *Hot Draw Knitting* (*HDK*) machine made by *Lawson-Hemphill.*

A cruder indication of the POY orientation can be obtained by carrying out shrinkage tests on a skein of POY in boiling water, though the accuracy and reproducibility of this procedure cannot be compared with the more specialised test methods described above.

8.2.2.7 Tensile properties of POY

Tensile tests on POY are often carried out in the laboratory. The manner in which these tests are performed is described in Section 8.3.2.1 below. They are usually performed on the same test equipment that is used for textured yarns. It should be noted that tensile test results obtained from different types of instruments cannot be directly compared (see Section 8.3.2.1).

These tests give an objective measurement of the physical strength of the POY by measuring the percentage extension to break and the load required to reach this so-called break elongation. Typically the elongation of polyester POY would lie in the range 120–140%. The measured breaking load will obviously differ according to the spun denier, but the tenacity or specific strength should remain stable between 2.1 and 2.4 cN/dtex with:

$$\text{tenacity} = \frac{\text{breaking load(cN)}}{\text{decitex (denier)}} \qquad [8.1]$$

When the polymer has been modified, for example to enable the yarn to be dyed with cationic dyes, the tenacity will be significantly lower with values in the region of 1.6–1.9 cN/dtex.

The break elongation percentage of nylon yarns is significantly lower. A range of 63–70% with tenacity values in the region of 3.5–4.0 cN/dtex is typical.

8.2.2.8 Filament cross-section uniformity

The uniformity in cross-section of the individual filaments that comprise the POY feedstock used on the texturing machine will have a significant bearing on the number of broken filaments generated. Variation will also cause dye problems. Those of smaller diameter, i.e. the weaker filaments, are more prone to generate broken filaments during texturing, whereas those of larger diameter will also tend to break because they are less able to withstand the mechanical deformation during drawing and twisting. These large filaments will show a dark dyeing fleck at the point of break when observed in fabric.

Filament cross-section uniformity is dependent entirely on the extrusion process. It can be caused by several factors including pockets of degraded polymer reaching the spinneret (unlikely in a well-designed spinning beam), partially blocked filters in the spinning pack or poor housekeeping procedures during the making up of the spinning packs. This can be conveniently and quickly checked by mounting a sample of the cross-section of the filament bundle in a suitable slide and by observing through an ordinary or a projection microscope.

8.2.2.9 POY package build faults

The build of the POY package will obviously impact upon its unwinding performance and therefore by inference impact on break rate problems that may arise in the texturing process. All of the package build faults discussed in Section 4.3.6 are just as applicable to POY packages as they are to textured yarn packages. These are best checked prior to the packages being loaded in the texturing machine creel. If necessary packages which do not conform can be segregated at this point. All POY packages should have a well-presented transfer tail (see Section 4.3.6.7). Obviously if this tail is missing, or badly presented, the package is incapable of transferring successfully to a second package and an unavoidable yarn break will be the consequence.

8.2.2.10 Package identification

Though seemingly obvious, it cannot be stated strongly enough that the POY must be correctly identified. With many different products running in a manufacturing environment each having a different denier, lustre and cross-section, the chances of a mix of POY on the texturing creel are real and the consequences of this can be disastrous, if it is not discovered until the yarn is in fabric.

The prime method of identification is by tube colour. Other methods are available such as the use of fugitive tints or a label in the tube itself with a product description. Whatever method is chosen, it is important that the labelling should be both highly visible and unique to each individual product.

It is advisable also that each individual POY package should be labelled in such a way that it can be traced to the exact position on the spinning machine on which it was produced and the time it was produced. Thus if a POY package is isolated due to an obvious problem, all other packages from that position on the spinning machine can be segregated prior to being loaded on the texturing creel and can be submitted for further testing. This is being facilitated by the introduction of bar coding.

8.2.3 Polymer chip

In the case of the BCF process the starting material is polymer chip or granules. Though normally carried out by the supplier of the polymer, the following tests may have to be carried out by the yarn producer:

1 relative viscosity (of the molten polymer);
2 moisture content;
3 amine end group count (nylon);
4 extractable impurities;
5 chip or granule particle size;
6 colour (visual inspection);
7 titanium dioxide content (dulling agent).

Most of these tests require specialised test equipment but there are service test laboratories that can be used if the testing is required infrequently.

8.3 Quality assurance of textured yarn

Quality assurance of the textured yarn product can be broken down into three distinct parts, the first being on-line process control, the second being off-line yarn testing and the last a thorough visual inspection of the package prior to packing and despatch.

Process control is carried out in the manufacturing environment itself, whereas yarn testing is done in a suitably equipped laboratory, which should be maintained at stable conditions of temperature and humidity. These laboratory tests will be considered separately below.

The aim of any quality assurance system must be to ensure that the physical and dyeable properties of the yarn are those that will enable it to perform satisfactorily in its destined end use. Circular knit, warp knit, woven goods, both as warp and weft, and of course automotive type products, all have their own distinct requirements.

The criteria used to classify the yarn will vary from product to product. Obviously a yarn destined for use in a warp must be of the highest quality, whereas one destined for use in the construction of undyed net curtain material does not have to meet the same critical requirements. Broadly, yarn can be classified into six major groupings as far as quality requirements are concerned, though obviously each manufacturing plant will have its own in-house classifications. These are:

1 automotive yarns;
2 weaving warp yarns;
3 weaving weft and circular knit yarn;
4 printed fabrics;
5 whites only;
6 off quality.

8.3.1 Process control

8.3.1.1 Machine monitoring

Process control can be defined as the constant auditing of parameters on the texturing machine. This is an active control system and consists of continually checking the production parameters on the machine itself to ensure that no parameter drifts outside the specified range. Process control can take the form of manually checking shaft speeds by use of a tachometer or stroboscope and comparing the result against its specified value, or of simple visual checks of the integrity of the yarn thread-path and monitoring of any services supplied to the machine such as compressed air.

On modern machinery there is often some form of self-monitoring which continually checks such factors as shaft speed and heater temperature. The system will show a visual alarm if the system detects any parameter outside pre-set limits. Though such systems are generally reliable, the question of who checks the checker will always arise and must be addressed as practically and economically as possible. Also to be included in this type of process control is the routine monitoring of thread-line tension, especially where polyurethane discs are involved because of their well-documented wear characteristics.

The items that should be considered in a process control system are those simple basic checks that at first glance may seem so obvious as to be totally unnecessary, but if not carried out conscientiously will be sure to lead to problems. Such checks should include the following:

1 correct POY or polymer feedstock;
2 all shaft speeds on the machine within tolerance;
3 all heater temperatures within tolerance;

4 friction units or other texturing device, with correct sense of rotation and disc stacking, if applicable;
5 correct jets on the machine operating at the correct air pressure and temperature, when in use;
6 all package build parameters such as taper angle, stroke length and cradle damping settings as specified;
7 the correct textured yarn tube in use on the machine.

These basic checks should be carried out at the start of each production run and then at such periods as are deemed necessary to protect the integrity of the product whilst it is in production.

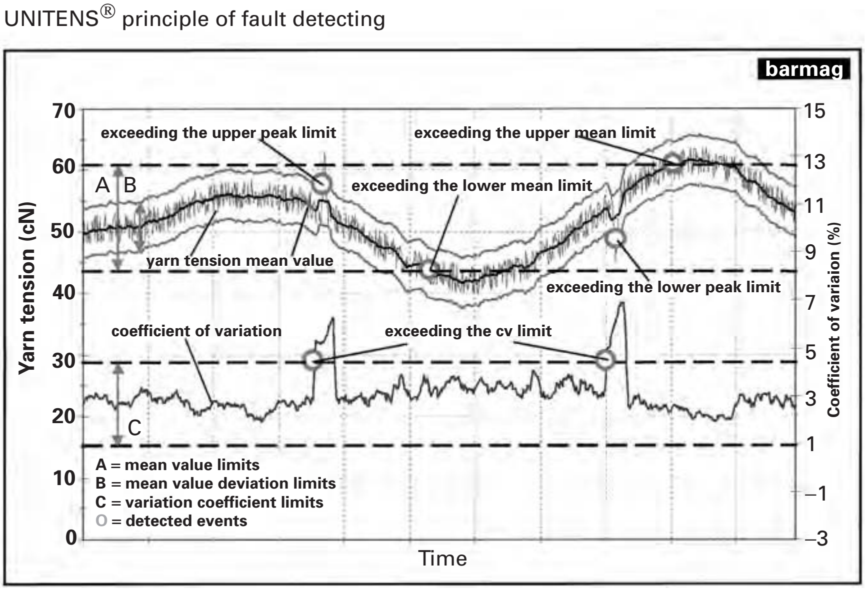
8.3.1.2 On-line monitoring

The most common form of on-line monitoring present on modern, false-twist texturing machines monitors the yarn tension. A suitable tension measuring head is mounted directly after the friction unit. This measures what is commonly known as the T_2 tension (see Section 4.3.3). The textured yarn continually runs over the tension head, stabilised by a suitable guide system.

There are two systems that are commonly in use for this purpose. The first of these relies on a Hall sensor (*Retech-Temco OLT*) whilst the second is based on an electronic strain gauge (*Barmag UNITENS*). Both systems continually display the tension measured at all running positions on the machine simultaneously in tabular and graphic form and in real time. Any deviations in tension measured, which fall outside pre-set limits, are automatically displayed against the position on the machine where the fault occurs and a historical record of that fault is logged in the computer memory. Faults stemming both from the POY and from within the texturing process are easily discernible by their characteristic fingerprints, when viewed in the form of a graphic (see Fig. 8.2).

These systems also hold a limited amount of historical information, which can be useful in segregating suspect packages of yarn. Faults are stored in the computer memory and a history of all faults occurring within a package during one doff can be created. The data can be compiled to present a detailed report of the number of faults generated within one package of yarn. This is then used to determine whether the package meets the criteria for a first-quality package or if the number and types of fault observed require it to be classified for a lower quality end use.

On-line yarn tension monitoring can also be applied to air-jet and hot-fluid jet processes. However, this is not yet common and may never become so, since the nature of jet processes means that other parameters give a more meaningful indication of divergent yarn quality.



8.2 Unitens trace. Courtesy of Barmag-Saurer Group.

Yarn clearers of the kind used during spun yarn production are sometimes fitted to air-jet texturing machines. The system software is designed to detect yarn defects after the texturing jet and to gather data on thick and thin places in the yarn. In the case of air-jet textured yarns it is the thick places, often resulting from bunched or excessive filament loops, that are counted and that indicate faulty yarn. Since these sensors also give an indication of the average denier of the yarn being textured, they are in some instances sufficiently sensitive to be used to signal missing ends.

On-line monitoring systems can be employed on both false-twist and air-jet texturing processes to monitor the number of ends down out of production at any one time. These types of monitoring system are obviously useful not only for collecting data on the performance and efficiency of individual products or processes but also for compiling to give an instantaneous picture of the overall efficiency of the plant.

There are also available systems that can be put on the false-twist machine that will continually monitor the degree of interlace placed into an air-entangled yarn. These systems, while being useful in determining if there are any positions running where the degree of interlace is outside pre-set tolerances, are of somewhat limited use as they cannot determine the strength of the interlace in the textured yarn. This can only be measured off-line either manually or by using suitable instruments.

On-line systems are invaluable as they both identify problems at source and also allow the problem package to be removed from the system at that point, saving any further testing or out-sorting. The faults observed, which are attributable to POY packages, are used to classify and identify suspect spinning positions. The POY packages thus identified are segregated before being put onto the texturing creel. In a vertical manufacturing plant this information can be passed directly to the extrusion plant for immediate corrective action. This is an obvious cost saving and as such should be enthusiastically pursued.

