2

Scientific and engineering principles in twist-texturing

2.1 Introduction

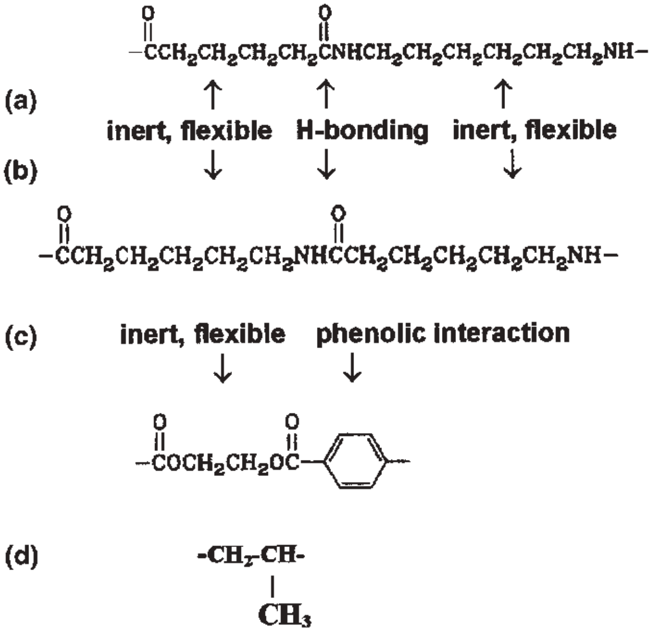
Like most developments on the mechanical side of the textile industry, the inventions and developments in yarn texturing have not come as a rational sequence from basic science, through engineering calculations to practical implementation. Empirical advance based on intuitive understanding has been the 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

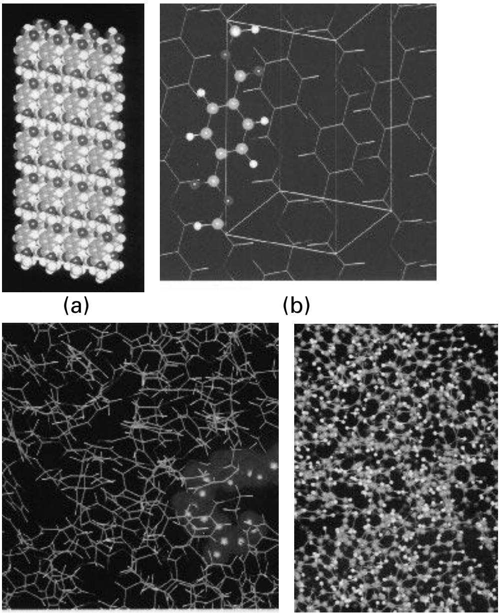


2.1 Features of the chemical formulae of (a) polyamide – nylon 66, (b) polyamide – nylon 6, two repeats, (c) polyester – polyethylene terephthalate (PET), (d) polypropylene.

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

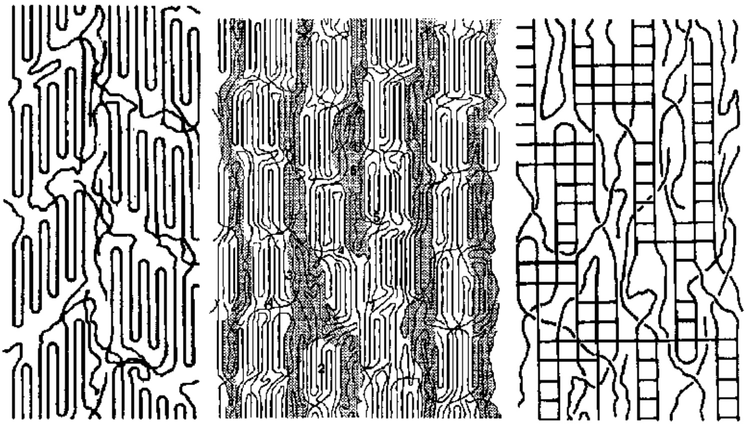


2.2 Computer-generated models of molecular packing in PET. (a),(b) Crystalline. (c),(d) Amorphous. Produced for *Polyester: 50 years of achievement*, Brunnschweiler and Hearle (1993) by Dr Andrew Tiller of BIOSYM Technologies Inc.

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;



(a) (b) (c)

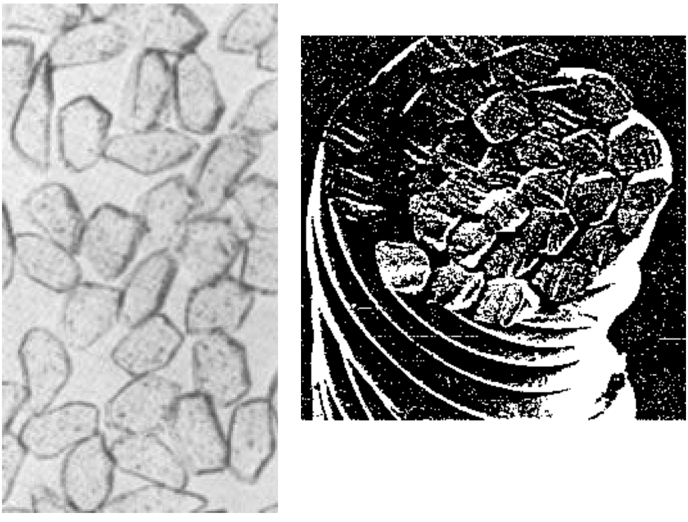
2.3 Fine structure of nylon and polyester fibres. (a) A view of the common working model by Hearle and Greer (1970b), drawn in order to show angled ends, related to the crystal lattice, as a cause of a feature of the small-angle, X-ray diffraction pattern of nylon 66. (b) A view by Murthy *et al* (1990),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

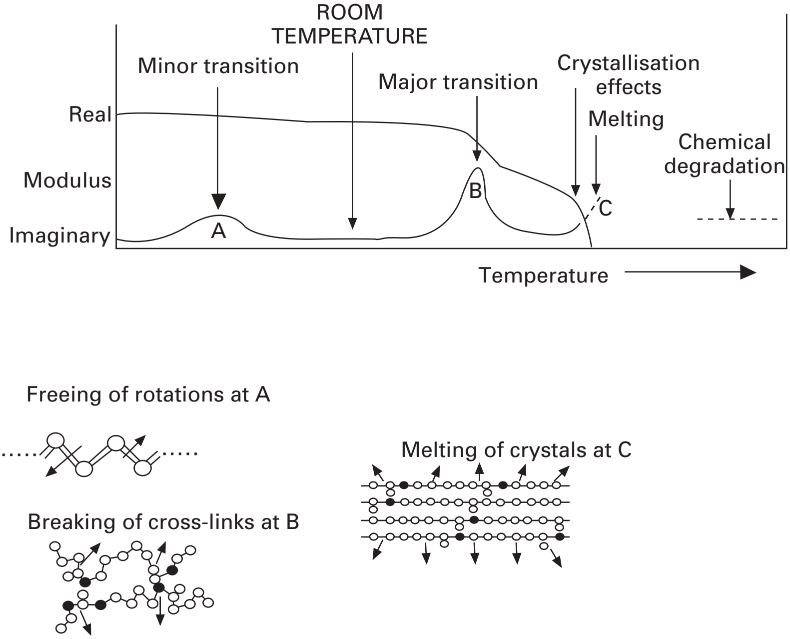
Nylon 66 and polyester (PET) fibres have five important regions of thermal transitions: at around –100°C, 100°C, 200°C, 260°C and 300°C. The


(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

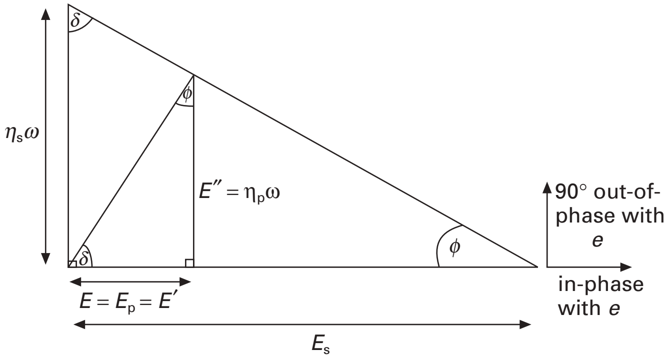
Representation	Elastic part (in-phase)	Viscous part (out-of-phase)
Simple related forms		
Spring and dashpot in parallel	Spring constant = E_p	Viscosity = η_p
Modulus and loss factor	$E = E_p$ = in-phase stress amplitude ÷ strain amplitude	$\tan\delta = \eta_p\omega/E_p$
Complex number	Real part = $E' = E = E_p$	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.

