XII SPECIAL TECHNIQUES

XII.1 Fibers with Noncircular Cross Sections

Generally, natural fibers do not have plain surfaces: wool has tiny scales, cellulosic fibers have other kinds of surface roughnesses. Fibers are produced with variegate surfaces not only to imitate nature, but also because certain fiber properties are affected by the surface structure. They are:

- Fiber-to-fiber friction , which affects the way fibers are processed and influences the resulting fiber and yarn properties.
- Fiber appearance is highly dependent on the surface. The more pleasing appearance is obtained with fiber cross sections of lower symmetry, *e.g.* cross sections with an odd number of lobes give a more eye-pleasing effect than do those with an even number of lobes.
- The bulk density of fiber changes somewhat. This is also a matter of bending rigidity and its dependence on the cross section. The bending rigidity and the density of fiber-to-fiber packing are responsible for the bulkiness and *hand*, that is the sensual perception to touch.
- Increase of the fiber surface area affects the sorptional properties, water retention, and dyeability.

Figure XII.1 presents some of the more common fiber cross section and the cross sections of the capillaries from which they were extruded (top row). The figure must be treated as an approximation only; the deformation from the capillary cross section to the fiber cross section is related to the die swell. The die swell depends on the nature of the polymer in question, and on the particular processing conditions; the larger the die swell the larger the deformation. Not without significance is time. The longer the filament remains hot after leaving the spinnerette, the larger the

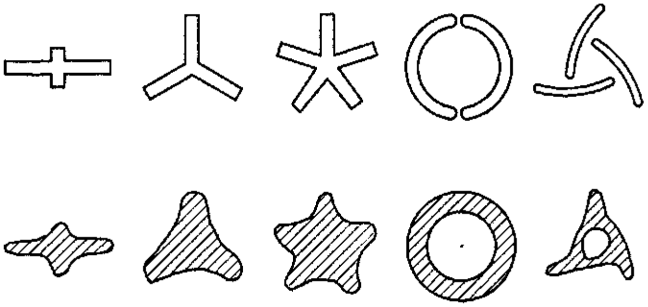

Figure XII.1: *Cross section of capillaries (top) and the approximate cross sections of resulting fibers (bottom).*

deformation of its cross section by the normal forces remaining after the capillary flow.[1] If the fiber stays hot for a prolonged time, the surface tension may also contribute to the deformation of the cross section, though the surface tension forces are much weaker.

Han and co-workers have studied the effect of diameter attenuation on the shape of the cross sections.[2,3] The authors have found that in wet formation, increasing extension decreases the changes of the cross section. In formation of polypropylene fibers from the melt, the cross sections were insensitive to the extention ratio.

The generalizations of flow in noncircular ducts are mathematically involved,[4–9] therefore for capillary design purposes, a simplified method developed by Miller[10] is more often used. According to Miller's view, for non- Newtonian fluids the relationship between the average wall shear stress and the apparent wall shear rate, to a good approximation, do not depend on the duct geometry. The average shear stress at the wall for noncircular cross section ducts is described as follows.

$$\tau = \frac{\Delta P \; D_h}{4 \; L} \tag{XII.1}$$

Here ΔP stands for extrusion driving pressure, L is length of the duct (capillary), and D_h represents the hydraulic diameter.

$$D_h = \frac{4 \; q}{S} \tag{XII.2}$$

where q is cross sectional area of the channel, and S is the wetted perimeter. For the circular ducts the hydraulic diameter equals the actual diameter.

The apparent shear rate at the wall is

$$\dot{\gamma} = \frac{Q \; \lambda}{2 \; q \; D_h} \tag{XII.3}$$

where Q is volumetric flow rate, and λ is the shape factor, which depends only on the geometry of the cross section, it is a product of Reynolds number, based on average velocity and hydraulic diameter, and friction factor for a given channel. Values of the shape factors for some shapes are given in table XII.1

The relationship between the fiber cross section and the capillary cross section is largely proportional to the die swell, which may be estimated from laboratory measurements and recalculated using the above given equations. Agreement between the recalculated predictions and experiment is not necessarily good.

Depending on the degree of sophistication of the capillary maker, some problems with the junction between the conical entry to the capillary and beginning of the capillary itself can be expected. The practical results are sensitive to this element of spinnerette construction. This is the reason why many noncircular capillaries are made with flat entries.

Generally, one hears just complains about die swell. For once, there is an advantage being taken of the die swell in the case of some types of cross sections,

Table XII.1
Values of shape factor for various cross sections.
After C. Miller[10]

Shape of cross section	Shape factor λ
Three-pointed star	6.50
Four-pointed star	6.61
Five-pointed star	6.63
Square	14.3

as may be seen in figure XII.1. This is particularly true in the case of hollow fibers, which may be produced also from capillaries having a solid core, although these are much more expensive to produce and much less durable.