Of course, extrusion, drawing and texturing are carried out in one sequence during the production of BCF carpet yarns. Various process parameters have been monitored on-line experimentally. There is no consensus concerning the parameter(s) to be monitored but there is a lot of development activity at the moment and it can be safely predicted that most BCF processes will be monitored continuously in the future.

8.3.2 Laboratory testing of textured yarn

The aim of laboratory testing is to ensure that the physical properties of the textured yarn are those that enable it to meet the requirements necessary for it to perform satisfactorily in its destined end use, whether it be warp or circular knit, warp or weft or in a carpet. These requirements can be sorted into four main categories:

1 those that affect its tensile (physical) strength;
2 those that affect its behaviour in carpet or fabric;
3 those that affect its dye uniformity;
4 those that affect its performance (process efficiency) during knitting, warping, weaving or tufting.

Obviously, when considering the above, it has to be understood that no one attribute of the textured yarn can stand alone. Each property of a yarn will inevitably impact upon another and, as such, a set of physical results that describe the character of a yarn should be looked at as a whole and not as a series of individual properties to be addressed. Some of these yarn tests are described briefly below.

8.3.2.1 Tensile testing

Tensile tests determine the overall strength of the yarn by measuring its resistance to stretching when pulled in one direction and are similar to those described for POY in Section 8.2.2.7 above. Tensile testing instruments, by exerting a force on the yarn and pulling it in one direction, measure both the overall percentage extension to break and the force required to reach that extension (breaking load).

It should be noted that the tensile testing results obtained from different test instruments cannot be directly compared, since each type of instrument will differ in the method of clamping the yarn, the specimen length and the rate of extension. Even though the last two of these parameters can, and indeed must, be preset if comparisons are required, this cannot be done if two different types of instrument are being used for the comparison.

From the results, together with the measured denier of the yarn (see Section 8.3.2.2 below), a calculated value of tenacity can be obtained using equation [8.1]. This is a measure of force per unit linear density; as such it can be used to compare yarns made from different polymers or which do not have the same structure. Examples would be yarns made from polymers intended to produce a different molecular structure, perhaps a higher tenacity or to compare the effects of applying alternative texturing processes.

8.3.2.2 Denier testing

The testing of the denier of a textured yarn is carried out in the same manner as described for POY (see Section 8.2.2.1 above). One major difference is that the yarn is now in a textured and hence elastic state (if it has been through a friction spindle). It is therefore usual for a small but constant load to be applied to the yarn during winding onto the wrap wheel. This helps to ensure constant length and therefore reduce errors caused by the elastic nature of the yarn. This traditional method of testing the denier of a textured yarn is described in ASTM D1577-96. There is a special section that describes the treatment of textured yarns (crimped fibres).

Denier testing can be automated or combined with other test procedures. One advantage of automated or semi-automated testing is that the winding tension is applied consistently and is capable of being pre-set according to the yarn being tested. The 'operator effect' is therefore eliminated. One such test method carries the ASTM number Z6996Z.

8.3.3 Fabric behavioural tests

By this heading is meant the yarn tests which predict how the yarn will perform during fabric formation and finishing.

8.3.3.1 Yarn-skein shrinkage

The shrinkage of the textured yarn, as developed on the texturing machine, can be measured in a bewildering variety of ways. Over the years, many different tests have been developed with measurements made both in hot air and in wet conditions. Within these two broad classifications many different variants exist. As with tensile testing above, care should always be taken to compare like with like when discussing the shrinkage values of textured yarns. The important point is that the measurements should give a reliable prediction of the development of bulk or crimp in the yarn during subsequent fabric finishing.

Opinions differ as to the relative merits of wet-versus dry-skein shrinkage tests; some believe that wet shrinkage methods give a more accurate representation of how the yarn will behave in fabric, or in the case of package dyeing, in the dye vessel. However, providing the results from these tests can be related to subsequent behaviour in downstream processing either method can be considered to be relevant.

The basis of any shrinkage test is to wind a skein of yarn, and measure the length of the yarn loop under load L_0. The skein is then subjected to either hot air or hot water, at known and constant temperature, for a stated period of time and the length of the skein measured again under the same loading L_1. The percentage difference in the two lengths is what is known as the yarn shrinkage. Hence:

$$\text{yarn-skein shrinkage } \% = \frac{L_0 - L_1}{L_0} \times 100\% \qquad [8.2]$$

The ASTM standard test procedure for this is D4031. It makes a distinction between skein shrinkage (as defined above) and crimp contraction, which it describes as the yarn's ability to contract under tension.

8.3.3.2 Degree of bulk, crimp or texture

Skein shrinkage as described above is used as an indication of the degree of bulk or crimp in North America. In Europe the properties of a textured yarn are defined (and therefore measured) differently. Crimp contraction (sometimes known as crimp retraction) starts with a loading which fully extends the yarn and measures the reduction in length when subject to certain standardised conditions of heat for a given time. The crimp stability is given by measuring the crimp contraction a second time after the textured yarn has been subjected to a greater load. The stability is the percentage crimp retained after the loading.

The crimp contraction properties of false-twist textured yarns are tested according to procedures which are defined in the standards. For example there is a DIN standard that describes the exact details for winding the skein, heating and measuring. Its number is DIN 53840–1 (11.83). The handling of the yarn is similar to that described previously for measuring yarn-skein shrinkage. It is therefore a laborious procedure. Instruments for measuring crimp properties are now in widespread use throughout Europe; these enable a number of hanks of textured yarn to be tested as a batch, thus introducing more standardisation to the handling and allowing the difference between hanks within a batch to be computed. The productivity of testing is also increased. The most widely used instrument for this purpose is the *Texturmat*.

An alternative, described in an ASTM test draft [Z7667Z], measures the crimp and shrinkage properties dynamically. In this test the yarn runs through the *TYT* (*Textured Yarn Tester*) test instrument continuously. The yarn is first tensioned at a pre-set level and is then fed through a feed roll into a 1.7 m tube heater. The heater generates crimp and shrinkage force. A set of intermediate rolls maintains the test yarn under a constant, low tension through the heating tube. The computer measures the speed variation of the two sets of rolls (R_1 and R_2) to calculate the total crimp recovery of the test yarn. The speed of the input roll is normally set at 100 m/min. The first zone sensor control is set at 1 mg/dtex:

$$\text{total recovery (a measure of crimp level)} = \frac{R_1 - R_2}{R_1} \times 100\% \qquad [8.3]$$

where R_1 and R_2 are respectively the roll speeds pre- and post-heater. This test method has two advantages over the static methods. First the result is available immediately at the computer. This not only enables comparisons between batches to be made, but also gives the ability to read out the standard variation within a sample as it passes through the instrument. This test instrument is also in widespread use for testing BCF carpet yarns. This is important because streaks in carpets have been found to have a high correlation with crimp rather than with dye variations.

8.3.3.3 Stability of bulk, crimp or texture

Both the test methods described in the previous paragraphs enable the sample to be treated further, in order to measure the stability of crimp or bulk. In the case of the dynamic test instrument there is a second sensor zone using the same principle. The speed of the third roll is set to eliminate the crimp generated after the heater, leaving only the residual fibre shrinkage in the yarn. To confuse everyone this value is defined as the fibre shrinkage in North America and as the crimp stability in Europe! Thus:

$$\text{yarn (fibre) shrinkage} = \frac{R_1 - R_3}{R_1} \times 100\% \qquad [8.4]$$

8.3.3.4 Bulk in an air-jet textured yarn

Because the bulk in an air-jet textured yarn is developed by the physical rearrangement of the filaments rather than by the application of heat, the bulk has to be characterised by the increase in specific volume. To make this clearer, when the process was developed originally, *DuPont* specified bulk by measuring the size of the textured yarn package and comparing it with a package of the same weight of yarn wound without texturing. Of course this was before the days of draw-texturing.

Current dynamic test instruments measure the core diameter of the yarn and also characterise the loop structure by counting the loops at different diameters. This is done by means of a sensitive camera with a scanning range of 2048 pixels horizontally and 1 pixel vertically for each reading (1 pixel = 3.25 μ) and the necessary PC with corresponding software. The instrument is known as *EIB* (*Electronic Inspection Board*) and is made by *Lawson-Hemphill*. This has resulted in the creation of a 'Bulk Index' using loop frequency and loop-size distribution to characterise and qualify air-jet textured yarns.

8.3.3.5 Assessment of expected cover in fabric

An assessment of the type of cover to be expected from a yarn when in fabric, particularly in knitted goods, can be obtained from the visual examination of an undyed, scoured, knitted sleeve. This is a subjective assessment and as such needs to be done by a skilled operator.

A knitted sleeve is placed in a dye bath and subjected to the same type of dye cycle as it would see in fabric dyeing. The exception is that the procedure is carried out with no dyestuff present in the system. The greige test sleeve is then removed and, after drying, examined on a black test board. The amount of black surface that can be seen when viewing through the test sleeve can be used to give a subjective assessment of the amount of cover to be expected from the test yarn when in fabric.

8.3.4 Package-to-package dye uniformity

Ensuring that all packages, within a specific product, dye uniformly is of paramount importance in ensuring that the finished fabric is of even appearance and free from either streakiness or barré. Examination of a dyed, knitted sleeve can prove invaluable in out-sorting packages of yarn that display not only variations in dye uptake but also specific physical faults that give the characteristic appearance of uneven dyeing.

A sample knitted sleeve is prepared on a small knitting machine. Each knitted sleeve is given its own unique reference and the order in which the packages of yarn are knitted in that sleeve must be accurately recorded. Care must be taken to ensure that all packages are knitted with the same yarn tension going into the knitting head. If this is not controlled, the tension variation from package to package will be apparent in the dyed sleeve, making a critical assessment impossible. For this reason specially designed laboratory knitting machines with automatic stitch control such as the *FAK* (*Fabric Analysis Knitter*) manufactured by *Lawson Hemphill* should be used. Automatic stitch control is essential when knitting false-twist textured yarns with stretch characteristics.

The test sleeve is dyed in a small dye machine using a suitably critical dyestuff. Since polyester is normally a disperse-dyeable fibre, the size of the dye molecule has a distinct bearing on its ability to penetrate the molecular structure and will affect the depth of shade achieved. Dye cycles, i.e. the temperature, time and pressure at which the knitted sleeve is dyed, must also be chosen carefully to give the maximum opportunity for level dye application.

The addition of a carrier agent is frequently incorporated during dyeing. This helps to swell the fibre and ensure better dye penetration. Dyeing carried out at atmospheric pressure is much more critical but this practice is not usual in day-to-day quality assurance testing. Dye assessment of nylon yarns is basically the same as for polyester but as nylon yarns are dyeable using acid dyes, a carrier agent is not required and dyeing carried out at atmospheric pressure can suffice for the purpose of routine quality assurance.

After the knitted sleeve has completed its dye cycle and been dried it is then inspected under suitable lighting conditions. It is advisable to carry out this assessment with the dyed sleeve being viewed against both a black and a white background, as the colour of the background can affect the manner in which the eye perceives the shade. Purpose-designed, colour-matching test equipment can be also used in the assessment of dye uniformity. Even though a visual assessment is somewhat subjective, assessment by a well-trained and skilled technician can detect subtle shade differences both package-to-package and along-the-length variations that can defy an electronic assessment.

From this assessment it is possible to identify those packages that show shade differences compared with the main body of the knitted sleeve and also any packages that show a tendency toward streakiness. These packages, which are removed, can be classified into a lower quality category, depending upon the severity of the fault, or simply designated for a whites-only end use.

8.3.5 Process efficiency tests

8.3.5.1 Oil on yarn

The amount of coning oil, if applied to the yarn after texturing, is determined by the fabric construction for which the yarn is destined. Application levels would normally lie between 1 and 3% but may vary from these figures. Usually those products destined for knitting end uses would have higher oil application than those destined for weaving. Some nylon yarns, particularly those for use on high-speed hosiery or sock knitting machines, may have higher levels.