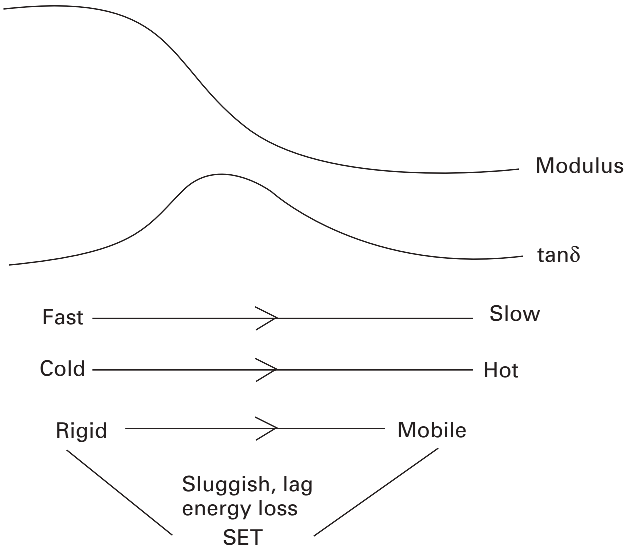
2.2.3 Dynamic mechanical analysis: temporary set

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).

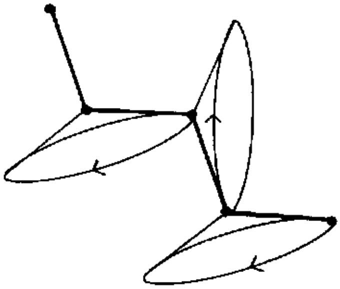


2.7 Features of a second-order transition.

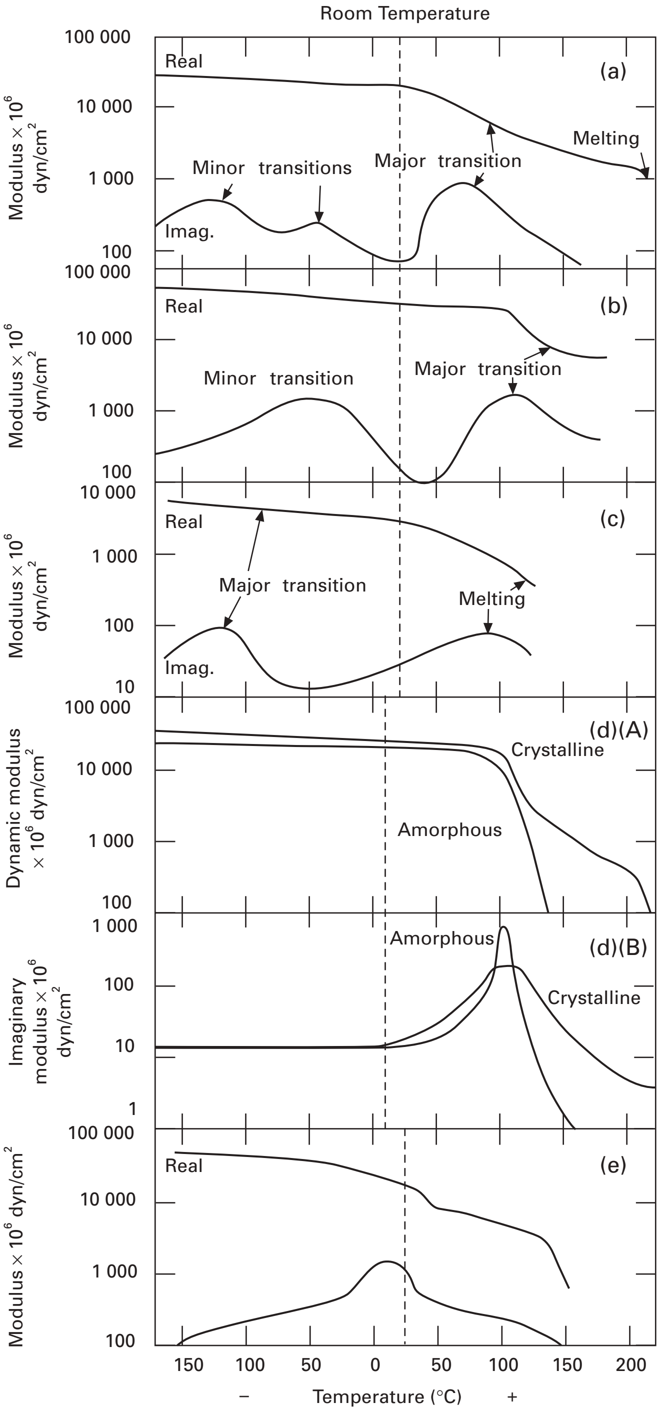
melting, is due to some element within the structure changing from a rigid form to a mobile state. The features of such a transition are shown in Fig. 2.7. The elastic modulus drops because the material is more easily deformed. The viscous part peaks because there is a sluggish response in going through 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



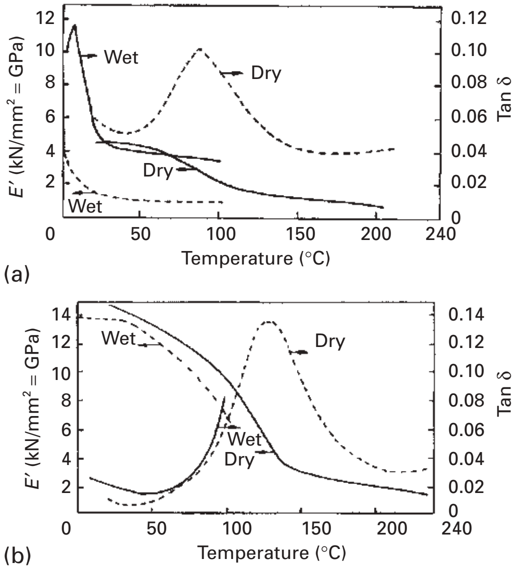
2.8 Rotation at tetrahedral carbon–carbon bonds.



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.

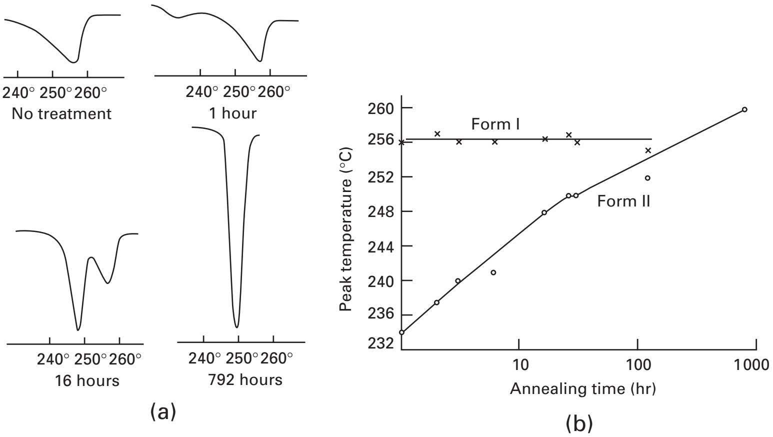


2.10 Dynamic modulus *E′* and loss factor tan δ, wet and dry, for (a) nylon 6 and (b) polyester (PET), from Van der Meer (1970).

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,



(a)

(b)

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.

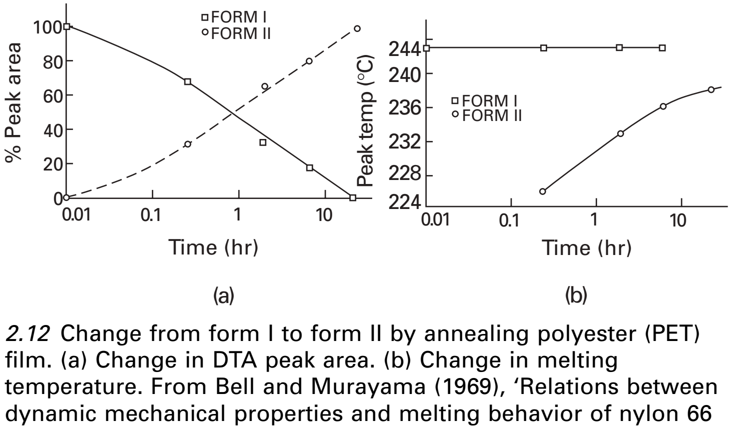
The situation is slightly different in polyester, because undrawn material is amorphous. This means that when a sample is heated in DSC, an exotherm appears at a temperature, typically around 120°C, at which crystallisation takes place. However, the melting behaviour is similar to nylon, as shown by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

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

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



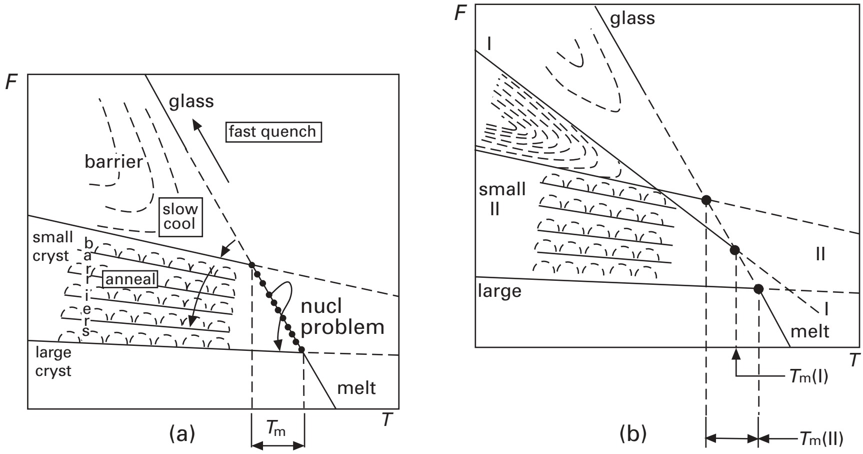
(a) (b)

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.