Cross sections with sharp points, for example, certain stars, may cause problems with local fracturing. This is often the reason that noncircular fibers are not much extended from the melt and even less neck drawn. The majority of this type of fibers is produced for the sake of their appearance and for their textile properties, there are no great demands put on their strength. Hollow, particularly circular hollow, fibers represent an exception. Their main application is for *reverse osmosis*: for desalination and purification of water, for dialysis, and the likes. The applications for reverse osmosis are demanding in terms of fiber quality.

With applications of hollow fibers other than reverse osmosis, particular care must be taken since various bacteria immensely enjoy the long "tunnels", and there is no good way to get them out of there.

XII.2 Crimping - Bulking - Interlacing

Beside the changes in the cross section of fibers, there is another way to make man-made fibers more like natural fibers – *crimping* or *bulking* or *texturing*. This means making the fibers wavy or spiral rather than straight. One needs to add that making the fibers more like natural fibers is not just a matter of empty copying, it is changing the fibers to fulfill the demands of textile structures and processing.

The techniques used for texturing fibers may be divided into two groups:

- Processes which take advantage of the thermoplastic properties of fibers to change the fiber axis into a curvilinear.
- Strictly mechanical processes to rearrange the positions of the fibers in a bundle so that the fiber axes will no longer be parallel.

Among the first group the most common are:

Gear crimping, which is based on heating a tow of continuous fibers to a temperature close to the onset of melting and passing it between a set of hot gears.

The gears force a wave shape on the hot fibers, and the new form is set by the subsequent cooling.

Stuffer box is a hot chamber into which a tow of continuous filaments is overfed and removed at a lesser velocity. The hard packing of the fibers forces the fibers to change their axes into an irregular three dimensional arrangement, which is fixed by cooling upon removal of the fiber from the chamber.

Bulked continuous filament, (BCF), process may be considered a modernization of the stuffer box process. High pressure hot air, or steam, instead of a mechanical device is used to pack the filament tow into a chamber and exert pressure. The changes imposed on the fibers are similar to those produced by the stuffer box. The quality of the three dimensional crimp is regulated by the design of the chamber, pressure, temperature, and speed of removing the tow. This method of crimping is used particularly often to produce yarn for the carpet industry.

False twisting is an operation where a tow of yarn is twisted, heat set, and untwisted in one line. The speeds of operation are reaching $1200 m/min$ with rotational yarn speed reaching $7,200,000 rev/min$. The spiral type of twist is responsible for high stretch of the yarn, and it is not suitable for every textile application; nonetheless, almost three quarters of crimped fibers are made by this technique.

"Knit - de-knit" texturing is similar in principle to the false twisting, the fibers have looping rather than spiral configuration. This technique is not very frequently used.

All the texturizing processes utilizing heat impose some damage to the fiber properties. The high temperature, close to the crystalline melting point, affects the fiber morphology; the high pressure treatment may also result in mechanical damage to the fibers, particularly in combination with high temperature.

Air jet texturing[11,12] is the only process which uses cold air and therefore the damage to the fibers is small. The device for the jet texturing is a nozzle which generates a supersonic, turbulent and non-uniform flow. When the filaments are overfed into the nozzle they are transported by the air flow and discharged from the texturing end. The supersonic turbulent air forces the individual filaments into all kinds of loops which are trapped in the tow (yarn) structure. The fibers are usually wetted before entering the nozzle. The entry and discharge of the yarn is, as a rule, perpendicular to the nozzle axis, while the compressed air is introduced into the nozzle on an angle of some 45° to the nozzle axis. There are, naturally, a great variety of different nozzle designs.[12]

The character of air jet textured yarn is different from the yarn textured by the processes of the first group. They remind one of yarn spun from staple fibers, both by their properties and appearance. Due to the entangled yarn morphology and due to the loops being locked between the neighboring fibers; the flat bundle of fibers has stable shape under normal use forces, contrary to false twisted yarn and other, the bulk of which decreases with imposed strain.

There is another group of crimping operations known which involve fiber formation processes like asymmetric quench and neck drawing over a sharp edge.

These processes yield a rather mild crimp, more like wavy fibers. Asymmetric quench is difficult to control well enough to assure sufficient reproducibility of the results. Drawing over a sharp edge cannot be done sufficiently fast, or break level is too high. In effect, these historical processes do not have a practical significance today.