The level of oil is determined by wrapping a suitable sized skein of yarn, weighing it (W_1) and then removing the oil and reweighing after drying (W_2), the oil content being the percentage difference between the two weights. Hence:

$$\text{percentage oil on yarn} = \frac{(W_1)-(W_2)}{(W_1)} \times 100\% \qquad [8.5]$$

The oil may be removed by traditional soxhlet extraction using a suitable solvent or by simply washing in hot water with detergent added. More sophisticated test methods can also be used, such as infrared analysis, but for everyday control of oil level, simple extraction tests usually suffice.

8.3.5.2 Intermingle or interlace testing

The level of intermingling applied to a yarn can have a profound effect on how the yarn will perform during both knitting and weaving but, of these two, the behaviour in weaving is more important (see Effect of intermingling in Section 5.3.5.2). This is because intermingling has largely replaced the twisting and sizing of warp yarns.

Intermingling of a yarn can be quantified in a variety of ways, various attributes of the quality of the intermingling being measured to quantify its characteristics. The number of entanglement points inserted, the regularity of these insertions and the strength (or resistance to removal) of the entanglements can all be used to quantify and qualify intermingling.

Several specialised pieces of test equipment are now in use, which are designed for quantifying the degree of intermingling present in a yarn. Though they operate by different principles of measurement they have the following in common:

1 an initial count (count 1) of the number of interlace points per unit length;
2 subjection of the yarn to a small and constant draw between two rolls. This draw, or extension, can be programmed for a series of stepped

increases so that a profile of the strength of the intermingling points can be found over a range of values;

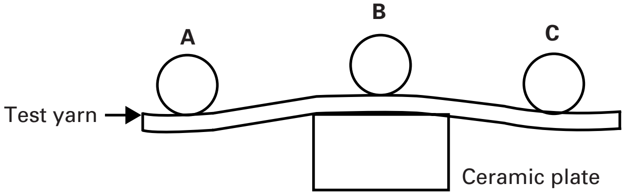
3 a second count of the interlace points (count 2). This enables the strength of the intermingling points to be calculated as a percentage of these points remaining after the yarn has been subjected to the drawing action:

$$\text{percentage knot retention or knot strength} = \frac{\text{count 2}}{\text{count 1}} \times 100\% \qquad [8.6]$$

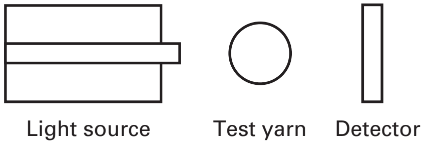
Instruments that enable this double count to be made include those by *Enka Tecnica* (*Itemat*) and by *Fibreguide* (*Fibrevision*). The *Itemat* works by scanning the variation in thickness of the yarn bundle under test. The yarn is subjected to small constant pressure which will tend to flatten the areas of non-interlaced yarn. When an interlace point is detected, the more compact circular form of the yarn at the actual intermingling point prevents the pressure applied from flattening the yarn bundle and hence the movement of the pressure plate is restricted. It is this variation in movement of the pressure plate which is used to determine the number of intermingling points present in the yarn (see Fig. 8.3).

The *Fibreguide* instrument works on a different principle. This instrument uses a laser to scan the yarn as it passes through the measuring head, detecting interlace points as the variation in the degree of light received by the detector which is placed opposite the light source (see Fig. 8.4).

Other information such as the distance between the interlace points and the length of the interlace points themselves can be presented both statistically and graphically if required.



8.3. The *Itemat* instrument. A and C are the thread guides and B is the measuring pressure plate.



8.4. The *Fibreguide* instrument.

The instruments that are used today either ‘feel’ the yarn or use optical methods including lasers to count the number of intermingled knots. An older technique inserts a short needle between the filaments of the yarn. Each time a knot passes the needle it is deflected and a knot is counted. This technique is still in use but mainly for counting knots in yarns that have not been textured.

For the day-to-day checking of the level of intermingling in the textile laboratory, it is quite feasible to quantify the interlacing present in the textured yarn by the simple expedient of counting the number of interlace points present in a measured length of yarn. This should be carried out with the yarn placed upon a suitable dark background. It is somewhat laborious and depends to a certain extent on the operator, since the tensioning of the yarn before counting and the decision as to what comprises a knot cannot be precise. The method chosen will depend to a large degree upon the criticality of the end-use yarn and on economic considerations.

Some yarns do not exhibit visible interlacing points. Laying the yarn on the surface of a water bath, where the water is replenished continuously, can still assess them. The surface tension causes the filaments to separate as far as possible, thus revealing the degree of entanglement. Again, it helps if the water bath is dark in colour, at least when assessing an undyed yarn. (This method is commonly used for assessing intermingling in POY.)

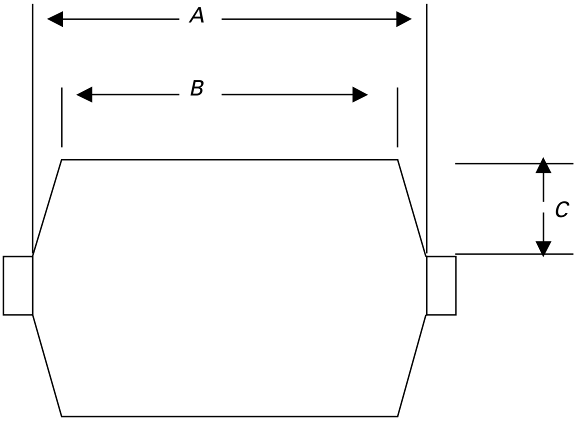
8.3.5.3 Package density measurement

The control of density on package dye yarns in particular is of vital importance, the density of the package having a dramatic effect on the ability of the dyer to obtain an even dye distribution throughout the package. This applies with equal importance to batch-to-batch shade uniformity. The density of the package can be measured manually by taking measurements of the initial and final stroke lengths and the depth of yarn on the package. From these measurements it is possible to calculate the volume of yarn on the package and then, by recording the net weight of yarn on the package, the overall density can be found (see Fig. 8.5) as follows:

$$\text{package density} = \frac{954.9297 \times D}{2(AC + 2BC + 112.5A + 112.5B)}\ \text{g/cm}^3 \qquad [8.7]$$

where A = initial stroke length, B = final stroke length, C = yarn depth (tube wall to outside of package), D = nett package weight in grams and 954.9297 is the reciprocal of 1/3 $\pi \times 1000$.

Making these measurements is not only time-consuming but is also a source of many errors, with the required number of measurements per package being high. Purpose-designed instruments are available for the measurement and calculation of package density. These incorporate a



8.5. Package density measurements.

weighing mechanism and package-dimension measuring devices that may be camera-based or simple mechanical swinging arms that converge on the package. These instruments can be linked to a PC and the data presented both as a table and graphically with full statistical analysis. Whichever system is employed, it is essential that the results are both reproducible and consistent or severe problems may be encountered by the dyer.

When measuring package density it is important that all packages tested should be of equivalent weight, i.e. use full-size packages wherever possible. This is to account for the apparent difference in calculated density from small and large yarn packages, which is caused by the change in winding tension from start to completion of package winding.

The on-line measurement of package density during texturing has been demonstrated and applied already in a few plants. On the other hand, there are new, more sophisticated take-up systems that have been developed for the latest texturing machines and which may also be available as conversion kits. These enable a much closer tolerance to be applied to the winding of the packages and hence to their density.

8.3.5.4 Package unwinding characteristics

An objective measure of how the yarn will unwind from the package can be made by the use of purpose-designed instruments such as the *PPA* (*Package Performance Analyser*) made and sold by *Rieter–Scragg*. These work by unwinding a package of yarn at constant speed over a tension-measuring head, the tension in the yarn as it unwinds being monitored continuously. The data from the tension head is sampled at up to 1000 times per second using the software provided.

This information is processed and stored in the form of a cumulative tension distribution and on completion of the test the stored data is analysed. Taking account of both peak (highs and lows) tension and the overall tension distribution observed during unwinding, a value known as the *PPF* (package performance factor) is calculated.

The *PPF* is a statistical value unique to the *Rieter–Scragg PPA* device and can be used to judge how the package will perform during subsequent unwinding. The instrument, as well as giving a simple statistical summary, can also show the unwinding of the package graphically. It does this by sectioning the overall unwinding time into 100 equally distributed time periods and displaying both the overall and peak unwinding tensions observed in the form of a histogram. This is particularly useful in determining if there is any particular region in the package which is subject to unusually large variations in unwinding tension.

Package unwinding is obviously important in any further processing, especially of fine decitex (denier) nylon hosiery yarns that are destined for use on high-speed four- or eight-feed knitting machines. As weavers are now exploiting advances in loom developments, package unwinding is assuming a greater importance in yarns for weft insertion.

The most up-to-date instruments also incorporate a package density measurement system that continually monitors yarn depth and package weight. The density value at any point in the package can be determined and checked for possible correlation against any suspect unwinding regions.

There is an alternative type of package analyser. This unwinds the yarn from the package at slow speed and charts an exact replication of the manner in which the yarn has been laid on the package by the traverse mechanism. Though of limited use in the routine day-to-day control of package unwinding, it is a useful analytical tool for determining if the stroke-modification system in particular is performing its correct function.

8.4 Visual inspection prior to despatch

The final stage in any quality assurance scheme must be a visual inspection of the finished package by a trained inspector prior to the package being boxed for despatch to the customer. This is the last line of defence in the manufacturing environment to prevent a faulty package getting into fabric at the customer and as such needs to be carried out conscientiously. To enable the inspector to carry out this work effectively, there must be established and clearly written standards for each product type, against which the package can be assessed.

At this stage the product should be segregated after classification into various qualities based upon physical properties and dye checks. The inspector is specifically looking for packages that fall outside these categories.

The categories are:

1 dirt marks on the yarn;
2 secure transfer tail;
3 package build faults that would lead to unwinding problems;
4 presence of high numbers of broken filaments;
5 uniform intermingling, if present;
6 damaged tube, container or bobbin;
7 package size and weight;
8 correct tube colour for the product.

All of the above, with the exception of 7, can be checked by a quick visual examination of the surfaces of the package and by simply unwinding a few metres so that the regularity of the interlace can be seen. Should any fault be noted, then its nature and the position on the texturing machine from whence it came should be recorded. The information should then be relayed to the manufacturing plant for corrective action and the faulty package downgraded into a suitable category.

For the measurement of package size and weight (7 above) it is advisable that all the packing stations should be equipped with both a simple go-no-go gauge for overall package diameter and a simple top pan balance of suitable capacity (see Section 9.4).

9

Textile yarn logistics

9.1 Introduction

The term logistics is here interpreted to encompass the areas of yarn handling, packaging, transport, both internal and external, and storage. The systems employed will to a certain extent depend upon the specific fibre, the type of package wound and the internal layout of the manufacturing environment, nylon yarns in particular requiring special storage and handling systems.

The aim of logistics within a manufacturing environment must be to maintain the security of the product all the way through the manufacturing process and to ensure that when the yarn eventually reaches the customer it is both in optimum condition and well presented. Within this brief both the maintenance of a safe working environment (wherever mobile equipment is used there is the potential for accidents to occur) and the achievement of economic cost, i.e. material flow, have to be considered. This starts from the time the POY is first loaded into the texturing machine creel and does not end until the customer unloads the product and takes responsibility for it.

9.1.1 Product identification

Any logistical system designed for the transport of yarn packages, either internally or for final shipment, will fall flat if the identification system fails. Every single package of yarn must have a unique identification that not only defines it as belonging to one specific product type, but also gives its time and place of production. In a manufacturing environment with many different products having combinations of denier, lustre, fibre cross-section and types of intermingling, this is essential in order to prevent the consequences of possible yarn mixes. This applies not only to the textured yarn but also, equally as important, to the POY feedstock used.