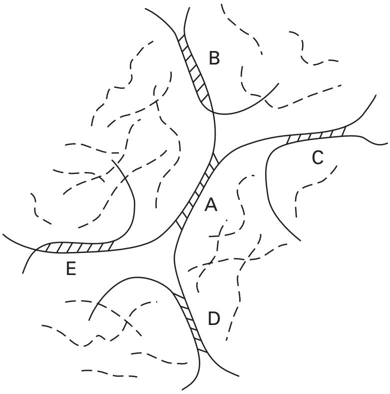
conventional picture is shown in Fig. 2.13(a). The line for the melt, which becomes a glass at low temperature, starts high but falls rapidly, because of the large values of *U* and *S*. The lowest line for a large, perfect crystal has a lower slope and cuts the melt line at the equilibrium melting point. 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

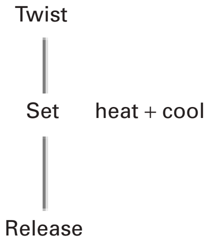
At last, we come to what is directly relevant to texturing. What happens at texturing temperatures between about 180 and 220°C? As already mentioned, there has been a lack of fundamental research on what happens in this temperature range, particularly in regard to the mechanisms involved and the structural 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.

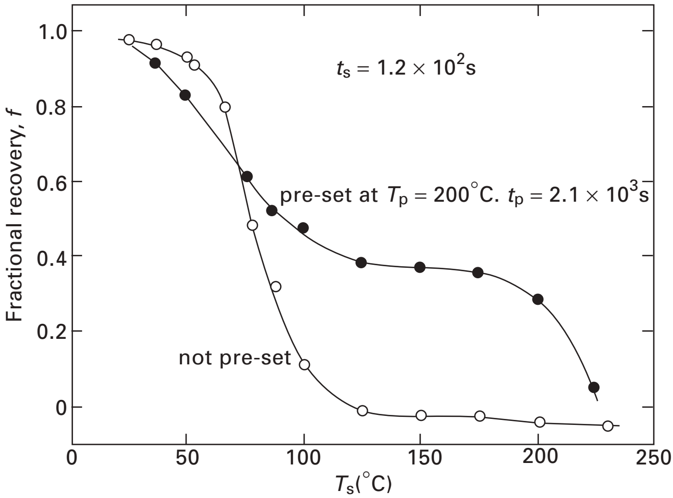
There is an interesting question in terms of the meaning of the word ‘*setting*’. A thermo-setting resin, such as the adhesive *Araldite*, is set by the action of heat, which cross-links the molecules; but, for thermoplastics such as nylon and polyester, setting requires heating and cooling. Heat puts 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).



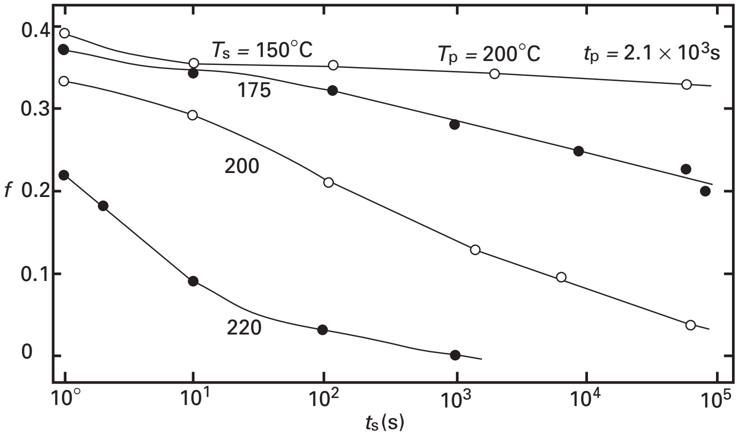
2.16 Fractional recovery after setting of polyester monofilament. From Salem (1982).

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.

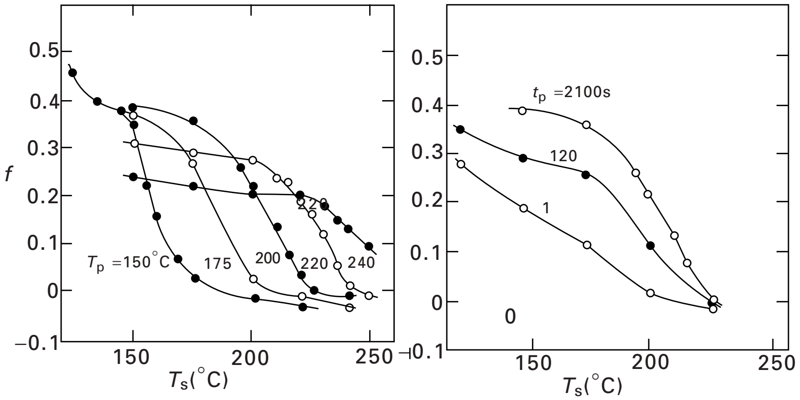
Figure 2.16 shows the change in recovery with setting temperature for both conditions. Effects in bending and twisting are similar. If the yarn had not been pre-set, the 100°C transition gives a sigmoidal plot from $f = 1$ to $f = 0$ between 50 and 125°C. There is full relaxation of the torsional stress 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 pre-setting 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.

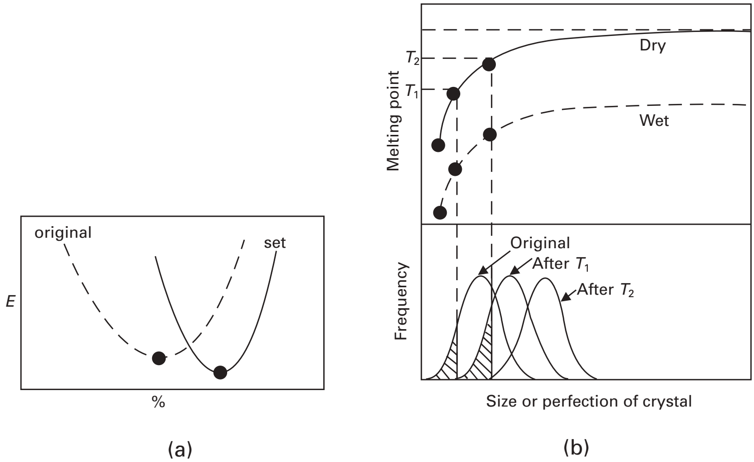
The use of steam does have advantages in efficiency of heating and, as described in Chapter 10, research has shown that it enables shorter heaters to be used. However, the practical difficulties of containing the steam have prevented its use in commercial false-twist texturing.

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.



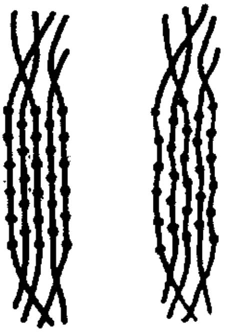
(a) (b)

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.

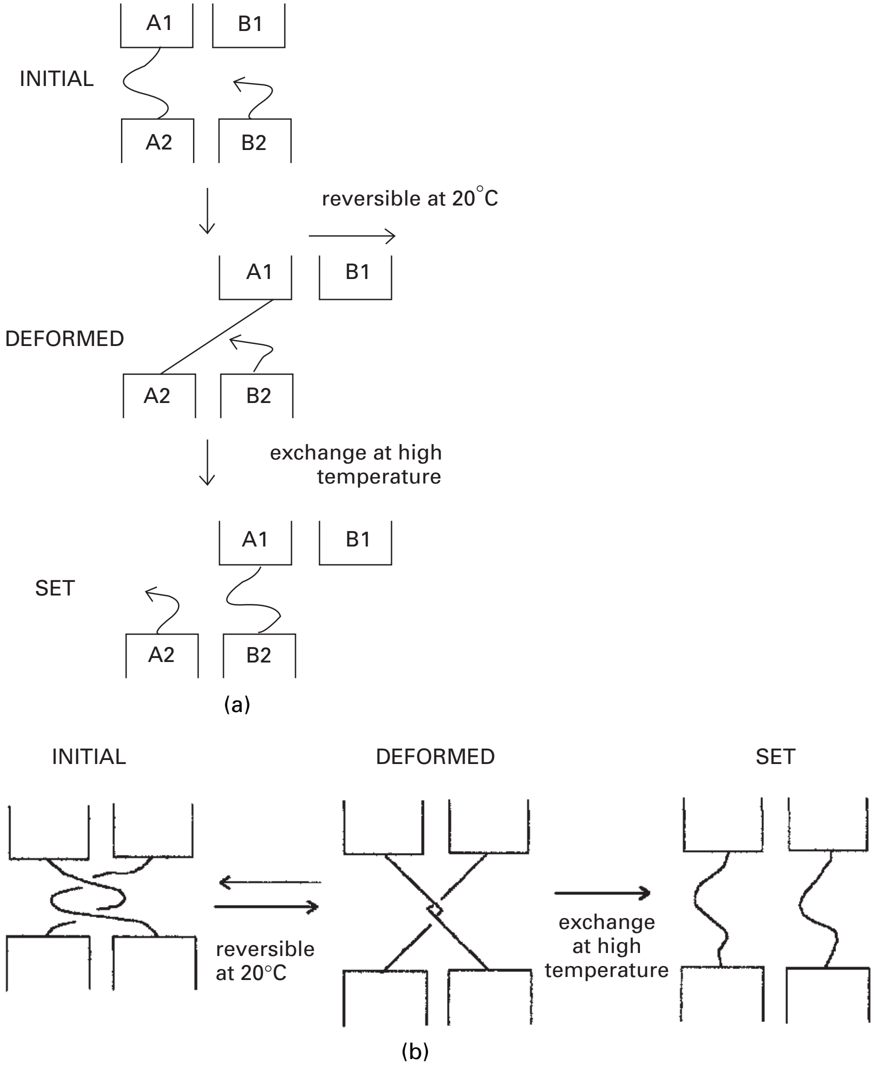
A more unusual suggestion (Hearle, 1994) is that polymer crystallisation involves quantum effects and is not a purely classical phenomenon. The quantum theory explanation of diffraction experiments with two slits through which an electron or a photon can pass, is that both possibilities exist until measurement 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.