The texturing operations are often done by the textile industry rather than by the fiber producers, and this is dictated by reasons such as adjusting the texturing to the demands of a given fabric, and that texturing velocities are closer to the velocities of textile processes rather than to the velocities common in a modern fiber production. The fiber industry textures mainly staple fibers. Because texturing is mostly connected to textile problems, the mechanical properties due to crimp are not quoted here and the interested reader is referred to the specialistic literature.[16,17]

Continuous filament yarn, consisting of straight fibers with flat surface, have neither high friction nor forces normal to the fiber axis which would hold the bundles together. Bulked yarn, say false twisted, also does not have the normal forces to hold the yarn together. This creates problems with winding and processing as the yarn may snatch between the overlapping layers, which leads to tension irregularities and breaks. To alleviate these problems the yarn might be sized or twisted, or both, but these operations are expensive. The situation was helped greatly when the process of *interlacing* (or *intermingling*) was developed.[13,14] The relative costs of the operations are *sizing : twisting : interlacing = 100 : 72 : 11.*[15]

Interlacing is an in-line process whereby the yarn is led through a tube to which a cold air jet is introduced mostly perpendicularly to the yarn. In the place where the yarn and the air jet meet the channel is slightly widened. However, there is a great variety of designs of the interlacing nozzles.[12,13] The turbulent air jet locally opens up the bundle of fibers and causes the fibers of the neighboring segments, up and down the line, to intermingle with each other to form a compact segments (so called *nips*). If an intermingled section moves in from up- stream, then the jet cannot open it. This leads to the situation where the interlacing works in segments.

The interlacing operations are done mostly by the fiber industry on the continuous straight filament yarn. The nozzle is placed usually after neck drawing and relaxing, just before winding. For intermingling are mostly used low pressure nozzles which produce continuous intermingling, without forming "nips",[14] tiny fiber bundles, which could be disturbing in the further textile processing or bulking of the yarn.

XII.3 Biconstituent Fibers

Utilization of two polymers for fiber making has been tempting fiber developers for a very long time and a substantial effort has been invested in this field. The main obstacle here is the small number of compatible polymer pairs.

The problems of polymer compatibility are being investigated from many different angles, primarily from the point of view of thermodynamics. [18–25] This field has not been developed to the point of applicability for the needs of technology. More suitable are the gains made in the field of rheology,[26–30] and particularly those efforts coupled to the investigations of the interfacial tension and glass transition temperatures.[30,31]

Helfand and co-workers[32–34] stressed the connection between the Flory-Huggins polymer - polymer interaction parameter, χ, and interfacial tension, $\gamma_{1,2}$.

$$\gamma_{1,2} = \sqrt{\frac{\chi_{1,2}}{6}} \cdot \rho_0 \; b \; k_B \; T \tag{XII.4}$$

In equation XII.4, ρ_0 is the number density of repeat units in pure polymer, b is the effective length per repeat unit, k_B is the Boltzmann constant, and T is absolute temperature. The interaction (or compatibility) parameter is related also to the solubility parameter, δ.

$$\chi_{1,2} = \frac{(\delta_1 - \delta_2)^2}{\rho_0 \; k_B \; T} \tag{XII.5}$$

Determination of the interaction parameter is almost as difficult experimentally as is the determination of the solubility parameters. On the other hand, determination of the interfacial tension in polymers also is rather difficult. A convenient way for these determinations has been suggested by Gramespacher and Meissner.[30] While analyzing rheological behavior of a series of polymer blends of different compatibilities, the authors have found that in oscillatory tests, the loss moduli of the blends are between the loss moduli of the components, and this is the case over the entire frequency range of four and a half decades. The storage modulus, however shows a dependence on the composition of the blend. The composition dependence is almost nonexistent above the frequency of about $\omega = 0.5 \; rad/s$, but becomes progressively larger with decreasing frequency.

In analyzing the frequency dependence of the complex moduli, the authors take into account the contributions of the viscoelastic properties of the components and of the interfacial tension. Thus, for the complex modulus we have:

$$G^*_{1,2} = G^*_{components} + G^*_{interface} \tag{XII.6}$$

The value of the modulus of the component the authors obtain from a simple additivity of the components.

$$G^*_{1,2} = \phi \; G^*_2 + (1 - \phi) \; G^*_1 + G^*_{interface} \tag{XII.7}$$

In equation XII.7, subscript 2 denotes the dispersed phase, subscript 1 is for the continuous phase, and ϕ stands for the volume fraction of the dispersed phase. To describe the influence of the interfacial tension on the moduli, Gramespacher and Meissner[30] take advantage of the theory of mixtures of Newtonian fluids developed by Choi and Schowalter.[35] The theory presents a constitutive equation for the rheological behavior of concentrated emulsion of two Newtonian liquids. Scholz and co-workers[36] simplified the equation by neglecting the nonlinear terms and derived the storage and loss moduli as follows.

$$G'(\omega) = \eta \frac{\omega^2(\theta_1 - \theta_2)}{1 + \omega^2\,\theta_1^2} = \frac{\eta}{\theta_1}\left(1 - \frac{\theta_2}{\theta_1}\right)\frac{\omega^2\,\theta_1^2}{1 + \omega^2\,\theta_1^2} \qquad \text{(XII.8)}$$

$$G''(\omega) = \eta \frac{\omega^3\,\theta_1\,\theta_2 - \omega}{1 + \omega^2\,\theta_1^2} = \frac{\eta}{\theta_1}\left(1 - \frac{\theta_2}{\theta_1}\right)\frac{\omega\,\theta_1}{1 + \omega^2\,\theta_1^2} + \omega\,\eta\frac{\theta_2}{\theta_1} \qquad \text{(XII.9)}$$