Thus identification can be sub-defined as:

1 product type;
2 package within product type

9.1.1.1 Product type

The primary method of defining the type of yarn wound on a package is normally by using a combination of unique code number and a tube whose colour is also unique to that product. However, other methods are also available such as the use of various colours of fugitive tints or stamping the yarn itself with a unique code number (also in fugitive tint) which equally well defines the product. The tube itself may also be stamped with a code which is unique to that product. Regardless of what method is chosen, the two most important factors are that the form of identification should always be both highly visible and unique to that product.

9.1.1.2 Package within product type

The identification of the individual package is important in order to allow the exact time, date and place of production to be determined should any problem arise with yarn from that package, either during subsequent in-house testing or at the customer. This identification would normally encompass the machine on which the package was produced, the position of the machine on which it was produced and the time and date it was produced. This would usually be encapsulated in a simple label and fixed to the inside of the tube as it is doffed from the machine. Bar coding is now a viable option to replace conventional printed labels.

It is important that package dye yarns are treated somewhat differently regarding identification, since a sticky label would dislodge from the tube during dyeing and could cause severe problems in the dye vessel. For this reason it is normal practice either to remove the package identification (ID) before shipping or to use water-soluble labels when shipping package dye products.

9.2 Handling

9.2.1 POY handling

Dependent upon the situation in the texturing plant, POY may arrive in a wide range of packaging from outside suppliers (external supply). However, if the texturing plant is adjacent to an extrusion plant (internal supply) then a different situation applies. No matter from where the POY originates the aim must be to maintain it in first-class condition until

Table 9.1 Typical POY tube sizes

Internal diameter (mm)	Outside diameter (mm)	Tube length (mm)
75.2	85.7	185
75.2	85.7	285
75.2	85.7	300
109.7	126	200

such time as it is transferred from its container and loaded into the texturing machine creel. When loading it into the creel, there must neither be disturbance to the wind nor any mechanical damage. The POY should be stored in conditions of temperature and humidity that are experienced in the manufacturing area (see Section 4.6.1). This is especially important in the case of nylon yarns, which are very sensitive to changes in humidity.

There are a wide variety of POY package sizes, dependent upon the equipment being employed in the extrusion plant. The overall dimensions of the POY package will have obvious implications for the design of any material-handling equipment. They range from peg spacing on storage trolleys to the diameter of a claw designed to fit the internal diameter of the tube. Some typical POY tube sizes are shown in Table 9.1.

It should be noted that these sizes are nominal and there will be a small manufacturing tolerance allowed on all dimensions. Other POY tube sizes exist; the ones quoted above are only a small selection of those available.

Automated systems are available for handling POY, which are usually custom-designed to suit that particular manufacturer's mode of operation. These can be sophisticated or simple as expenditure will allow. A comprehensive system, for internal supply, would start with automatic doffing of the POY package in the extrusion plant and range through to cassette loading of the texturing machine creel – in effect, a 'no touch' system from the time the POY package is doffed in the extrusion plant until the transfer tail is dressed and spliced in the texturing creel. This of course is the ideal system, which avoids the chance of accidental mechanical damage to the POY package. However, the cost of such a system may well be prohibitive. Therefore most manufacturers will use either a wholly manual system or a semi-automated system.

In situations where a wholly manual system is employed it is essential that all operatives involved in the handling of POY packages are given training in the correct method of lifting and handling them. This is necessary not only to help prevent damage to the POY itself but, equally important, to ensure that the operators incur no repetitive strain injuries. POY packages are heavy, often in the region of 12–20 kg weight. In some cases POY packages substantially heavier than these can be produced. These very heavy package weights require specialised handling equipment to prevent injuries to operators.

For handling of the POY in the texturing environment, there should be provided at the least some sort of manual assist that can fit inside the core of the POY tube, that will enable it to be lifted by the operative onto the texturing machine creel. With such an assist, it should be possible to load the package without the yarn being touched and sustaining any disturbance to the package wind. Such devices can range from a simple, hand-held claw which fits inside the tube core to overhead hoists mounted adjacent to the machine creel. Mobile devices that have provision to carry a palletised container for the POY and which also incorporate some form of mechanical lift are available.

9.2.2 Textured yarn handling

With the advent of texturing machines with automatic doffing the handling of textured yarn packages has been revolutionised. Prior to the arrival of these machines, all packages had to be removed from the machine by hand and placed upon a suitable trolley, or palletised at the machine. As can be appreciated, this resulted in an increased risk of incurring dirt marks on the yarn itself, or the possibility of either the yarn or the tube sustaining some form of mechanical damage.

9.2.2.1 Manual doffing

Manual doffing of texturing machines can be accomplished in a variety of ways, largely determined by the speed of the process and the denier of the textured product. It is possible for a trained operator to hand doff a machine with the assistance of the machine aspiration system, if both the yarn speed and the denier do not exceed a value of 700 in either case. At speeds greater than this it is usual for a simple suction gun to be employed either with its own mobile vacuum system or which simply plugs into the machine aspiration system. If the yarn denier is greater than 700 it becomes impossible for the operator to break the running thread by hand and scissors are normally used. Whatever method is employed the next step in the process is the removal of the yarn package from the machine. It is usually placed upon a trolley and the running thread is entrained on an empty tube.

In the case where a low-density dye pack on a compressible tube is being doffed and placed on a trolley, it should be handled with care. Harsh handling may cause the body of yarn on the package to move thus making that package an automatic downgrade after examination even prior to any subsequent testing.

It is essential at this stage that the package of yarn is labelled in a unique manner immediately after removal from the machine for subsequent identification during testing or subsequent processing.

The trolley on which the textured yarn package yarn is placed may come in a variety of designs. Whatever the design, it must have the following features:

1 peg spacing large enough to accommodate the textured yarn packages with no chance of adjacent packages hitting or rubbing against each other;
2 not be so large that the weight of the trolley plus yarn packages becomes too heavy to be pushed by the operator without chance of injury;
3 be narrow enough to fit within the machine-operating aisle;
4 have a wheelbase that gives stability to the trolley and also a low centre of gravity to prevent it from toppling over;
5 have some provision for identification of the product that is stored on the trolley;
6 possibly have some linking mechanism so that trolleys can be linked together for towing by a small, motorised tractor unit.

As with POY, texturing tubes come in a variety of sizes dependent upon the design of the machine and these dimensions must be taken into account when considering any transport system for moving textured yarn around the plant. Some examples are shown in Table 9.2.

As with POY tubes there will be a small manufacturing tolerance allowed on these dimensions.

Table 9.2 Typical texturing tube sizes

Internal diameter (mm)	Outside diameter (mm)	Length (mm)
57.0	64.5	230.0
57.0	64.5	265.0
42.0	49.7	265.0
73.0	79.2	238.0
73.0	79.2	290.0
57.2/68.3*	74.7	290.0
58.0/69.0*	74.5	289.0

* Indicates tubes of bull-nose design, which have different internal diameters at each end of the tube. These tubes offer the customer improved off-winding compared to straight-cut tubes.

9.2.2.2 Automatic doffing

Automatic doffing of texturing machines is a comparatively recent innovation. Apart from the obvious implication for labour, and hence cost saving, it also has major benefits in improved handling of the textured yarn package. Automatic doffing lends itself to automatic package retrieval either by machine-dedicated robots or remote-roving robots. The type of robotic system employed will be determined by the design of the machine itself. Is the machine inboard doffing or outboard doffing? An inboard doffing machine doffs the full-sized, textured yarn package inwards into the operator aisle, i.e. towards the centre line of the machine. An outboard doffing machine doffs the full-size package toward the back of the machine, i.e. towards the POY creel. As can be appreciated, space restrictions with an inboard doffing system lean this system towards a machine-dedicated, robotic system, whereas outboard doffing gives more freedom regarding space requirements so that in this case either machine-dedicated or remote robotic systems can be considered. Both systems have their own advantages and the choice of which one is employed will take into consideration both plant layout and economics. As will readily be appreciated any robotic system can greatly reduce the incidence of dirty packages of textured yarn and can significantly reduce occurrences of yarn damage by poor handling techniques.

With all robotic systems, it is imperative that the textured yarn package is identified before leaving the texturing machine. Regardless of whether the package has been doffed by robot or not, the next step in the process is as described above in that the yarn will normally be placed upon a trolley for transport to a storage area before being released for packing. Should this be the case then the statements made in Section 9.2.2.1 above hold.

If package collection is made by remote robots, there exists the possibility of using the robot to transport the packages to a packing area which itself may be automated. This will be discussed in Section 9.4 below. It is important to note that if the textured yarn packages are transported automatically to the packing area, the texturing machine should be equipped with some form of on-line monitoring. By this means the quality can be determined and logged for each package on the machine prior to its removal by the robot.

9.3 Internal transport systems

The transportation of yarn packages within the manufacturing environment can be accomplished in a variety of ways. No matter what type of system is used, there are two overriding considerations. These are:

1 the systems should be designed to be safe and prevent as far as possible accident or injury to those working in the plant;
2 they should be designed to protect the product from damage.

Obviously, when considering how yarn is to be transported around a manufacturing plant, economic considerations must be taken into account as well as the factors mentioned above. Transport systems can be as simple or complex as desired ranging from simple, hand-pushed trolleys to fully automated systems either suspended from overhead rails or using wire-guided robots.

Simple systems may consist only of hand-pulled trolleys and hand-operated pallet trucks to move either textured yarn or POY around the plant. Of course this could be taken a stage further and be motorised. Electrical power is preferred, provided by rechargeable batteries to reduce the element of pollution from either diesel or propane-powered vehicles. A more complex machine-dedicated or remote robotic system offers the potential of long-term cost savings owing to reduced manning requirements. It also has benefits in reducing the incidences of mishandled packages.

When designing any logistical system, the physical layout of the plant is important. Any mobile equipment employed must be capable of negotiating aisle ways, doorways and any corners that are encountered. This may seem obvious but could be the source of some embarrassment!

9.4 Packing line

The overall design of the packing line has to be considered from the standpoint of achieving a swift and economic flow of material such that the minimum of floor space is occupied and there is a quick turnaround of storage trolleys. To this end it is preferable that several packing stations are joined to one conveyor line and that all cartons are then delivered to a central location for weighing and palletising.

Each packing station should have room for at least two storage trolleys, the yarn is being unloaded from one for inspection and packing and a second to hold any packages of yarn rejected by the inspector. There should be an adequate supply of plastic bags, empty cartons and labels available at each packing station. It is also advisable to have each packing station equipped with a top pan balance, capable of weighing up to 10 kg, and size-gauging equipment, so that each package can be checked for correct weight and size range if applicable to that product. Consideration should be given to the installation of a second conveyor system to deliver empty cartons to each packing station.

Automatic packing is now a feasible and cost-effective option. Packages of yarn can be delivered to a conveyor line by remote robots and the robot itself can place these packages on to suitable dollies for transporting along the line. The only operation that requires manual input is the final checking of the package by a trained inspector, and even this can be semi-automated by having the package of yarn automatically rotated in front of a seated inspector. Subsequent operations such as bagging the package and placing it into a carton and finally weighing and labelling the cartons can all be easily accomplished by robotic means. Such systems would usually be custom-designed to meet the requirements of the manufacturing plant.

These systems are obviously expensive to install but can be justified by the long-term cost savings provided by reduced labour requirements. They should therefore be given serious consideration.

9.5 Yarn packaging

Packing yarn for shipment is a process that requires some thought if it is to be accomplished in the most economic manner. All transport is expensive and every effort should be made to maximise the weight of yarn shipped per load in order to keep the transport cost per kilogram of yarn as low as possible. Consequently it follows that the design of any cartons or pallet packs are such that they maximise the available space for packages of yarn. Most modern cartons or pallet packs within mainland Europe are designed either to fit the format of the so-called 'Europallet', which is 750 mm wide × 1120 mm long, or to be multiples of this size. These are designed to maximise the space available within a 12 m container. Obviously these dimensions will differ in other regions, particularly within the United States.