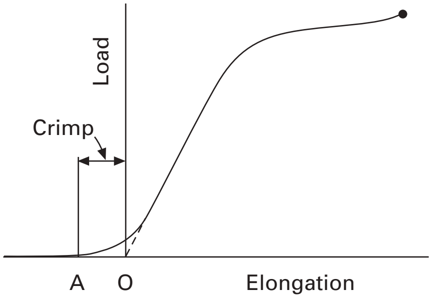
2.2.8 Fibre extension, bending and twisting

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

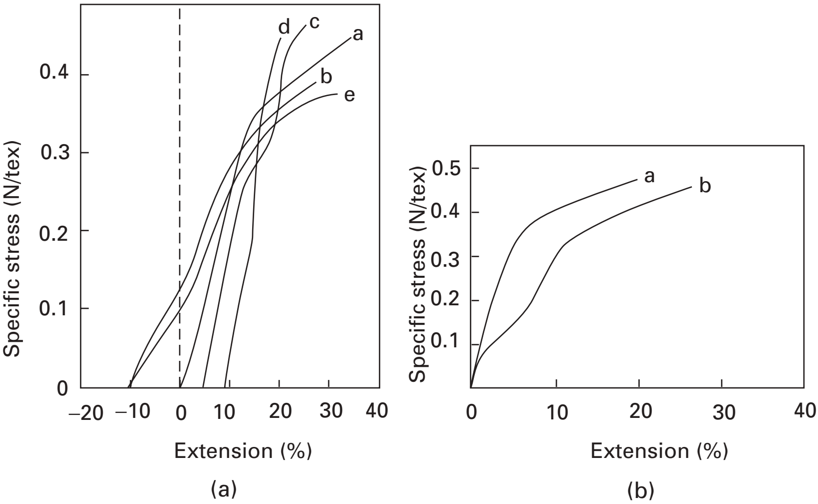


2.21 Two ways in which breaking and re-forming of tie-molecules could act as a mechanism of setting. (a) Interchange of free end; (b) Break and re-formation of tie molecules.

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

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[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:

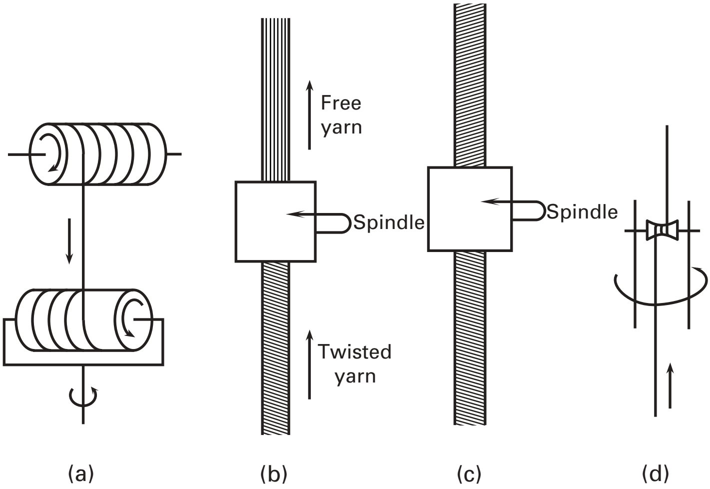
1. at high speed between yarn and drive surfaces, including friction discs, where friction must be high enough;
2. at low speed between filaments to allow fibre migration to occur in twisting, for which friction must be low enough.

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:

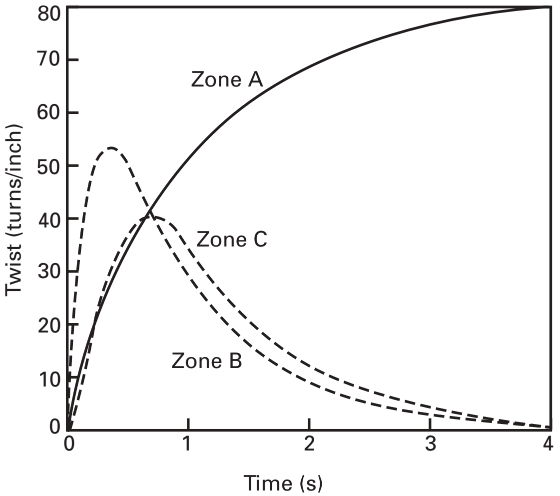
$$N_1 = N[1 - \exp(-\nu t/a)] \qquad [2.4]$$

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

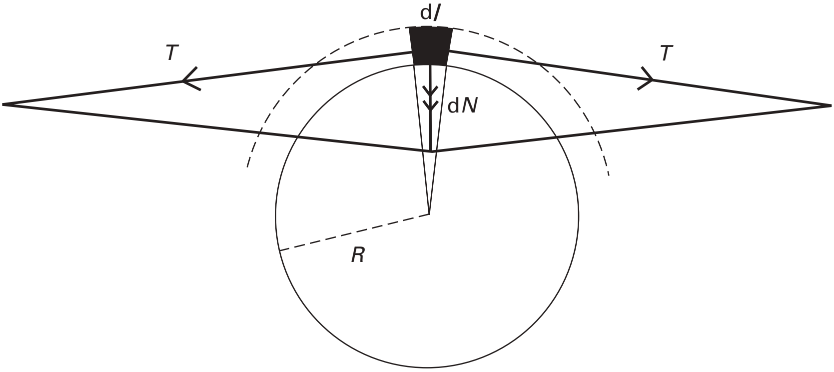
2.3.2.1 Twisting actions

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 dl of yarn under a normal force dN is given by μdN, 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, dN 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



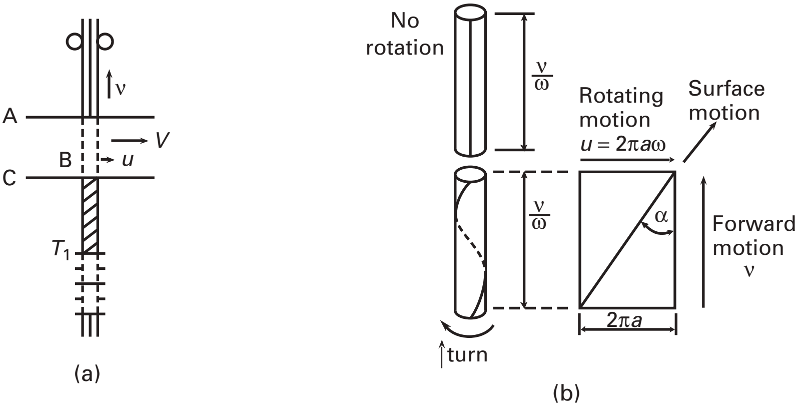
2.26 Normal load d*N* due to curvature of yarn path.

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

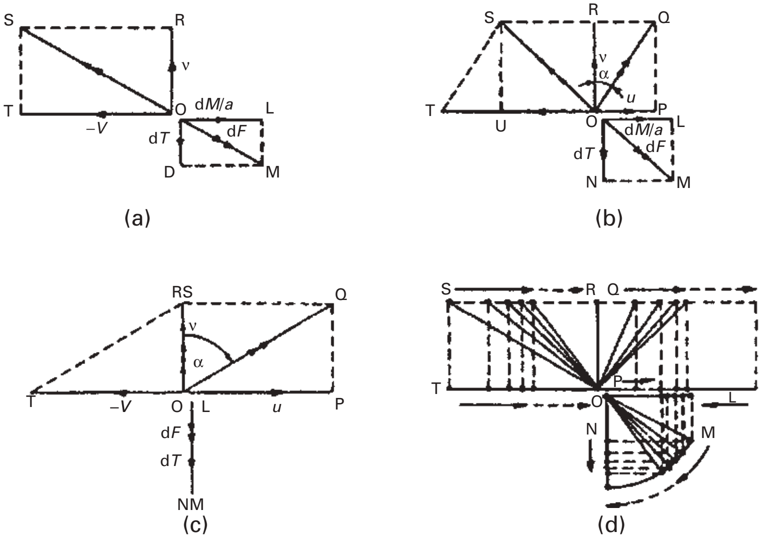


2.27 (a) Yarn running past a twist stop onto a moving belt. (b) Vector diagram of motions. From Hearle (1979a).