Here θ is relaxation time, η represents the Newtonian viscosities of the two components; in both cases the subscripts determine as above, 2 for the dispersed phase. If we designate

$$k = \frac{\eta_2}{\eta_1} \qquad \text{(XII.10)}$$

then viscosity may be further defined as follows.

$$\eta = \eta_1\left[1 + \phi\cdot\frac{(5k+2)}{2\,(k+1)} + \phi^2\cdot\frac{5\,(5k+2)^2}{8\,(k+1)^2}\right] \qquad \text{(XII.11)}$$

$$\theta_1 = \theta_0\left[1 + \phi\cdot\frac{5\,(19\,k+16)}{4\,(k+1)(2\,k+3)}\right] \qquad \text{(XII.12)}$$

$$\theta_2 = \theta_0\left[1 + \phi\cdot\frac{3\,(19\,k+16)}{4\,(k+1)(2\,k+3)}\right] \qquad \text{(XII.13)}$$

$$\theta_0 = \frac{\eta_1\,R}{\gamma_{1,2}} \times \frac{(19\,k+16)(2\,k+3)}{4\,(k+1)} \qquad \text{(XII.14)}$$

In equation XII.14 R stands for the radius of the monodisperse inclusions.

The emulsion has elastic properties as described by the storage modulus (equation XII.8) despite the Newtonian character of both its components. The reason for this is the interfacial energy on the boundary of the two phases. In equation XII.9, the last term on the right hand side does not depend on the interfacial tension but results from the viscosities of the Newtonian fluids. In equation XII.8 the interfacial tension comes only in the first term on the right side.

The reason for the greater influence of interfacial tension on the storage modulus at low frequencies is this: this region of the viscoelastic behavior is dominated by viscous effects. Therefore to describe the complex modulus at the interface Gramespacher and Meissner[30] take advantage of equation XII.8 and only the first term of equation XII.9. In equation XII.10 the viscosities η_1 and η_2 are taken as zero-shear viscosities of the matrix and dispersed phase, respectively. Thus the final equations will have the form as follows.

$$G'_{1,2} = \phi\,G'_2 + (1-\phi)\,G'_1 + \frac{\eta}{\theta_1}\left(1 - \frac{\theta_2}{\theta_1}\right)\frac{\omega^2\,\theta_1^2}{1 + \omega^2\,\theta_1^2} \qquad \text{(XII.15)}$$

$$G''_{1,2} = \phi\,G''_2 + (1-\phi)\,G''_1 + \frac{\eta}{\theta_1}\left(1 - \frac{\theta_2}{\theta_1}\right)\frac{\omega^2\,\theta_1^2}{1 + \omega^2\,\theta_1^2} \qquad \text{(XII.16)}$$

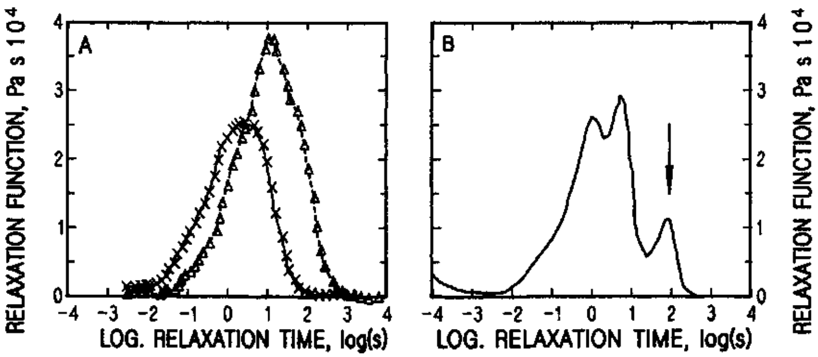

Figure XII.2: *Weighted relaxation spectra, $\theta\ H(\theta)$. A. For poly(methyl methacrylate) and polystyrene, B. for a blend of the two polymers (8% PS). The arrow indicates the relaxation time θ_1. After Gramespacher and Meissner.*[30]

The term $(\eta/\theta_1)(1-\theta_2/\theta_1)$ represents the spring modulus of a simple Maxwell model with relaxation time of θ_1.

Equations XII.15 and XII.16 describe the dynamic behavior of the polymer blends, if the interfacial tension is known. Gramespacher and Meissner[30] have shown that the reverse is also true, that interfacial tension can be determined from the oscillatory experiments. If one obtains the relaxation spectra of the pure components and of the blend, and if the weighted spectra are plotted *versus* the logarithm of the relaxation time, as it is reproduced in figure XII.2, than one may notice that in the spectrum of the blend appear three peaks. Two peaks correspond to the relaxation times of the two components of the blend, matrix and dispersed phases. The third peak (marked with an arrow) increases with increasing content of the dispersed phase. The relaxation time corresponding to the third peak is related to the interfacial tension. The value of the third relaxation time, equal to θ_1, may be converted to the interfacial tension using equations XII.12 and XII.14.