After visual inspection by a trained inspector, the package is usually placed in a plastic bag and then into a cardboard carton. For some end uses, notably package dye yarns, the actual yarn package may be shrink-wrapped in perforated film so as to minimise disturbance to the wind of the package during the dyeing process.

The cartons may be constructed to take various numbers of packages and may be sized to take six or 12 full-size packages, i.e. two layers of six packages, though the number actually placed in each box will differ according to the finished package size. Some fabric manufacturers' equipment may dictate that they cannot accommodate full-size packages. The cartons are transported either by hand or by conveyer line to a staging area where they are stacked onto pallets and bound in some way to prevent cartons toppling over during subsequent transport.

In instances where customers have their own in-house systems that can accommodate larger palletised deliveries, there is a trend toward the use of bulk packs which can accommodate far more packages than the 12 mentioned above. Where it is possible to use such systems, this should be pursued to take advantage of the obvious cost savings involved. Not only are there savings to be gained in the cost of raw material, i.e. fewer cartons used per kilogram of yarn, but they also allow the use of more substantial types of packaging such as polypropylene mouldings. These can be used over and over again so further reducing the overall packaging costs. In all other respects, such as the labelling and weighing of these larger bulk packs, the same rules apply as for normal palletised consignments.

It is of vital importance that all cartons are labelled in a manner that immediately informs the consumer of the contents of that carton (see Section 5.2). Though the format of the label will obviously differ from location to location, it should contain at least the following information:

1 product description indicating ply, denier, filament count, lustre, twist direction and cross-section;
2 quality code or description;
3 date and time of packing;*
4 gross weight;
5 net weight;
6 some form of identification of the person who packed the carton.

As a matter of course, to enable accurate accounting, the exact weight of yarn must be accurately recorded for all qualities including those which arise from downgrading. It is usual for the boxed yarn to be weighed prior to despatch. Therefore it is essential to engage a reputable supplier of packaging materials so that the net weight of the packaging does not vary from batch-to-batch outside of the agreed limits. When placed on a pallet for shipment, it is prudent to secure the cartons to the pallet itself either by suitable strapping or by shrink-wrapping the whole assembly.

9.6 Warehousing

The final stage of the process is to store the palletised yarn in a warehouse prior to despatch. A properly organised and maintained warehouse requires sufficient rack space in which to store all the yarn. A series of unique racking positions needs to be allocated in which yarn belonging to each product category can be stored.

Aisle ways between the racks must be wide enough to enable access for stacking trucks and for reasons of operator safety all stacking trucks should be fitted with either audible or visual warning devices. Also ease of access to loading bays should be of paramount importance to facilitate the quick turnaround of transport.

---

* The date and time of packing are especially important in the case of nylon yarns, which are age sensitive and should be used in date order.

Yarn is stored usually until such time as either the customer calls off a delivery or sufficient yarn is available to make up a full load to meet a much larger on-going order. This is why having a precise record of where each pallet of yarn is stored is important so that a load can be assembled quickly and economically.

In the case of nylon yarns the recording of where each pallet is stored must be accompanied by a date code. Owing to the fact that nylon yarns are age sensitive the yarn must be shipped from the warehouse on a first in, first out basis (FIFO) (see below).

It is possible to automate a warehouse fully and should the volume of yarn passing through the warehouse be large enough, this can be a cost-effective option. In this case all rack positions are bar coded and stacking trucks rove between the aisle ways, automatically depositing the pallets in the predetermined rack positions by reading the bar code at each available position. Similarly when removing pallets from storage for shipment to the customer, a listing of the required rack positions can be fed to the robotic stackers by the software and the pallets can be picked out automatically for loading into the container for shipment.

9.7 Product logging

Each pallet, when it arrives from packing, must be given its own unique space on the racks; this is to enable it to be easily picked for shipment at a later date. This rack position together with all details relevant to that pallet must be accurately recorded and passed forward to the accounting department, i.e.

1 net and gross weight;
2 product description;
3 quality;
4 date of packing.

Similarly this information must also be logged as each pallet is removed from the warehouse for shipment to customers. The date of first racking is particularly relevant to nylon yarns which, as they are age sensitive, in a well-managed warehouse, are shipped on a first in first out basis.

The information above is vital to the running of an efficient business with accurate accounting systems. Without this information, it is impossible to balance the worth of finished goods against the manufacturing costs or to know the amount of money tied up in finished goods held as stock at any time.

Any business whose prime accounting method is dependent upon the weight of goods shipped and on knowing the worth of each kilogram of these goods, must have an accurate weighing system. As such, all balances, scales and weighbridges must be regularly and routinely calibrated with known international standard weights and accurate records of these calibrations must be maintained.

9.8 Load planning

For economic reasons the planning of the load which goes into each container for shipment requires careful thought. As the cost of transport is an ever present and rising cost, loads should be planned so that whenever practical:

1. all of one load goes to one customer; or
2. different loads within a shipment are planned so that two or more customers that lie within a small radius of each other can be serviced from one load (the yarns should be placed in the container in the reverse order to the order of unloading).

Also, if at all possible, it should be arranged that the lorry never returns empty to the manufacturing plant. It should be loaded to return with either re-usable packaging from the customers or raw materials needed to service the plant. Careful planning can substantially cut transport costs leading to a more economically viable operation.

10

Retrospect and prospect

10.1 Introduction

This final chapter covers a variety of topics. First, there are comments on some old methods that are no longer in commercial use, but which may return, perhaps in a variant form, in future. Second, it covers one minor texturing process which is still used. Third, it mentions some related technologies that give texture to yarns, though these do not involve subsequent manufacturing operations on continuous-filament yarns, which is the subject of this book. Finally, the future of texturing is considered, and some recent research, which may have commercial application in future, is described.

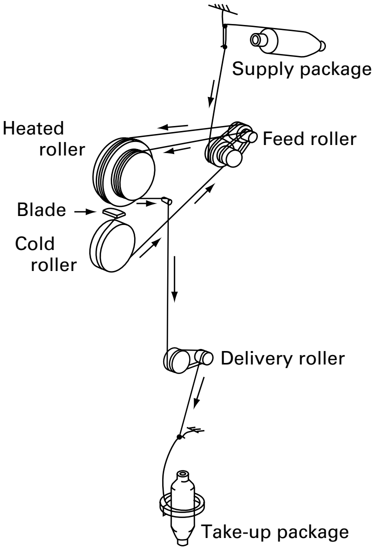
Two old processes need only a brief mention. Gear-crimping is an obvious way of imposing crimp by forcing yarn between intermeshing gear teeth which determine the crimp amplitude, shape and period. Trapped-twist texturing is a variant of false-twist texturing in which two ends of yarn are fed into heating and cooling zones where they are twisted together and then removed separately at the end.

10.2 Past technologies

10.2.1 Edge-crimping

When a fibre is pulled over a sharp edge it curls up, owing to reorientation of molecules near the scraped side. Figure 10.1 shows a photomicrograph, taken through crossed polars, of nylon filaments that have been edge-crimped. The flattening on one side is obvious. The light regions indicate that the molecules are oriented more-or-less perpendicular to the fibre axis and the dark regions parallel to the axis. In a multifilament yarn, not all of the fibres will make contact with the edge. However, bending of a yarn over an edge will cause all the fibres to be bent, generating tensile stress on the

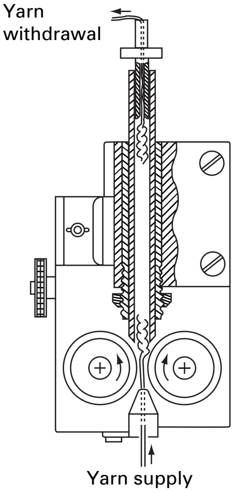
10.1 Filaments from edge-crimped yarn viewed through crossed polars. From Weller (1960).



10.2 Edge-crimping process. From Weller (1960).

outside of the bend and compressive stress on the inside. If the yarn is hot there will be rapid stress relaxation and the fibres will become set in the bent form. Filaments treated in this way will act in the way described in Section 2.6.3. As in false-twist texturing, the restraints on the ends of the yarns prevent the filaments taking up their most preferred form, and therefore stresses are relieved by buckling into another form. Because they want to bend, but are not allowed to twist, they will form alternating helices, as shown in Fig. 2.50.

Edge-crimping was used commercially around 1960. Figure 10.2 shows the arrangement in the *Agilon D* process. Nylon yarn is taken round a hot roller, over a blade and then round a cold roller. At this point, the yarn can



10.3 Stuffer-box. From McCormick (1960).

be taken to the delivery roll for take-up of the production of a high-stretch yarn in which the filaments form tight helices. In the arrangement shown in Fig. 10.2, the yarn continues to a set of smaller feed rolls, which allow it to contract to a limited extent and then to another set of hot rolls. This gives a modified yarn, with low stretch and high bulk.

10.2.2 Stuffer-box crimping

Ban-Lon yarns, produced by the stuffer-box method, were also commercially successful around 1960. Figure 10.3 illustrates the equipment used. Yarn is fed into the bottom of a tube, so that it is forced to buckle, usually in an approximation to a planar zig-zag form. The bottom of the tube is hot and the top is cold, so that the fibres are set in this form. In contrast to false-twist texturing, the fibres are able to take the form in which they have been set.

10.2.3 *Fibre M*

In the 1970s, *Heathcoat* developed a texturing process known as *Fibre M* and used it commercially for several years. The yarns produced were competitive with set-textured, polyester yarns from false-twist processing, though with some difference in character. The process, illustrated in Fig. 6.9, has affinities with jet-screen BCF texturing (Chapter 6), but, after bulking in the jet, the yarn cools in a tube under zero tension. The bulk comes from the asymmetric heating of the yarn in the hot jet, as described in Section 3.2.4. The process uses sequential draw-texturing. POY yarn is drawn through rollers and then fed into a high-pressure steam-jet. It emerges upwards into the tube, is pulled off at the top and goes to take-up. After *Heathcoat* ceased production, modifications of the process were applied by *ICI* in an integrated, yarn spinning (extrusion) and texturing operation, and by *Mackie* in the production of textured, high-denier, polypropylene yarns.

There are two points of particular interest in this process: speed and control. Commercially, *Heathcoat* ran the machines at about 1000 m/min. However, at ITMA 1975 they demonstrated its operation at around 4000 m/min with high-speed winders. The control mechanism operates through action on the steam temperature based on the bulk of the yarn in the tube. The incoming mass flow is governed by the incoming yarn linear density (tex) and its speed through the rollers. The outgoing mass flow is given by the linear density of the bulked yarn, which has contracted due to the fibre crimp, and the withdrawal speed. If the bulk is too great, the linear density will be too high and excess yarn will be removed; the level in the tube will fall. Conversely, if the bulk is inadequate, the level will rise. Consequently a level detector at the top of the tube can act as a sensor, with information fed back to the steam-temperature control. The control mechanism ensures that the yarn produced has uniform bulk, and, provided dye uptake correlates with bulk, uniform dyeability.

10.3 Current technology

10.3.1 Knit-de-knit process and yarns

Of the 12 texturing methods listed in Table 1.1 one of the few still in use is the knit-de-knit process. As the name implies, this comprises three separate stages, namely knitting on a single-feeder knitting machine of small diameter, heat-setting the knitted sleeve in a steam autoclave and then unravelling and rewinding the textured yarn.

Why has it survived into the new century in spite of the cost disadvantage arising from its three separate stages? First the process uses simple machinery, which only requires slight modifications of a single-feed knitting machine and a suitable winder. Second, the textured yarn characteristics are different from those produced by the three processes described in detail in this book.

The knitting machine itself resembles closely the type that is used in laboratories for checking the dye-uptake of textured yarns (see Section 8.3.4). In fact they are interchangeable. In some plants, knit-de-knit machines are used for dye testing. In others, laboratory knitting machines are used for experimental work with knit-de-knit yarns.