'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, dF, 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 dF 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 dF can be represented by a vector **OM**, opposed in direction to **OS**, and resolved into a component **OL**, causing a transverse force, dF_t, giving a yarn-torque increment, $\mathrm{d}M = a\mathrm{d}F_t$, and **ON**, causing a yarn-tension increment dT.



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***.

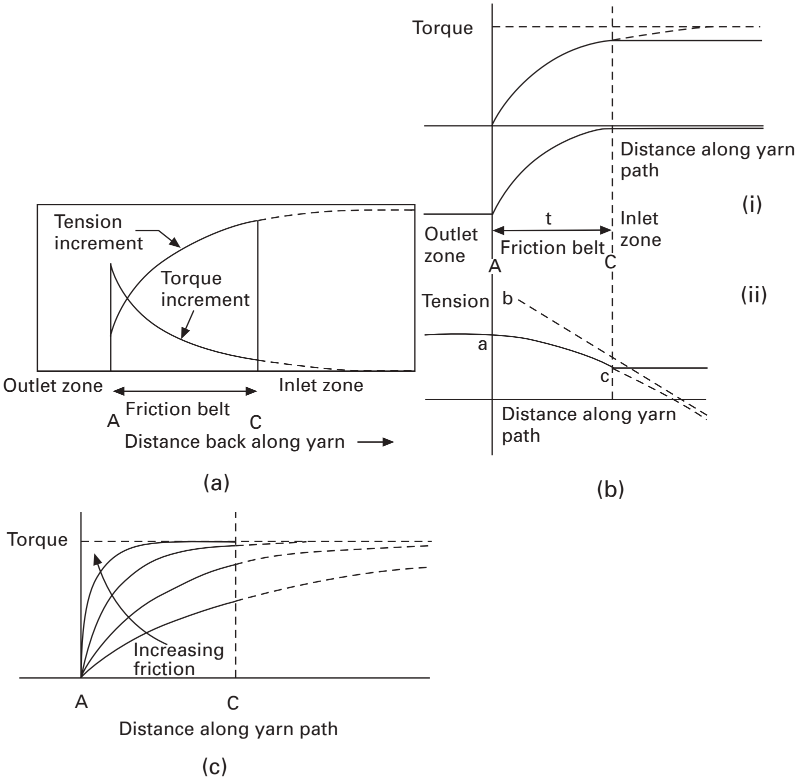
The limiting situation is shown in Fig. 2.28(c). When the yarn twist reaches a value such that the rotational velocity of the surface, u, equals the belt velocity, V, the relative velocity of the surfaces is along the yarn axis, and as a result the frictional force contributes a tension increment but 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:

torque increment → twist change → rotational velocity change → torque increment
→ tension increment.

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:

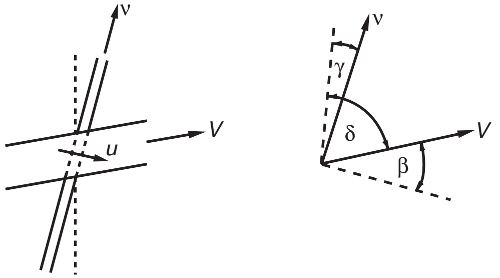
$$\tan\alpha = 2\pi R\omega/\nu \qquad [2.7]$$

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).

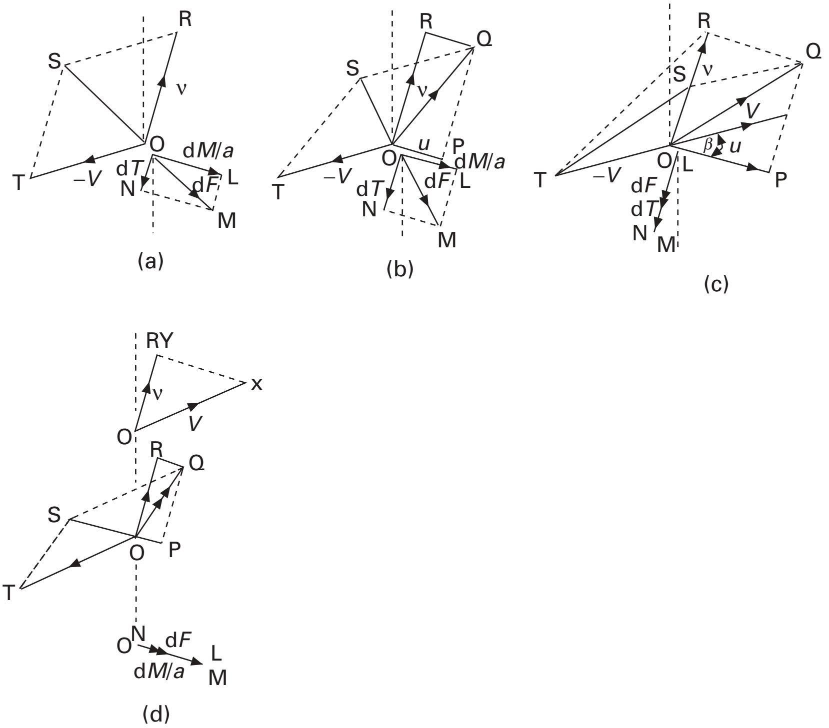
In the simple geometry of Fig. 2.30, the yarn makes an angle γ with the straight line through the device and the friction-surface makes an angle δ, then the angle β between the surface movement and the normal to the yarn direction is given by:

$$\beta = \gamma + \pi/2 - \delta \tag{2.9}$$

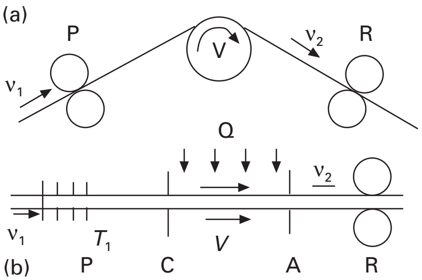
The vector diagrams of Fig. 2.28(a)–(c) are then modified as shown in Fig. 2.31(a)–(c). Depending on the angles, the tension may increase, decrease, or, as shown in Fig. 2.31(d), be unchanged. The condition for change from tension drag to tension push is $V \sin \beta = \nu$. There is also a limiting 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, ν_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 ν_2, and will be negative when the belt is slower than the output velocity as occurs when yarn is being drawn.

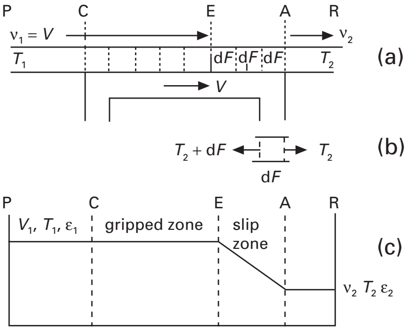
Where does the frictional force act in the positive mode? The situation is illustrated in Fig. 2.33. Since the yarn is being forwarded, its velocity, ν_2, where it leaves the belt, must be less than the velocity, V, of the belt. Therefore it must be slipping at this point. This generates a friction increment, 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.

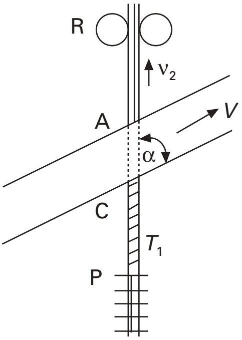
Table 2.3 Positive mode without twist

Zone:	PC	AR
Tension	T_1	$T_2 = \text{arc}\, f_1(e_2)$*
Strain	$e_1 = f_1(T_1)$	$e_2 = (\nu_2/\nu_0) - 1 = [(1 + e_1)\nu_2/V] - 1$
Velocity	$\nu_1 = V = (1 + e_1)\nu_0$	$\nu_2 = (1 + e_2)\nu_0$

* 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:

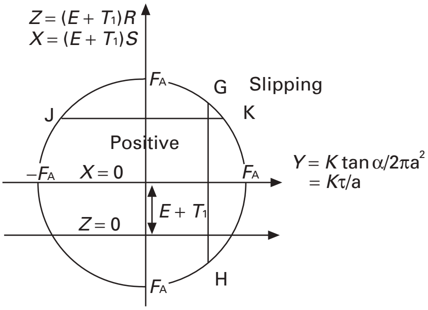
$$F_T = T_1 - T_2 \quad F_M = (M_1 - M_2)/a \qquad [2.10, 2.11]$$

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

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; $M = \mathrm{k}\tau$, 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,

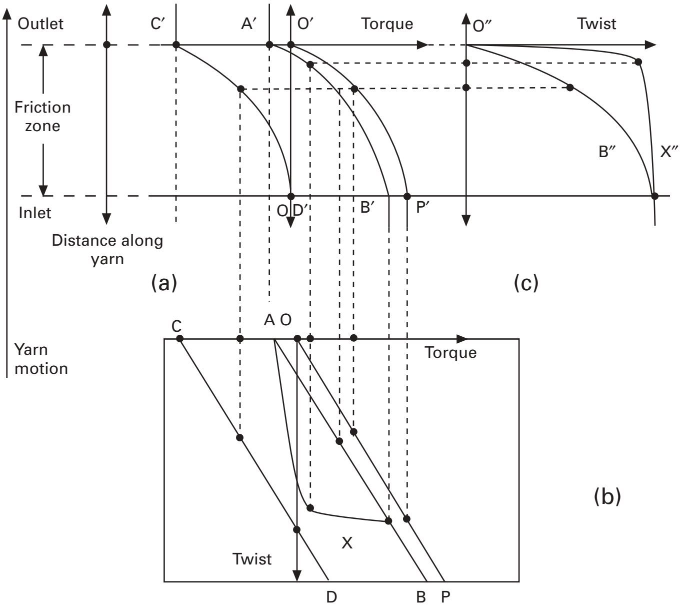
Table 2.5 Complications in real false-twist texturing systems

- 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).