A comparison of the values of interfacial tension determined by other methods and by the described above "rheology" method is very good, though perhaps the rheology method is more accurate. The rheology method is particularly convenient, since it may be obtained as a "byproduct" of the rheology measurements, which are necessary also for other reasons. Any more serious work with biconstituent systems is hard to imagine without rheological determinations, methods of obtaining viscoelastic spectra are many and well described,[37-42] while other methods of determination of interfacial tension would have to be made *ad hoc*.

Another, theoretically fairly easily determinable property which may detect compatibility is glass transition temperature. Incompatible polymers show two transition points as for pure components, while the compatible ones, molecular solutions give one transition point. Nonetheless, in practice it is not so convenient; glass transition is a range rather than a sharp point and the spread of the glass transitions for the interesting pair of polymers may be not a large one. This may often lead to situations of an insufficient resolution, or outright indeterminability. Interfacial tension, as a competitive method, has a certain range, a scale of gradation permitting to judge changes, to observe trends.

Knowledge of the interfacial tension or of the interaction parameter does not solve the whole problem at once. If interfacial tension is equal zero then we have a solution, a molecular dispersion. How high a value of the interfacial tension may be accepted to be still deemed as compatible one cannot say. In this respect compatibility is similar to the solubility, equality of solubility parameters does not give a guarantee of solubility. Similarity to van der Wals forces and hydrogen bonding must be considered in addition.[43] The unpleasant point here is that compatibility depends on the ratio of polymers and on temperature. Experimental determination of the materials of interest is unavoidable. The methods of rheology allow for rather convenient experimentation within wide range of conditions. One may expect that oscillatory measurements performed on solids should give equally good results.

XII.3.a Bicomponent Fibers

Originally, bicomponent fibers were developed to impart a crimp to the fibers, a crimp which would be "built-in" without the need for additional operations. To have such properties, the fiber was to be made of two different polymers formed side-by-side. The fiber cross section consisted of two approximately equal parts, each made of a different polymer. The polymers must have sufficient compatibility to assure adhesion between the two halves of one fiber.

During the formation process, both polymers experience the same conditions but their behavior and/or response to these conditions almost certainly is different. The differences become most strongly evident after neck drawing. At this point the difference in the post draw relaxation of the two halves of the fiber leads to the formation of, mostly helical, crimp.

Only about fifteen per cent of the polymer pairs investigated thus far have been found compatible, and majority of these pairs is unsuitable for fiber formation. Unfortunately, this good idea may find only a limited realization.

The majority of those bicomponent fibers which enjoy commercial success are of the type *side-by-side*, that is, the type which mainly serves as crimped fibers with a fair amount of elasticity. The largest field of application is women's hosiery. A simplified sketch of the spinnerette and polymer distribution plate is given in figure XII.3.[44] Each of the two polymers is guided between two rows of entry channels to the capillaries. A partition passes through the middle of the capillary entrance and prevents the two polymers from contact before they enter the delivery channels leading to the capillaries.

There have been many patents issued for the design of the distribution plates. The design may be sometimes complicated, specially if the plates are to cooperate with round hole patterns of large spinnerettes. For rectangular spinnerettes the design is simpler. More complications may arise if the two polymers have largely different viscosities or elastic behavior. Longer capillaries are advantageous, recov-

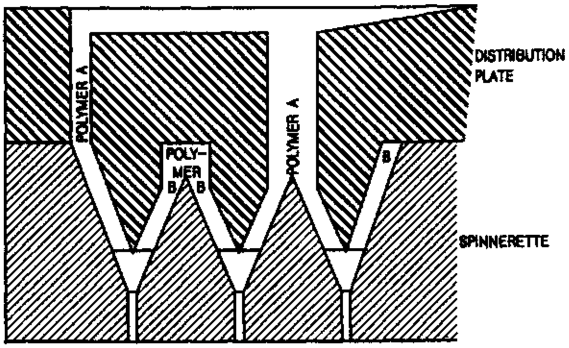

Figure XII.3: *Simple sketch of an assembly of a spinnerette and a polymer distribution plate for formation of side-by-side bicomponent fibers.*

ery in die swell may represent difficulties if the compatibility of the two polymers is marginal at the extrusion conditions.

The "imbalance" of the melt viscosity of the two polymers used for side-by-side formation may influence cross section of the fiber, it is the distribution of the two polymers (see figure XII.4.). The symmetric cross section is obtainable when both polymers, A and B, have practically the same melt viscosity. If viscosity of polymer B increases than the fiber cross section changes from I to II, and to III. Cross sections like the case III in figure XII.4 may be obtained when fibers are made of the same polymer but of much different molecular mass, what is sometimes practiced.