However, production machines are usually installed in banks, to facilitate material flow and control. A typical bank would consist of six knitting heads. Because of the simplicity of the process, there has been little development of the machinery used, but with one exception. Since the availability of POY it is now possible to purchase knit-de-knit heads fitted with a pre-drawing unit. In the case of polyester and polypropylene there would need to be a yarn heater between the two draw rolls. In most cases a hotpin of the type used in air-jet texturing would suffice (see Section 7.3.2).

Alfred Buck, whose company are (or were) makers of knit-de-knit machines reported equivalent yarn speeds of up to 720 m/min (Innes, 1980). It is more common for the knitting speed to be set so that yarn is consumed (and hence drawn) at around 500 m/min. This lies well within the performance capability of the standard hotpin.

The process variables consist of the stitch length and the setting temperature. The gauge of the knitting cylinder employed must match the decitex range of the yarns to be textured. Otherwise the major choice that must be made is the type and specification of the feeder yarn. In spite of the paucity of process variables, a wide range of yarns can be textured by this process, provided that a suitable knitting cylinder is specified. Of course, the yarn must be thermoplastic or else no significant heat-setting will be possible.

What are the characteristics that distinguish a knit-de-knit yarn? The setting and unravelling of the knitted loop results in a two-dimensional, wave-like crimp. This differs from both false-twist and air-jet texturing where the filaments are no longer parallel to each other. In fact the yarn does resemble that produced by stuffer-box texturing and indeed by the obsolete gear-crimping process.

Like a stuffer-box textured yarn, the crimp can be removed by a relatively low extension but it also returns on relaxation of the same yarn, provided no heat was applied whilst in its extended state. The second characteristic is the light reflectance that results from the parallel structure of the filaments. This enhances the ‘brightness’ of a trilobal yarn that has no delustrant. Thus the end uses are predominantly in the knitting industry, where a lustrous appearance is desired.

The properties of the textured yarn should be self-evident from this. Gupta and El-Sheikh (1982) showed that the load/elongation behaviour should result in a higher extension under a given load for a knit-de-knit yarn compared with either a stuffer-box or a gear-crimped yarn. The addition of a drawing unit adds a further dimension to the achievable textured yarn properties. Two ends can be knitted together, one being drawn differently to its partner so that it has a higher residual shrinkage. This means that the bulk is further enhanced during heat-setting.

If there is one lesson to be drawn from the survival of the knit-de-knit process, it is the fact that a process that can be made on modified machinery that is generally available has a much better chance of surviving than one requiring highly developed, specialised equipment. The exceptions that prove the rule are those described in this book. Why? Because the resulting products find a very wide appeal or the process itself proves to be very versatile.

10.4 Related technology

10.4.1 Bicomponent fibres

Another way of introducing crimp is to produce bicomponent fibres. The origins of the method date back over 100 years to waved 'Angel's hair', composed of two types of glass, and it was also used before 1950 on regenerated cellulose fibres. Crimped viscose rayon utilised the fact that the core could be caused to break out of the skin after the initial coagulation of the viscose solution on the fibre surface. Since the introduction of synthetic fibres, bicomponent-fibre yarns have moved from commercial to obsolete in various forms. Piller (1973) listed over 25 producer-textured bicomponent yarns, few if any of which are now in production. However, the advantages of the method ensure its revivals. In 2000, *DuPont* announced a new, nylon, bicomponent fibre.

In order to produce crimpable, bicomponent fibres, the usual method is to feed two streams with different composition to two sides of the spinnerets. Subsequent heat treatment causes differential shrinkage, which forces the fibres to bend. Since there can be no net twist, the filaments form alternating helices with reversals between, as described in Section 2.6.3.

10.4.2 Mixed-shrinkage fibres

A method that is much used for staple fibre yarns, but, in principle, could be applied to continuous-filament yarns is to combine mixed-shrinkage fibres. A particular example consists of acrylic fibres, which have a high shrinkage after stretch-breaking. Mixed shrinkage is achieved by combining relaxed and unrelaxed tows. When the mixed yarn is heated, the shrinkable fibres contract into the core of the yarn and the non-shrink ones form loose buckles on the outside.

10.4.3 Fibre form

Another way in which bulk can be increased, though without crimp and with less effect on texture, is by fibre form. Fibres with complicated shapes will fit together less well than circular fibres, so that higher packing factors result. Fibre volume itself can be increased, without increasing mass, by making hollow fibres.

10.5 New research and development

10.5.1 Activity

Most activity is centred upon increasing the achievable processing speed of false-twist texturing. There are two apparent aims that are being pursued:

1 incremental increases from the current 1100 m/min;
2 targeting speeds of 2000 m/min and over in order to make possible a link with spinning.

10.5.2 Incremental increases

By attention to the three main elements in the texturing zone, namely heating, cooling and twist insertion, and by maintaining the present machine concept, progress is being reported (Schmenk and Wulfhorst, 2000).

High-temperature heaters are fitted to present-day texturing machines (see Section 4.2.7.2). Their limitations have been described. Because the yarn has to withstand a higher ambient temperature and contact with individual ceramic guides rather than a long heater track, new finishes have been made necessary. An alternative approach has been to use a more conventional vapour-phase heater (see Section 4.2.7.1) but filled with a eutectic diphase liquid that has a higher temperature operating range. Such heaters may make fewer demands on the feeder yarn and the spin finishes employed.

Cooling tracks that guide, stabilise and cool the yarn have been used for many years. In order to increase cooling efficiency without extending the cooling zone various methods of intensifying the cooling have been tried. They involve cooling the cooling track, by circulating either air or water through the body. These solutions are not new but are perhaps now being applied seriously for the first time. As far as is known, intensive cooling is both practicable and effective within the range of incremental speed increases that are being attempted.

Similarly work to improve the efficiency of twist insertion is concentrated mainly upon the size, material and profile of the friction discs (see Section 4.2.9.1).

The result of this work has been to lift the achievable speed of texturing to 1500 m/min at least under controlled laboratory conditions. It may be assumed that new and modified machines will enable maximum speeds to be increased from 1100 to 1500 m/min during the coming years.

10.5.3 Target speeds > 2000 m/min

In order to consider the achievement of processing speeds of around or above 2000 m/min, most will agree that new machine concepts need to be considered. The objective of this thinking is to shorten the texturing zone from the present length of several metres to one of between 1.0 and 1.5 m. This should not only reduce the torque level that has to be provided by the friction spindle but also increase the limiting, surging speed. This latter is an assumption that is made widely but, as far as is known, has yet to be proved.

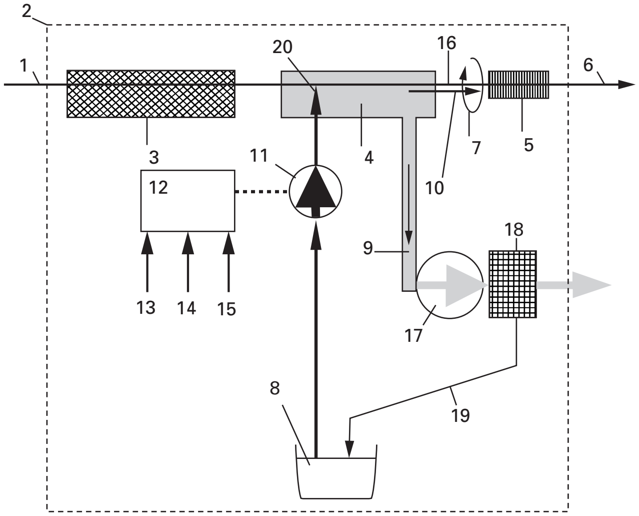
One approach has been to use a steam heater. One such heater, which was developed originally by *Heathcoat* for the *Fibre M* hot-fluid texturing process (see Section 10.2.3), has been used as a primary heater according to Foster (*et al* 1992). The rate of transfer of heat from a superheated fluid such as steam to yarn is very high and enables higher speeds to be used.

Why is it then that hot air is favoured over steam in many BCF processes (see Section 6.3.7)? This probably dates back to the early days of producing BCF yarns from nylon in the USA. It was found that textured nylon that had been heated by steam and subsequently dyed showed a greater tendency to dye shade changes in the Florida sun than if the same yarn had been heated using hot air. At this time nylon was the predominant textured carpet yarn in the USA where the industry grew rapidly. Thus hot air was preferred and there has been as yet no compelling reason for this to change.

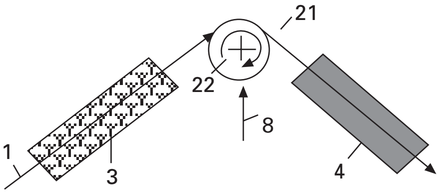
A second approach to the intensive heating of yarn during a short time period is to use the type of heated godet roller that is widely used for drawing immediately after spinning (see Section 6.2.3). One such 'concept' machine was shown by *Retech* at the ITMA exhibition in 1999 (Jaeggi, 1999). This type of heated godet is proven and the necessary spin finishes are well known. The initial cost may be higher compared with a conventional contact heater. On the other hand the achievable processing speeds and the fact that godets, like contact heaters, can be used to process more than one thread-line, reduces this apparent cost disadvantage. Since godets are already in widespread use for heating all types of fibre, it is logical to attempt to develop texturing processes using the existing process technology. This applies both to the roll surface specification and to the types of finish that are applied to the fibres before they reach the godet. So there are at least two types of heater that are capable of heating a yarn but which take up a few centimetres of space rather than 2.0–2.5 m.

Similarly work on intensive cooling has resulted in at least two cooling units which are able to cool the thread-line in a matter of centimetres. In one case this is achieved by the direct action of circulated water in a sealed chamber (Foster, 2001). The work at UMIST has shown that if the yarn is finish free when it reaches the spindle, the yarn tension is lower.

In research at ETH in Zurich, Meyer (2001) and his team have concentrated on improving the efficiency of fluid cooling in such a way that the twist insertion is enhanced, Fig. 10.4. Referring to this figure, water plus finish [8] is applied directly [20] to the heated and highly twisted yarn in a cooling zone [4]. An amount of finish [10] remains on the yarn after partial evaporation, which both protects the yarn and improves the effectiveness



10.4 Cooling by direct action of water in false-twist texturing process. From Meyer (2001). 1) Filament yarn; 2) Texturing machine position; 3) Heating zone; 4) Cooling zone; 5) Twisting unit; 6) Textured yarn; 7) Twist; 8) Fluid; 9 and 10) Vaporised residues; 11) Dosing pump; 12) Pump drive; 13) Yarn speed; 14) Yarn temperature; 15) Electrical resistance; 16) Yarn segment; 17) Vapour extract; 18) Condensate; 19) Condensate return.



10.5 Use of a twist stop in false-twist texturing process. From Meyer (2001). 1) Filament yarn; 3) Heating zone; 4) Cooling zone; 7) Untwisted yarn; 8) Twist stop; 21) Twisted yarn; 22) Free rotation of twist stop.

of twist insertion. In order to ensure that a proportion [10] of the total liquid is applied to the highly twisted yarn [7] and does not condense [9] the application is achieved by means of a metering pump [11] with an independent drive [12]. Process parameters such as the yarn speed [13] and its temperature [14] are part of the pump drive control input. Furthermore, to monitor the finish applied, the electrical resistance of the yarn [15] is measured at a point [16] before the twisting unit.

The first stage of yarn cooling follows as a result of the evaporation of the cooling fluid [8]. To prevent pollution of the air around the threadline, fume extraction [17] together with a condensate return [18 and 19] is recommended. In order to maintain constant processing conditions, the fluid [8] is cooled to below room temperature.