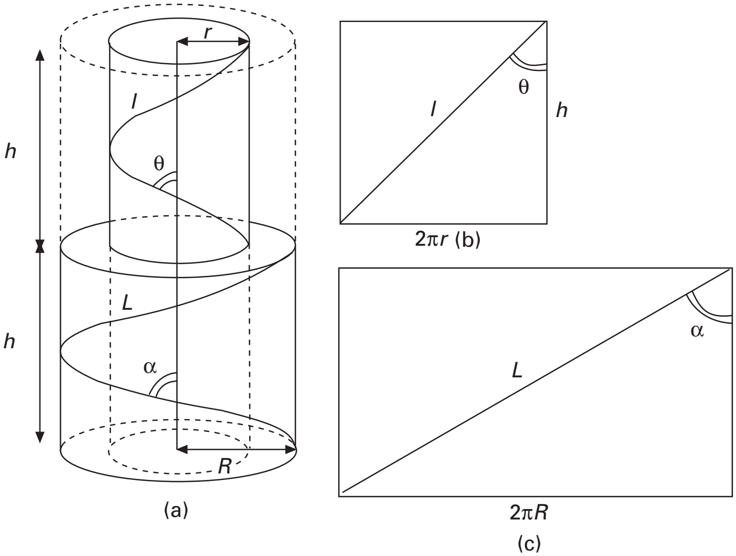
very close to its final twist value. This result would justify the treatments in the literature that deal with the friction twister as a whole instead of considering it in increments.

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.

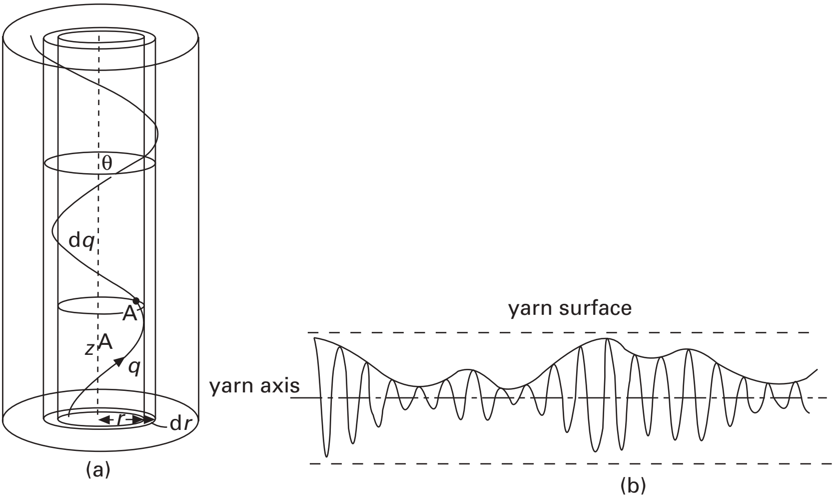
The geometry of the idealised form is easily seen by imagining cuts to be made along the cylinders of Fig. 2.37(a), and then opening them out flat to give Fig. 2.37(b,c). The sort of equations used in the analysis of the structural mechanics are Pythagoras’s theorem and trigonometrical relations:

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

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

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

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 dr 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 ($2500/\nu_y^{1/2}$) $\text{tex}^{1/2}$ 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.

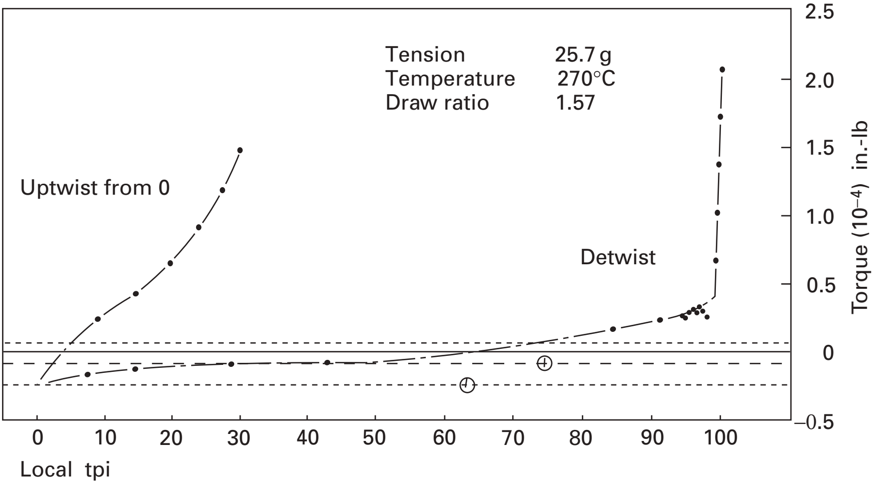
As the yarn comes onto the heater, the resistance to drawing drops, so that there is an increase in length. The torque and bending-moment contributions to yarn torque reduce, so that there is a twist increase. The yarn-tension component remains and controls the twist over the heater. This twist level 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.

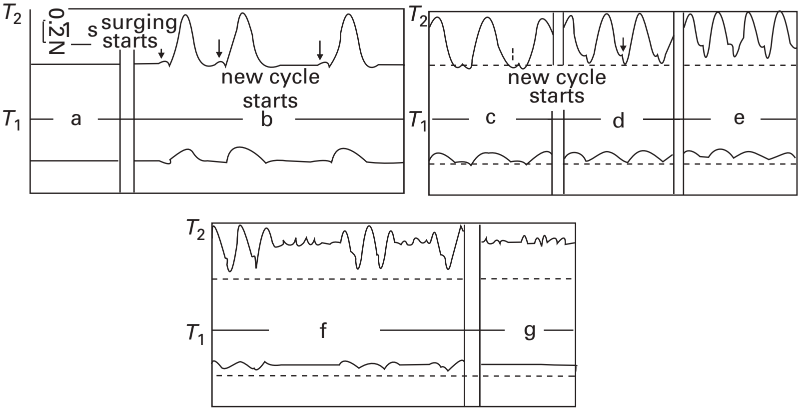
In order to reduce the length of heaters, the first section can be at a higher temperature than the last section. There is then a faster initial increase in temperature towards a higher asymptotic value, which is followed by slower approach to the final temperature.

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.

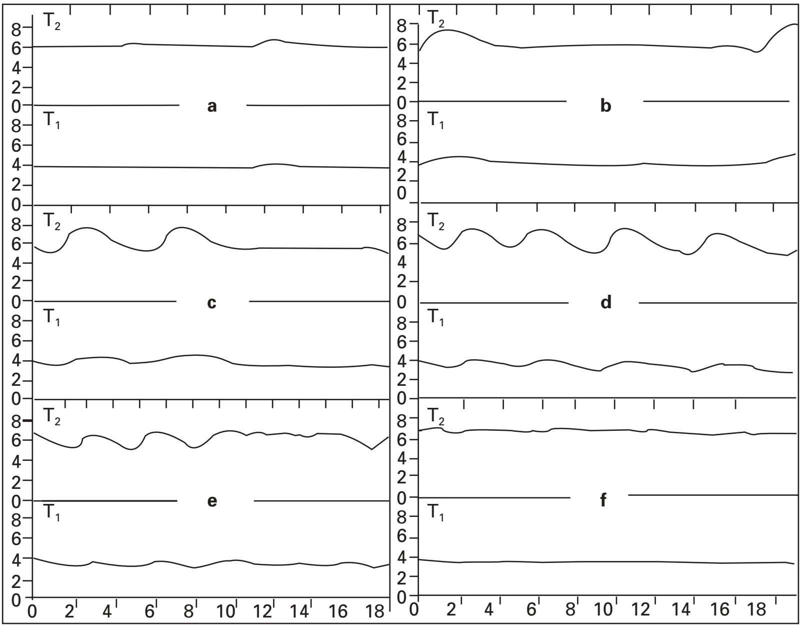
Du and Hearle (1989a,b) have reported a study of the incidence of surging. Figure 2.40 shows plots of tension, T_1 before and T_2 after the spindle, at increasing speed when texturing polyester yarn on a single-heater, commercial machine. At 710 m/min, the tensions are almost constant and good yarn is 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.