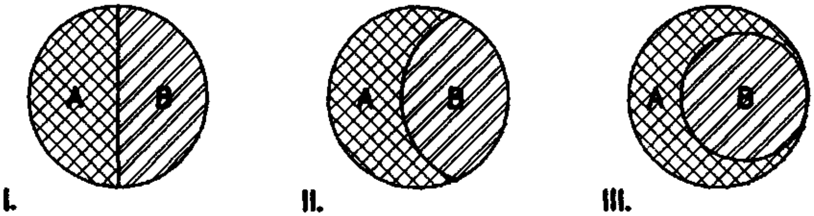

Figure XII.4: *Cross section of side-by-side bicomponent fibers with various melt viscosities of the components: I.* $\eta_A = \eta_B$; *II.* $\eta_A < \eta_B$; *III.* $\eta_A \ll \eta_B$.

Naturally, side-by-side fibers may have a ratio of polymer volumes other than 50 : 50. The ratio of the two polymers may have an influence on the type of crimp. Development of bulk in the fiber is by no means the only effect on fiber properties. Nevertheless, other properties like moisture regain, different *hand*, dyeability and other optical effects may be affected and they may very well serve as a good reason for development of such fibers. Naturally, the properties may change equally well for the better as for the worse. One of the more sensitive is dyeability, which may lead to very interesting effects as well as to disastrous difficulties.

Another type of bicomponent fiber is the *sheath and core* variety. The main reason for production of such fibers is to change the character of the fiber surface, and in such cases a very thin sheath may suffice to assure dyeability, change the *hand*, or perhaps affect the moisture regain or electrostatic properties. The core is usually the main element providing the strength; nevertheless, the difference between the properties of the sheath and the core cannot be too large for the sake of the fiber integrity under load. Polymers with any degree of compatibility do not have such large difference in their properties anyhow. In order for the fiber to keep its integrity, for the sheath not to turn loose from the core, the degree of polymer compatibility must be higher than for the side-by- side fibers.

The sheath - core bicomponent fibers represent also a good raw material for nonwovens; they are used mainly for the "classic" processes, rather than for spunbonded. The sheath serves as the binder for thermal bonding. *e.g.* through air bonding. Side-by-side types of bicomponents sometimes are also used for the same purpose, particularly when a bulkiness of the fabric is important.

In general, the principles of fiber formation are valid for bicomponent fibers as in every other case; there are only additional complications: two polymers instead of one and matching them all the way from the raw polymer to the fiber properties.

Since the bicomponent fibers are produced primarily for creation of the crimping effect, it seems appropriate to quote the work of M. J. Denton[45] on the crimp curvature of such fibers. The general equation for the crimp curvature is given as:

$$R\,\Delta = \frac{I_0}{A_1\,u_1} + \frac{m-1}{A_0\,u_1}\left(I_{1P} - \frac{A_2}{m\,A_1}I_{2P} - \frac{m-1}{m}A_1\,u_1^2\right) \qquad \text{(XII.17)}$$

In equation XII.17 the meaning of the symbols is as follows. R is radius of the crimp curvature (of the fiber axis), Δ is the fractional differential shrinkage between the components of the fiber, and is expressed as

$$\Delta = \delta_2 - \delta_1 = F\left(\frac{1}{E_1\,A_1} + \frac{1}{a_2}\right) + \frac{1}{R}(u_1 + u_2) \qquad \text{(XII.18)}$$

δ is fractional shrinking potential of the respective components, F is compressive force owing to the higher shrinkage potential of the other component and this forms two bending moments M of the appropriate components.

$$M_1 + M_2 = F\,(U_1 + u_2) \qquad \text{(XII.19)}$$

where u are the distances from the geometric centers of the two component cross section from the geometric center of the entire cross section, P. A are cross sectional areas of the respective components, E are moduli of the components, I_1 and I_2 are second moments of the respective component cross sections about the axis connecting the geometric centers of these cross sections, and the second moment of area of the whole cross section is I_0 (about the axis over the geometric center of the whole fiber and approximately parallel to the line dividing the different polymer sections).

$$I_0 = I_{1P} + I_{2P} \qquad \text{(XII.20)}$$

I_{1P} and I_{2P} are the moments of the cross section segments about the axis of the whole cross section. $m = E_2/E_1$ is the ratio of the moduli.