Figure 10.5 illustrates the function of a twist-stop situated between the heating and cooling zones of the false-twist texturing process. In order to ensure a stable threadpath in the cooling zone of the process, the twist at the outlet of the heating zone [3] is held back by a twist-stop [21] of a known type, consisting of a rotating divergence roll [22]. The cooling fluid [8] is applied to the yarn [1] immediately after the twist-stop, but preferably at the divergence roll [21] itself.

Provided the yarn is hot when it reaches the twist-stop, twist-setting is achieved by inserting the maximum twist at this point, and then cooling the yarn before untwisting in the friction spindle. The lack of twist in the yarn on the heater and the resulting open structure of the yarn will cause faster heating. The result of this is that texturing speeds of up to 2000 m/min have been achieved.

A further aspect of this work is that, whereas a proportion of the applied cooling fluid is retained by the yarn as a lubricant, any excess after condensation and lubrication is recycled.

The final piece of the jigsaw is the insertion of twist at very high speed. Much of the work to date has centred upon the further development of the stacked disc or friction spindle. A spiral spindle with integral yarn cooling has been reported by Callhof (2000) from RWTH Aachen.

At UMIST work is proceeding to perfect a twist insertion system based on fluids (Foster 2001). This holds much promise, because it should be capable of providing the required level of torque, unlike air. There is also a neat symmetry in a new process involving superheated steam for heating and a second fluid both for cooling and twist insertion.

10.5.4 Authors' comments

Work to increase the processing speed of the false-twist texturing process, whether by stages or by a leap of faith into the 2000 m/min range can only be commended. Like motor racing there is always a considerable and beneficial spin-off that results in improvements to existing machines and processes.

There are considerable obstacles to the achievement of speeds at or over 2000 m/min, not least the need for a machine maker to provide the resources required to convert laboratory rigs into commercial machines. The costs may not be justified for a doubling of speed. The real challenge would be to match current winding speeds in excess of 5000 m/min. Technical factors include the fact that any process that requires heating and cooling of a thermoplastic yarn must take into account that molecules do not change their structure instantly. There may be a point at which the texturing zone is simply too short, so that the time required for the yarn to be successively heated, cooled and twisted exceeds the elapsed time. There are examples that can be quoted from the drawing and relaxing of thermoplastic yarns after spinning that bear this out. Certainly the results will vary from fibre to fibre. In comparison with conventional heating and cooling there is no doubt that the use of certain fluids will result in a much more rapid transfer of heat to or from the yarn at high speeds. However, any fluid that comes into direct contact with a yarn is going to wash off some of the applied lubricant together with monomer and other impurities. This opens up a new can of worms!

Now that automatic doffing is a proven technique not only at spinning but also after texturing, one of the objections to high-speed processing has been removed. Handling techniques have been developed to enable spinning and winding to be operated at over 5000 m/min and the BCF process shows that a spinning, drawing and texturing process can be operated successfully at speeds approaching this level.

Does it make sense to integrate spinning with false-twist texturing? Perhaps not for yarns of below 500 dex. The loss of flexibility and the difficulties involved in maintaining product quality with such a complex process militate against its widespread use in the near future. But that does not mean that it will not be attempted. Advanced sensing techniques linked to computer control may enable quality to be maintained and allow processing parameters to be automatically changed to provide product variety. There may well be niche products that lend themselves to an integrated process. Indeed production of the *Mitrelle* ® yarn launched by *ICI Fibres* some years ago used a steam-heated *Fibre M* ® jet in direct line with spinning at speeds of over 6000 m/min. New integrated processes may well appear as a result of the demand for BCF yarns in ever finer counts. This will inevitably revitalise efforts to combine spinning with false-twist texturing. Who knows?

There are also challenges for academic research. If the comparative ignorance of synthetic fibre fine structure, its formation and its link to properties and performance were replaced by scientific understanding, a new generation of feed yarns might become available. Linked to this is the need to have better models of heat-setting – and to know which of the various suggested mechanisms occur in reality. The mysteries of modern physics may be involved in fibre structure formation and modification, if there is any validity in Hearle's (1994) speculation that these processes may involve quantum superposition. For the false-twist process itself, there would be benefit from knowing how the process operates in the post-surging mode. If this was understood, it might be easier to find ways of avoiding it and so increase the speed at which the pre-surging mode breaks down and surging starts. Finally, advances in CAD/CAM will come in the 21st century. Computer models will lead to a numerically predictive, engineering design approach to textile processes and products, in place of the traditional empiricism of trial and error.

Appendix 1

Textured condition reference chart

Effect upon → Increase in ↓	T1 Tension	T2 Tension	Tension ratio	T3 Tension	Twist	Broken filaments	Tight spots	Dye shade depth	Decitex	% elongation	Tenacity	% Shrinkage	Bulk	Webbing	Bulging	Undwinding breaks	Snow generation	Package density	Knots per metre	Knot retention
Throughput speed	↗	↗	⇗	⇗	→	⇗	→	↗	→	↳	→	→	⇘	→	→	→	↗	→	↘	→
Draw ratio	↗	↗	↗	⇗	⇗	↗	↘	↘	↘	↘	↗	⇗	⇘	↱	→	→	⇗	⇗	→	→
Primary heat	→	⇘	⇘	→	→	⇗	→	↘	→	→	↳	↗	↗	→	→	→	↳	→	→	→
D/Y ratio	⇗	↘	↘	⇘	→	↘	↗	→	→	↳	↳	→	↗	→	→	→	↱	→	→	→
Disc numbers	↘	↘	↘	⇘	↗	↘	↗	→	→	→	⇘	→	↗	→	→	→	↗	→	→	→
Secondary heat	→	→	→	↗	→	↱	↗	→	→	→	→	↘		↱	→	→	→	↗	↘	→
Secondary overfeed	→	→	→	⇘	→	→	⇘	→	→	→	→	↗	⇗	→	→	→	→	↱	⇗	↱
Take - up overfeed	→	→	→	↘	→	→	→	→	→	→	→	→	→	↘	→	↗	→	↘	→	↱
Wind angle	→	→	→	↗	→	→	→	→	→	→	→	→	→	↗	↘	↗	→	↗	→	→
Taper angle	→	→	→	⇗	→	→	→	→	→	→	→	→	→	⇗	→	↗	→	→	→	→
Jet pressure	→	→	→	↱	→	↱	→	↱	⇗	→	⇘	⇘	⇘	↱	→	↘	→	⇗	↗	↗

Key guide

Increase	↗
Decrease	↘
NO effect	→
Slight decrease	⇘
Slight increase	⇗
VARIABLE but tends towards	↱
VARIABLE but tends towards	↳

Appendix 2

Machine speed and general calculations

D/Y ratio

$$\text{D/Y ratio} = \frac{\text{disc dia.(meters)} \times \pi \times \text{disc rpm.}}{\text{throughput speed}}$$

Disc rpm

$$\text{disc rpm} = \frac{\text{throughput speed} \times \text{D/Y ratio}}{\text{disc dia(meters)} \times \pi}$$

Input shaft speed

$$\text{input shaft speed} = \frac{\text{centre shaft speed}}{\text{draw ratio}}\,\text{m/min}$$

Bottom shaft speed

$$\text{bottom shaft speed} = \text{centre shaft speed} \times \frac{(100 - \text{SH overfeed \%})}{100}$$

Take up shaft speed

$$\text{take up shaft speed} = \text{centre shaft speed} \times \frac{(100 - \text{take up overfeed \%})}{100}$$

Traverse rate

$$\text{traverse rate} = 2 \times \tan(\text{wind angle}) \times \text{take up speed}$$

Production rate

production in kgs/machine/hour at 100% efficiency

$$= \frac{\text{POY decitex} \times \text{input shaft speed} \times \text{no of spindles} \times 60}{10\,000 \times 1000} + \text{\% oil on yarn}$$

Taper angle

$$\text{taper angle} = \tan\left(\frac{\text{yarn depth on package (mm)} \times 2}{\text{(initial stroke} - \text{final stroke) mm}}\right)$$

Ribbon phase diameters

$$\text{diameter} = \frac{\text{take up speed (m/min)}}{(\text{Traverse cycles per min.} \times \pi \times N)} \times 1000 \text{ mm}$$

where N is a whole number between 1 and 9

Package density

A = initial stroke length (mm)
B = final stroke length (mm)
C = yarn depth on package (from tube wall to outside of package) (mm)
D = nett weight of package in grams

$$\text{Density} = \frac{954.9297 \times D}{2(AC + 2BC + 112.5A + 112.5B)} (\text{g/cm}^3)$$

To convert rpm to metres per minute

$$\text{metres per min.} = \text{shaft diameter in metres} \times \text{rpm} \times \pi$$

To convert metres per minute to rpm

$$\text{rpm} = \frac{\text{shaft speed (m/min)}}{\text{shaft diameter in metres} \times \pi}$$

To convert decitex to denier

denier = decitex × 0.9
i.e. 167 dtex = 150.3 denier

To convert denier to decitex

decitex = denier × 1.11
i.e. 70 denier = 77.7 decitex

To convert units of specific stress

$$1\,\text{N/tex} = 10\,\text{cN/dtex} = 11/3\,\text{g/den} = 102\,\text{gf/tex}$$

$$\text{i.e. N/tex} \times 11.3 = \text{g/den} \quad \text{where } 11.3 = \frac{1}{0.9 \times 9.81} \times 1000$$

To calculate mingle air comsumption. m^3/hr/JET

Constants 1bar = 14.504 psi
$1\text{m}^3/\text{hr} = 0.588$ cfm
Z = No. of air orifice within jet
D = Diameter of air orifice mm
Pe = operating pressure (bar)

$$\text{Air consumption m}^3/\text{hr/jet} = (Z^2 \times D \times 0.4648) \times (Pe + 1)$$

To convert to ft^3/min multiply by 0.588

General conversions

To convert metres to yards multiply by 1.0936

e.g. 100 metres × 1.0936 = 109.39 yards

To convert yards to metres multiply by 0.9144

e.g. 500 yards × 0.9144 = 457.2 metres

To convert inches to metres divide by 39.37

e.g. 100 inches/39.37 = 2.54 metres

To convert inches to centimetres multiply by 2.54

e.g. 12 inches × 2.54 = 30.48 centimetres

To convert square yards to square metres multiply by 0.8361

e.g. 8 square yards × 0.8361 = 6.6888 square metres

To convert kilogrammes to lb multiply by 2.2046

e.g. 100 kilogrammes × 2.2046 = 22 046 lb

To convert lb to kilogrammes multiply by 0.4536

e.g. 100 lb × 0.4536 = 45.36 kg

To convert ton to metric tonne multiply by 0.9842

e.g. 2 ton × 0.9842 = 1.9684 metric tonne (i.e. 1 968.4 kg)

To convert gallons to litres multiply by 4.546

e.g. 5 gallons × 4.546 = 22.73 litres

To convert pints to litres multiply by 0.5682

e.g. 5 pints × 0.5682 = 2.841 litres

To convert pressure, in bar, to psi multiply by 14.504

e.g. 2.5 bar × 14.504 = 36.26 psi

To convert flow (air comsumption) from m^3/hr to ft^3/min, multiply by 0.588

e.g. 6.0 m^3/hr × 0.588 = 3.528 ft^3/min

To convert degrees to radians

$$1 \text{ radian} = \frac{\pi}{180} \text{degrees}$$

Bibliography

Extensive reviews of the literature (a total of 923 references) on yarn texturing are given in the following issues of Textile Progress: Wilson (1977, 1978), Wilson and Kollu (1987, 1991). An extensive bibliography is also given by Demir and Behery (1997). Earlier accounts are in publications by Monsanto: Chemstrand (1962, 1963, 1967); Monsanto (1974). The list below contains, in addition to the above entries, only references cited in the text.

Acar M and Wray G R (1986a), 'An analysis of the air-jet yarn-texturing process. Part I: A brief history of developments in the process' *J Textile Inst* **77** 19–27.