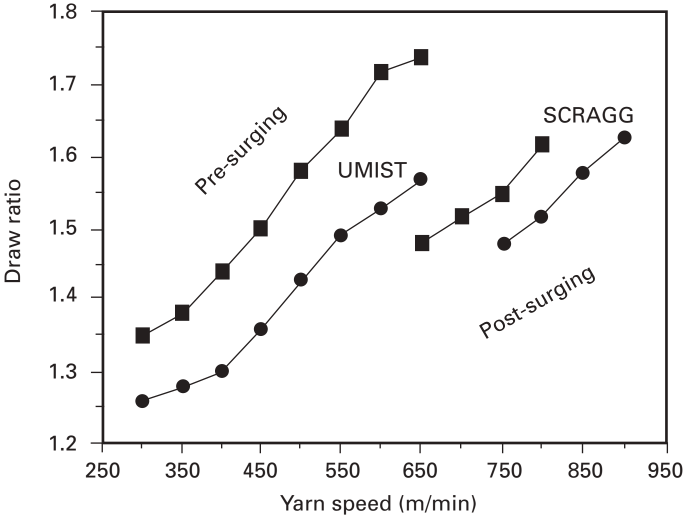
2.40 Profiles of tension T_1 before spindle and T_2 after spindle at increasing speeds, when texturing polyester yarn on a commercial machine. Yarn speed in m/min: (a) 710; (b) 720; (c) 740; (d) 770; (e) 800; (f) 820; (g) 830.

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.

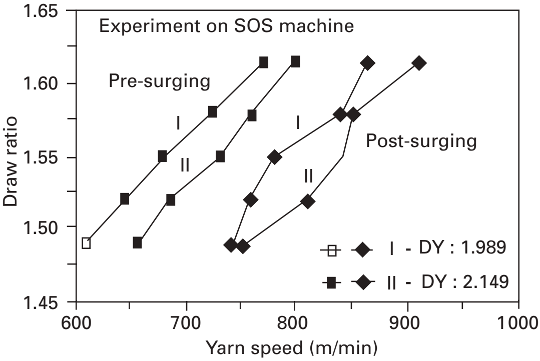
There are many possible causes of unstable texturing operation. Intermittent twist slippage occurs if there is an inadequate grip of the yarn on the spindle. At low tension and high twist, there may be intermittent double-twisting, which is another name for the cylindrical snarling described in Section 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



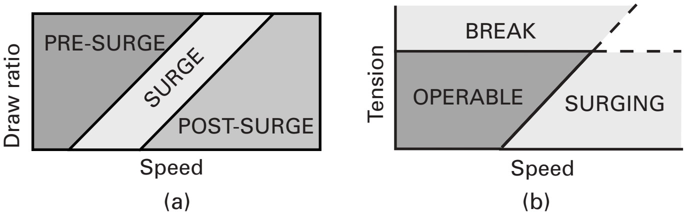
2.41 Profiles of tension T_1 before spindle and T_2 after spindle at decreasing draw ratio at 650 m/min, when texturing polyester yarn on a laboratory rig. Draw ratios: (a) 1.73; (b) 1.71; (c) 1.70; (d) 1.65; (e) 1.60; (f) 1.57.



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.



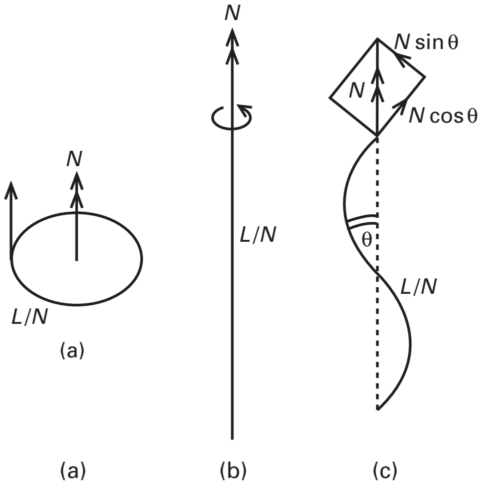
2.44 (a) Schematic of conditions for surging. (b) Operable zone for texturing.

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:

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

and

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

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

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

and

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

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.

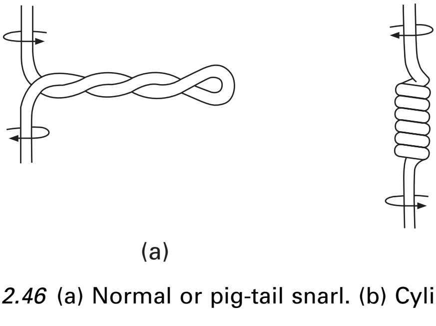
2.6.2 Snarling of a straight twisted filament

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.

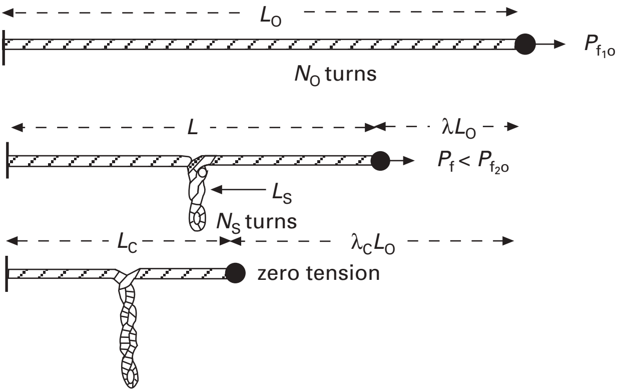
If the rod is very highly twisted, it buckles in a different way and forms a '*cylindrical*' snarl as shown in Fig. 2.46(b). The latter is not relevant to textured yarns as products, but it is the form taken up if an attempt is made to insert excess twist during texturing. This is referred to in Section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



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



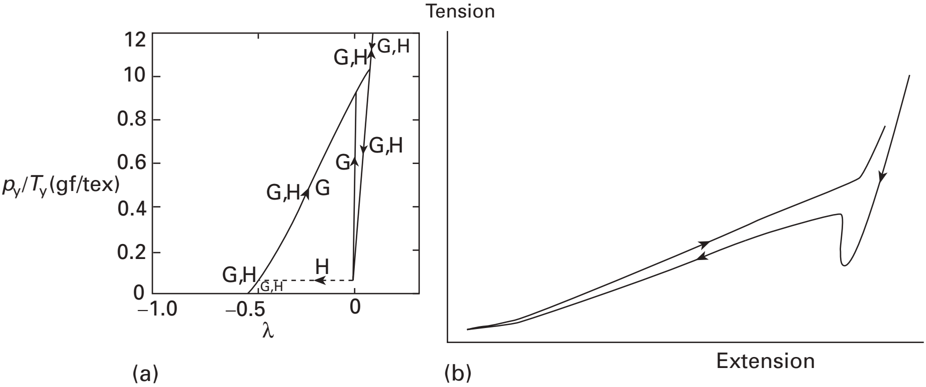
2.47 Snarling in a twisted rod at reducing tension. (λ is extension ratio).

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



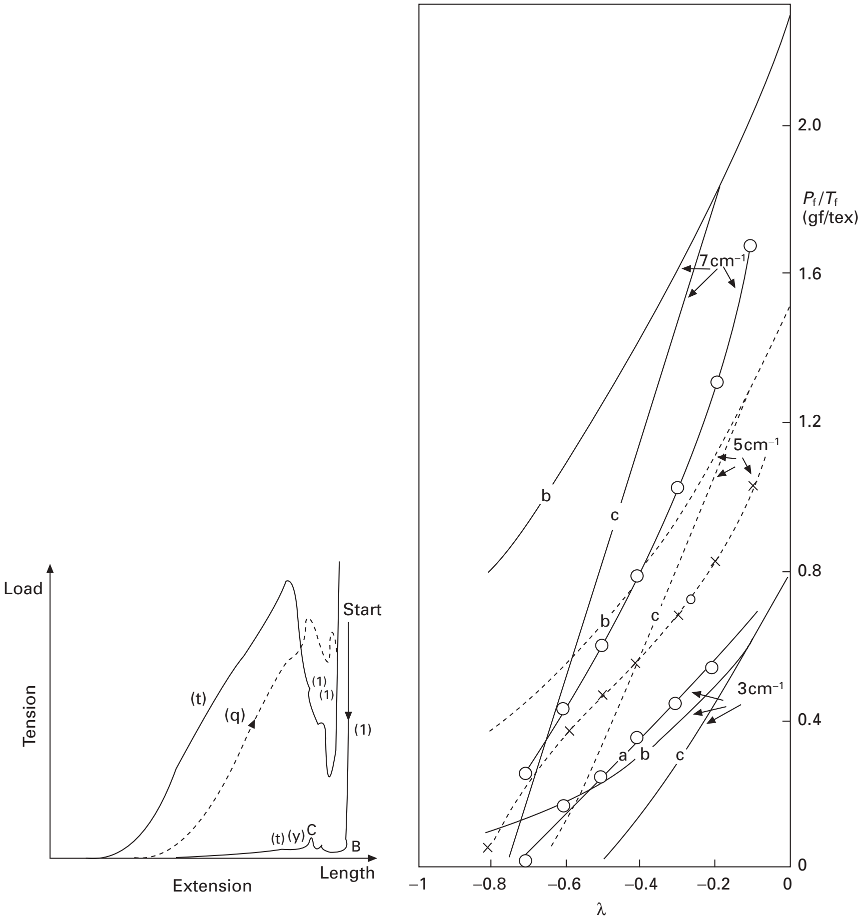
2.48 (a) General form of predicted relations. G–G is the expected form in constant rate-of-extension testing and H–H is expected in constant rate-of-loading. The recovery line is put between those for locked and redistributed theory. From Hearle (1966). (b) Observed response of a twisted rubber rod.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