If the cross section is symmetrical around its axis, then equation XII.17 simplifies to

$$R\,\Delta = \frac{2\,I_0}{A_0\,u_1} + \frac{(m-1)^2}{2\,m\,A_0\,u_1}\left(I_0 - A_0\,u_1^2\right) \qquad \text{(XII.21)}$$

It is important to note that crimp depends on m, on the ratio of the moduli, not on the absolute values of the moduli. On the other hand, when m is either very small or very large then R becomes large, which means that the crimp is small or none. Denton[45] suggests therefore that, except of the fibers consisting of a hard polymer and an elastomeric polymer, m may be taken as unity. This leads to another simplification of equation XII.17.

$$R\,\Delta = \frac{I_0}{a_1\,u_1} \qquad \text{(XII.22)}$$

Equation XII.22 may be expressed in a verbal form:

$$\frac{1^{st}\ \textit{moment of area of one component cross sect.} \times \textit{differ. shrink.}}{2^{nd}\ \textit{moment of area of the whole fiber cross section}} \qquad (XII.22\,a)$$

The above calculations are to be taken, to some extent, as an approximations. For details of the derivation and some additional elaborations the reader is referred to the original source.[45]

XII.3.b Fibers from Blended Polymers

Blending of polymers has been initiated in the plastics industry. One of the earliest products, ABS (acrylonitrile - butadiene - styrene) or high impact polystyrene, has long been very successful. The idea of blending was transplanted also to the fiber industry, but it may be difficult to name a very successful product in this

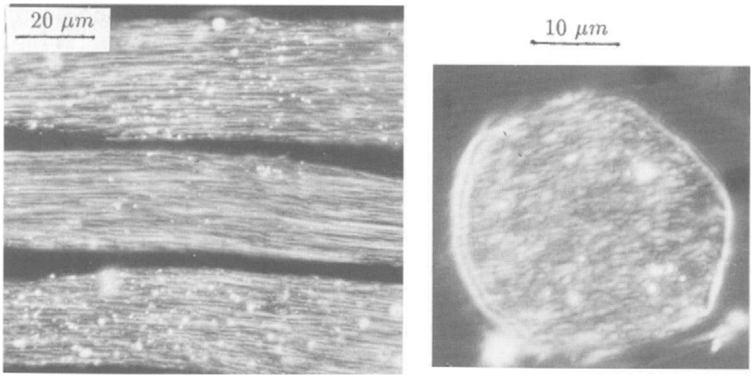

Figure XII.5: *Dark field photomicrographs of a longitudinal, 1 μm thick, cross section (left) and transverse, also 1 μm thick, cross section (right) of a fiber from blended polymers. The protofibrillar nature of the inclusions is well visible.*