Acar M and Wray G R (1986b), 'An analysis of the air-jet yarn-texturing process. Part VII: 'The effects of processing parameters on yarn properties' *J Textile Inst* **77** 371–376.

Acar M, Turton R K and Wray G R (1986a), 'An analysis of the air-jet yarn-texturing process. Part II: 'Experimental investigation of the air-flow' *J Textile Inst* **77** 28–43.

Acar M, Turton R K and Wray G R (1986b), 'An analysis of the air-jet yarn-texturing process. Part III: 'Filament behaviour during texturing' *J Textile Inst* **77** 247–254.

Acar M, Turton R K and Wray G R (1986c), 'An analysis of the air-jet yarn-texturing process. Part IV: 'Fluid forces acting on the filaments and the effects of filament cross-sectional area and shape' *J Textile Inst* **77** 255–262.

Acar M, Turton R K and Wray G R (1986d), 'An analysis of the air-jet yarn-texturing process. Part V: 'The effect of wetting the yarns' *J Textile Inst* **77** 359–370.

Acar M, Turton R K and Wray G R (1986e), 'An analysis of the air-jet yarn-texturing process. Part VI: 'The mechanism of loop formation' *J Textile Inst* **77** 371–376.

Arthur D F (1960), *Bulked yarns by the false-twist method* in Wray (1960).

Bell J P and Murayama T (1969), 'Relations between dynamic mechanical properties and melting behavior of nylon 66 and poly(ethylene terephthalate)' *J Polymer Sci* **A2** **7** 1059–1073.

Bell J P, Slade P E and Dumbleton J H (1968), 'Multiple melting in nylon 6' *J Polymer Sci* **A2** **6** 1773–1781.

Bösch F (2000), 'Airjet texturing 1950–2000' *Chemical Fibers Int* **50** 166–168.

Brunnschweiler D and Hearle J W S, editors (1993), *Polyester: 50 years of achievement*, The Textile Institute, Manchester, UK.

Callhoff C *et al* (2000), 'New solutions for the high-speed false-twist texturing process' *Chemical Fibers Int* **50** 490–493.

Chemstrand (1962), *Stretch woven fabrics*, Chemstrand Corporation, Decatur, Alabama, USA.

Chemstrand (1963), *Textured yarns of Chemstrand nylon*, Monsanto Chemical Company, USA.

Chemstrand (1967), *Textured yarn technology* 2 *Stretch yarn machines*, Monsanto Company, USA.

Coats, J & P, Ltd (1981), 'Synthetic yarn and yarn-like structures and a method for their production' EP 0 057 583 B2 (GB 4 Feb., 1981).

Davis H, McGregor R, Pastore C and Timble N (1996), 'Human perception and fabric streakiness' *Textile Res J* **66** 533–544.

Demir A (1987), 'The air-jet texturing process with particular reference to the nozzle design and improved test methods' *PhD thesis*, Loughborough University of Technology, England.

Demir A and Behery H M (1997), *Synthetic filament yarn: texturing technology*, Prentice Hall, Upper Saddle River, NJ, USA.

Denton M J (1968), 'The development of false twist in bulking' *J Textile Inst* **68** 344–350.

Du G W and Hearle J W S (1989a), 'Threadline instability in the false-twist texturing process. Part I: Experimental observations of surging' *J Textile Inst* **80** 203–215.

Du G W and Hearle J W S (1989b), 'Threadline instability in the false-twist texturing process. Part II: The influence of process parameters on threadline instability' *J Textile Inst* **80** 203–215.

Foster P W (2001), private communication, UMIST, Manchester, UK.

Foster P W *et al* (1992), 'Constant bulk false-twist texturing' presented at Conference of the Textile Institute Fibre Science Group, 1992, The Textile Institute, Manchester, UK.

Goswami B C, Martindale J G and Scardino F L (1977), *Textile yarns: technology, structure and applications*, Wiley-Interscience, New York, USA.

Gupta A K and El-Shiekh A (1982), 'Load-deformation behaviour of two-dimensional crimped filaments' *Textile Res J* **52** 621–632.

Hearle J W S (1966), 'Structural mechanics of torque-stretch yarns: the mechanism of snarl formation' *J Textile Inst* **57** T441–T460.

Hearle J W S (1967), 'The structural mechanics of fibres', *J Polymer Sci, Part C, Polymer Symp* **No. 20** 215–252.

Hearle J W S (1978), 'On structure and thermomechanical responses of fibres and the concept of a dynamic crystalline gel as a separate thermodynamic state', *J Appl Polymer Sci: Appl Polymer Symp* **31** 137–161.

Hearle J W S (1979a), 'Studies in friction-twisting. Part I: A simple treatment of the slipping mode' *J Textile Inst* **70** 287–297.

Hearle J W S (1979b), 'The difference between pin-twisting and friction-twisting' *J Textile Inst* **70** 321.

Hearle J W S (1994), 'Does quantum magic impinge on polymer physics?' *Polymer Eng Sci* **34** 260–265.

Hearle J W S and Beech S R (1980), 'Studies in friction-twisting. Part II: 'The positive mode' *J Textile Inst* **71** 225–235.

Hearle J W S and Greer R (1970a), 'Fibre structure', *Textile Progress* **2** No. 4.

Hearle J W S and Greer R (1970b), 'On the form of lamellar crystals in nylon crystals' *J Textile Inst* **61** 240–244.

Hearle J W S and Miles L W C, editors (1971), *The setting of fibres and fabrics*, Merrow, Watford, UK.

Hearle J W S and Yegin A E (1972a), 'The snarling of highly twisted monofilaments. Part I: The load-elongation behaviour with normal snarling' *J Textile Inst* **63** 477–489.

Hearle J W S and Yegin A E (1972b), 'The snarling of highly twisted monofilaments. Part II: Cylindrical snarling' *J Textile Inst* **63** 490–501.

Hearle J W S and Yegin A E (1973), 'The mechanics of torque-stretch yarns: a correction' *J Textile Inst* **64** 601–606.

Hearle J W S, Burnip M S and Wray G R (1961), 'The technology of the production of false-twist textured yarns' *J Textile Inst* **52** P343–366.

Hearle J W S, Grosberg P and Backer S (1969), *Structural mechanics of fibers, yarns and fabrics*, Wiley-Interscience, New York, USA.

Hearle J W S, Sultan M A L and Govender S (1976a), 'The form taken by threads laid on a moving belt. Part I: Experimental study' *J Textile Inst* **67** 373–376.

Hearle J W S, Sultan M A L and Govender S (1976b), 'The form taken by threads laid on a moving belt. Part II: Mechanisms and theory' *J Textile Inst* **67** 377–381.

Hearle J W S, Sultan M A L and Govender S (1976c), 'The form taken by threads laid on a moving belt. Part III: Comparison of materials' *J Textile Inst* **67** 382–386.

Hearle J W S, Thwaites J J and Amirbayat J (1980), *Mechanics of flexible fibre assemblies*, Sijthoff & Noordhoff, Alphen den Rijn, Netherlands.

Innes R (1980), 'New knit-de-knit circular machine designed' *Knitting Times*, February, 8.

Isaacs G E (1990), *Recent developments in technology for false twist texturizing*, 29th International Man-Made Fibres Congress, Dorn Urin 1990.

Jaeggi M (1999), 'TEX2000 – a new concept for false-twist texturing' *Chemical Fibers Int* **49** 428–429.

Kollu T (1982), 'Structure and properties of air-jet textured yarns' *MSc thesis* University of Manchester, England.

Kollu T (1985), 'Air-jet textured yarns' *PhD thesis* University of Manchester, England.

Konopasek (1980), in Hearle *et al* (1980) 255–310.

Kugler J, Gilmer J W, Wiswe D, Zachman H G, Hahn K and Fischer E W (1987), 'Study of transesterification of poly(ethylene terephthalate) by small-angle neutron scattering' *Macromolecules* **20** 1116–1119.

McCormick W H (1960), 'Bulked yarns produced by a stuffer box method' in Wray (1960) 111–121.

Meyer U (2001), private communication, ETH, Zürich, Switzerland.

Miller R W (1994), 'Influence of Suessen and Superba heat setting on optical streak intensity in finished nylon carpets' *Textile Res J* **64** 75–87.

Miller R W and Southern J H (1991), 'Nylon 66 carpet streaks versus fiber crimp and dyeability' *Textile Res J* **61** 61–70.

Monsanto (1974), *Draw-textured yarn technology*, Monsanto Textiles Company, USA.

Morton W E and Hearle J W S (1993), *Physical properties of textile fibres*, 3rd edition, The Textile Institute, Manchester, England.

Murata Machinery Ltd (1993), No. 334 Mach Crimper, Cat. No. 218602 93-10-3 (NS).

Murthy N S, Reimschussel A C and Kramer V J (1990), 'Changes in void content and free volume in fibers during heat setting and their influence on dye diffusion and mechanical properties' *J Appl Polymer Sci* **40** 249–262.

Penrose R (1989), *The Emperor's new mind*, Oxford Univ Press, England.

Piller B (1973), *Bulked yarns: production, processing and applications*, The Textile Trade Press, Manchester UK.

Salem D R (1982), 'Micromechanisms involved in the texturing of polymeric fibres' *PhD thesis* University of Manchester, England.

Schellenberg H (1984), 'Developments and tendencies in BCF texturing' *Chemiefasern/Textilindustrie* **34/86** E122–E125.

Schmenk B and Wulfhorst B (2000), 'Reduction of process interferences in high-speed texturing' *Chemical Fibers Int* **50** 496–501.

Takayanagi M (1963), 'Viscoelastic properties of crystalline polymers' *Mem Fac Eng Kyushu Univ* **23** 41–96.

Thwaites J J (1970), 'The mechanics of friction-twisting' *J Textile Inst* **61** 16–138.

Thwaites J J (1978a), 'The dynamics of the false-twist process. Part I: The process surveyed' *J Textile Inst* **69** 269–275.

Thwaites J J (1978b), 'The dynamics of the false-twist process. Part II: A theoretical model' *J Textile Inst* **69** 276–286.

Thwaites J J (1984a), 'The dynamics of the false-twist process. Part V: Response to variations in feedstock' *J Textile Inst* **75** 112–122.

Thwaites J J (1984b), 'The mechanics of friction-twisting reassessed. Part I: The yarn path in a disc spindle' *J Textile Inst* **75** 285–297.

Thwaites J J, Brookstein D S and Backer S (1976), 'Deductions about the false-twist process from observations of the variation of torque on detwisting a twisted heat-set yarn' *J Textile Inst* **67** 183–186.

Thwaites J J and Hooper C W (1981a), 'The dynamics of the false-twist process. Part III: Experiments with fully drawn yarn' *J Textile Inst* **72** 239–248.

Thwaites J J and Hooper C W (1981b), 'The dynamics of the false-twist process. Part IV: Draw-texturing experiments' *J Textile Inst* **72** 249–257.

Van der Meer S J (1970), 'Dynamic mechanical properties of yarns, cords, and plain-weave fabrics', *Doctoral thesis* Technical University of Delft, Netherlands.

Weller A F (1960), 'Bulked yarns produced by edge crimping' in Wray (1960) 122–132.

Wilson D K (1977), 'The production of textured yarns by methods other than the false-twist technique' *Textile Progress* **9** Number 3.

Wilson D K (1978), 'The production of textured yarns by the false-twist technique' *Textile Progress* **10** Number 3.

Wilson D K and Kollu T (1987), 'The production of textured yarns by methods other than the false-twist technique' *Textile Progress* **16** Number 3.

Wilson D K and Kollu T (1991), 'The production of textured yarns by the false-twist technique' *Textile Progress* **21** Number 3.

Wray G R, editor (1960), *Modern yarn production*, Columbine Press, Manchester, UK.

Yegin A E (1969), 'Structural mechanics of torque-stretch yarns', *PhD thesis* University of Manchester, England.

Index