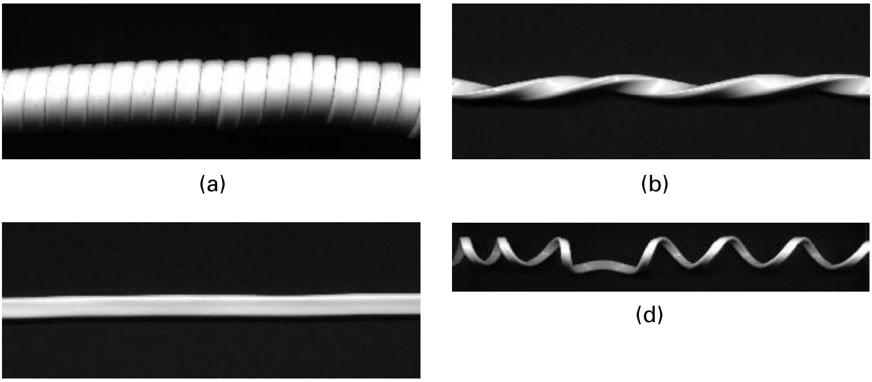
The second case to consider is the behaviour when the set deformation is bending without twisting. If a virtual rod is bent round at constant curvature, it would form a series of overlapping identical circles. Mathematically, this is possible, but the closest in reality is a closely packed coil, such 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)

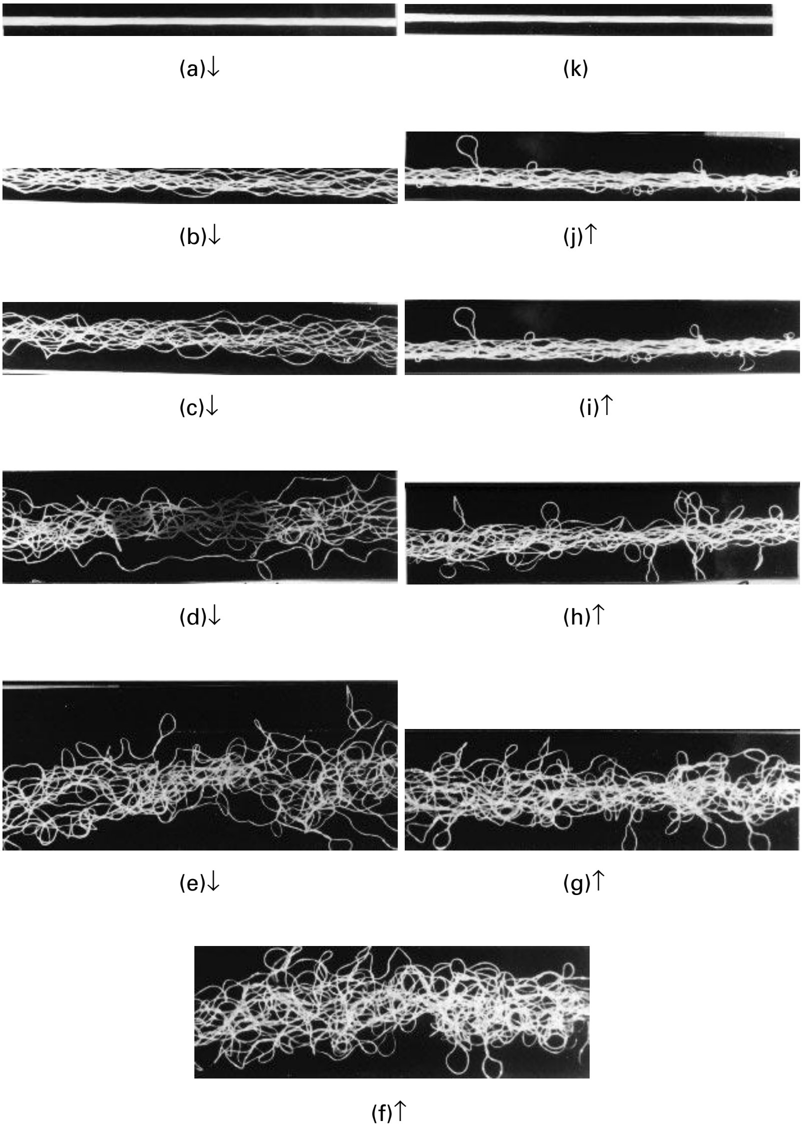
(d)

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

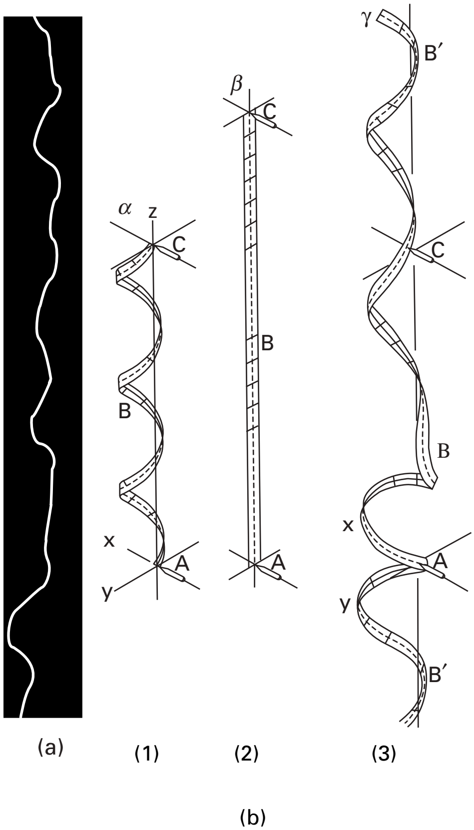
The untwisted, straight filaments in a torque-stretch yarn are in more complicated and varied states of strain than the two cases considered so far. In the set yarn, fibres at the centre will be purely twisted, but those out from the centre will be both bent and twisted with the helix angle increasing 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.



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:

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

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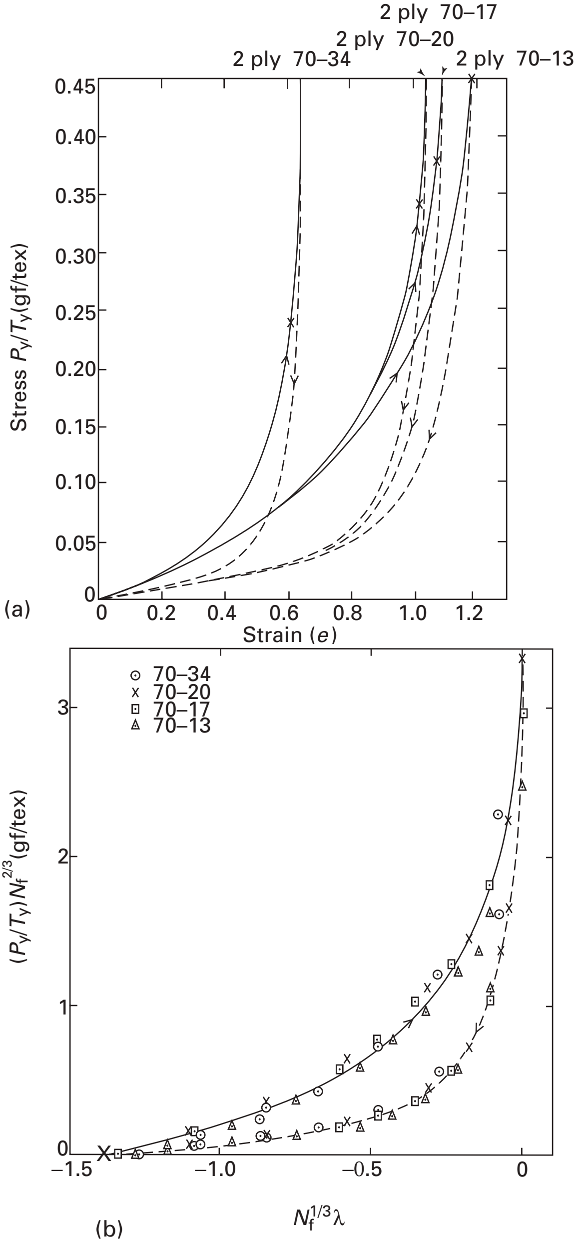
[3] Terminology is various. '*Crimp contraction*' or '*crimp retraction*' is the preferred term in Europe; '*crimp rigidity*' relates to a particular test method for crimp contraction. In the USA, textured yarns are usually characterised by the '*skein shrinkage*' (sometimes called '*residual shrinkage*'),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