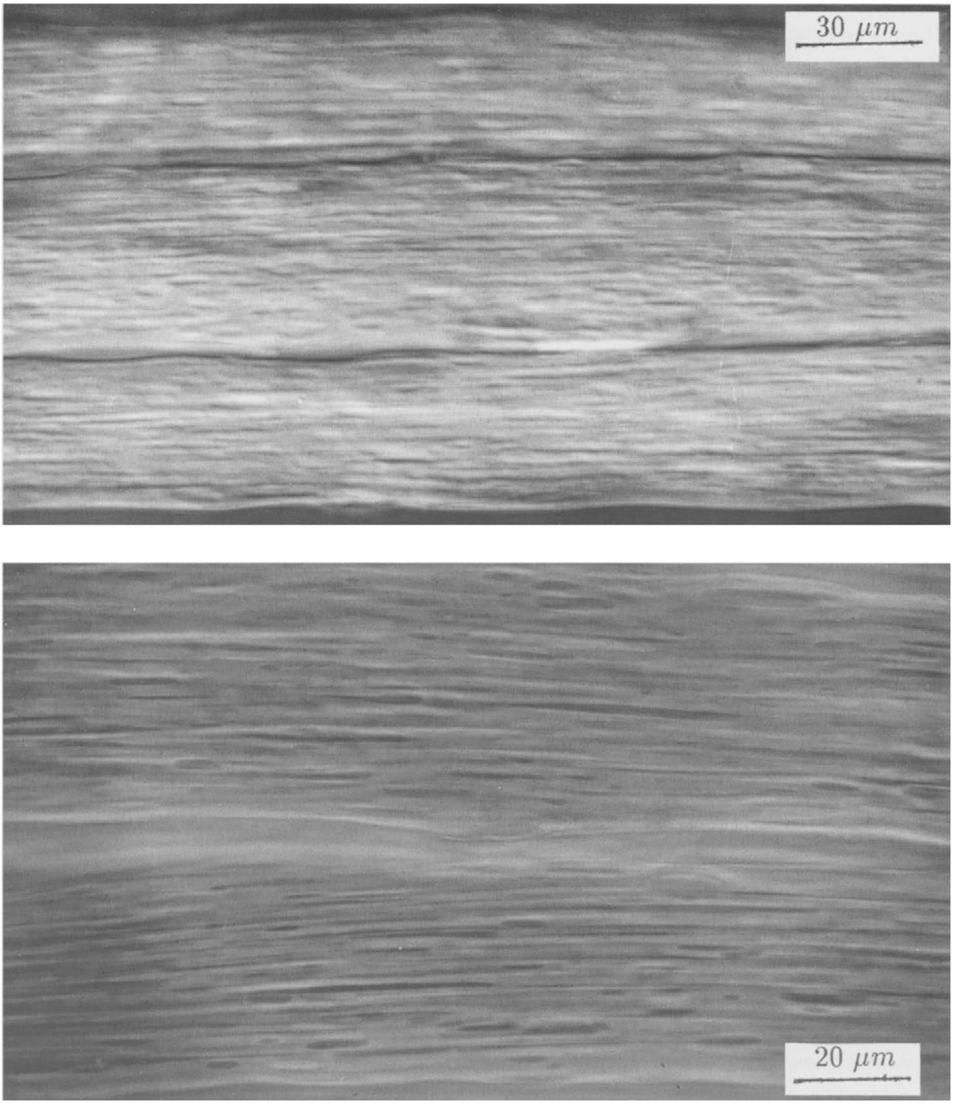

Figure XII.6: *Photomicrographs of a fiber from blended polymers, similar to those in figure XII.5, 1 μm axial cross sections. Top: differential interference contrast by Nomarski. Bottom: phase contrast in polarized light. The lateral sizes of the structures range from 3000 Å to 7700 Å.*

group. It appears that the big difference between the two types of industries, plastics and fibers, is created by the the very small size of fiber diameters.

As mentioned above, if a blend is to have reasonable mechanical properties, there must be a good compatibility between the two components, a good adhesion between the phases. Generally, crystallinity does not help adhesion and fiber forming polymers are predominantly crystalline for now. The neck drawing of fibers creates additional obstacles. As it may be seen in figures XII.5 and XII.6, neck drawing transforms the inclusions of the dispersed phase into elongated shapes of *protofibrils* or fibrils. The dimensions of the structures in figures XII.5 and XII.6 range from about 3000 Å to about 7700 Å, they are relatively large and the size justifies the term *protofibrils*. The fibers in figures XII.5 and XII.6 were not extensively drawn, but fibers from blended polymers can rarely be drawn more anyway. In plastics, the inclusions retain mostly spherical shape, unless subjected to high shearing forces at not too high a temperature. The fibrillar structure of fibers is responsible for the relatively low lateral strength and the fibrils of dispersed phase may only decrease the transverse properties even further.

The structure of fibers prepared from polymer blends, as well as of the bicomponent fibers, requires a substantial research effort. Investigation of the bicomponent structures using classical methods is very difficult, and next to nothing has been published in the field. Availability of the electron microscopes with spectroscopic imaging appears to be ideal for the purpose; distribution of the dispersed phase and of the interphases may be well visible. Nevertheless, judging from the scarcity and the character of the published information, there appears to be quite a sizeable effort being spent on the development of all sorts of biconstituent fibers, however, the effort appears to be an exercise in the "Edisonian approach", if to use the common euphemism.

True, blending of polymers expands the possibility of varying fiber properties and the technique is relatively simple, if not simplistic. Much more promise, however, is carried by the application of block copolymers. This possibility requires much more effort, mainly intellectual, to realize; but the potential gains are many times larger since one may obtain whole groups of polymers leading to "tailor made" properties.

XII.4 Microfibers

Very thin fibers of fractional decitex, usually referred to as *microfibers* have been found to offer unusual and interesting textile properties. It was mentioned several times above that obtaining very thin fibers with the standard processes of diameter attenuation and neck drawing becomes difficult and expensive once the barrier of three or two decitex is crossed. The incompatibility of polymers, so bothersome in case of polymer blends and bicomponent fibers, has been utilized as one way of solving the problem of microfibers.

The first commercial microfibers were obtained by way of coextrusion of polyesters or polyamides with another polymer, mostly polystyrene. Due to the lack of compatibility the sections of different components usually separate during neck drawing. The relatively easily soluble polystyrene may be dissolved away while the wanted fine fibers remain intact. The need of dissolution makes such processes exceptionally cumbersome and expensive.

Using the similar principle of coextrusion, high molecular mass polystyrene, or similar, may be substituted with either low molecular mass compounds or water soluble polymer in as small ratios as possible. In this way the burdensome process of dissolving relatively large quantities of polymer in organic solvents may be simplified, becoming more like a wash.

The essential part of the method – coextrusion – imposes limitations on the shape of the cross sections of the microfibers. The simplest way is to divide the round cross section of the capillary into sectors of a circle which have a cross section close to a triangle – a cross section well acceptable for the textile purposes.

Another variation on the theme is the use of two incompatible polymers which split in cold drawing but both of them remain in the fiber blend. A high molecular mass fiber finish, which has a surfactant like nature, may be used as a "separator" for the coextruded sectors. This area presents a really large room for inventiveness.

> *"Felix qui potuit rerum*
> *cognoscere causas."**

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*Happy are those who possessed the cognition of the nature of matter. *Publius Vergilius Maro*: Georgica, **2**, 490.

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