Physics of textiles

The availability of a wide choice of polymeric fibers has stimulated great interest in their physical properties and in the principles involved in their manufacture into yarns and fabrics.

L. R. G. Treloar

While the basic processes of spinning and weaving were developed empirically, the problems and processes of the textile industry have in the last 25 years been the subject of intense scientific activity. The stimulus to this activity has arisen mainly from the impact of the newer polymeric fibers, which have introduced possibilities of improved properties and radically different methods of production and processing. In place of the very small number of fibers supplied by nature, we are now able to select from a great variety of materials, differing widely in both chemical and physical properties, to meet any particular demands. Moreover, these new materials are not limited to textile applications, but are in many cases available also in the form of films for packaging, or in bulk for engineering or other uses. Their study has thus become a branch of the science of polymeric materials, which is one of the most lively fields of scientific activity at the present time.

Textile materials combine a number of distinctive properties, the most important of which are strength, flexibility and lightness. The flexibility is a basic property of the structural element, that is, the fiber or filament; it increases as the filament diameter is decreased. Textile structures, typified by woven or knitted fabrics, are assemblies of filaments held together by purely *geometrical* constraints in such a way that the basic strength and flexibility of the filaments is preserved and utilized to the maximum advantage in the finished structure.

While all textile materials possess a number of properties in common, the importance of any particular property is dependent on the use to which it is to be put. For clothing purposes comfort and warmth are the primary considerations; these are determined by the water-absorbing properties of the filament material, and by the transfer of heat (mainly by convection) through the fabric structure. The absorption or release of water from the material plays an important role in the adjustment of the body temperature to variations in temperature and humidity of the surrounding atmosphere. For undergarments a structure of low density (that is, one that contains a large proportion of air space) is desirable. Traditional materials such as wool and cotton, which are made up of relatively short fibers, automatically produce an open type of yarn structure owing to the presence of loose fiber ends and the general irregularity (crimp) of the filaments. These materials are also capable of absorbing large amounts of water (35% by weight in the case of wool and 20% for cotton). In this respect both cotton and wool satisfy the basic requirements for comfort. Equally satisfactory is viscose rayon produced from wood pulp—one of the earliest and still one of the most extensively used of the man-made fibers—which is normally supplied in the form of "staple" (short-length) fibers prepared by chopping up the continuously extruded filaments.

For outer garments resistance to tearing and abrasion, desirable draping and handling properties, resistance to creasing and stability of form (including retention of pleats or folds) are some of the more important of the physical properties to be taken into account. These are complex properties, dependent on the type of fabric structure as well as on the inherent properties of the filament material. Chemical properties also are involved in dyeing, laundering and other processing treatments.

An important section of the textile industry is concerned with industrial yarns and fabrics, for example, tire cords, conveyor belts, parachute materials, and so on. For these, high impact strength and abrasion resistance are primary considerations.

In many applications no one fiber has all the desired properties. In such cases the most effective results are obtainable by the blending of two or more different components. Thus polyester fibers, which possess outstanding tensile strength but do not absorb water to a significant extent, are frequently blended with wool or cotton to produce a clothing material combining high strength and resistance to abrasion with acceptable hygroscopic properties.

Basic mechanical principles

The production of a textile fabric involves two essential stages, namely the assembly of the original fibers or filaments into the form of a yarn followed by the geometrical interlocking of the yarn threads by weaving, knitting or other processes. The processes of yarn formation, developed on the basis of natural fibers, include the initial separation and randomization of the fibers by a combing or "carding" operation, the subsequent drawing together or "drafting" of the fiber assembly to form a loose roving of approximately aligned fibers, and the final spinning or twisting operation, in which the filaments are compacted to form a dense coherent structure. The strength of the yarn is a function of the frictional forces between the helically conformed fibers; without twist the inter-fiber friction would be insufficient to maintain a coherent structure.

With the introduction of man-made

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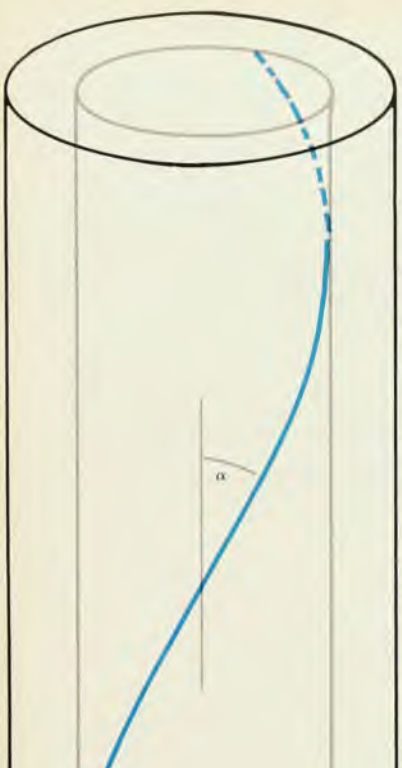


Coaxial helix model of yarn structure. A single yarn is produced by twisting together a large number of continuous filaments; this model assumes that each filament lies on a helix coaxial with the yarn axis. Figure 1

fibers, produced in the form of continuous filaments, the necessity for the traditional sequence of processing operations is no longer apparent. This does not necessarily imply, however, their immediate (or even their ultimate) disappearance. Twist, for example, is essential even in continuous-filament yarns, for without twist the yarn would have no resistance to disruption by lateral forces—it would be an uncoordinated array of floating filaments. Again, the packing density of the filaments in twisted continuous-filament yarns is much higher than in corresponding short-filament (staple) yarns; fabrics produced from such yarns lack the softness and warmth of comparable fabrics from staple yarns, and are unsuitable for many textile applications on this account.

One obvious way out of these difficulties is to chop the continuous filaments up into short staple lengths, randomize them into a form quite similar to absorbent cotton, and then pass them through the whole range of traditional processing procedures. In fact, as noted above, a large proportion of the production of viscose rayon yarns is carried out in this way.

In the course of time, however, it is likely that many of the older traditional methods of yarn and fabric production will be substantially modified or replaced by more economical processes specifically adapted to the new materials now available. Developments along these lines are the subject of active investigation throughout the textile industry at the present time. One example may suffice to illustrate this trend: the development of methods of production of more open or "bulked" yarn structures directly from continuous-filament yarns by so-called "texturizing" processes. Among the proposed texturizing processes, the simplest is perhaps the "false-twist" process. In this technique, twist is introduced into a segment of yarn and the resulting helical structure of filament is "set" by heating to an appropriate temperature. The same segment is later subjected to an equal rotation in the opposite direction. Owing to the setting of the original structure this rotation does not simply restore the initial untwisted state, but produces a complex and irregular structure of comparatively low density.

The mechanics of yarns and cords

We turn now to the question of the quantitative interpretation of the properties of textile structures. The procedures involved may be illustrated by the simplest of such structures, namely a single yarn, as produced by the twisting together of a large number of continuous filaments. If we assume each filament to lie on a helix whose axis coincides with yarn axis (figure 1), the application of a strain in the direction of the axis will produce easily calculated strains in the individual filaments; these strains are a maximum (equal to the yarn strain) for the central filament and decrease progressively as we proceed outwards. For small strains Hooke's law may be assumed to apply, and the stress in a filament at any radial position is therefore directly obtainable. Taking the component of stress in the axial direction and summing over all filaments, we obtain the modulus of the yarn, E_y, in the form

$$E_y = E_f \cos^2\alpha_m \qquad (1)$$

where α_m is the angle of the outermost filament and E_f is the modulus of the filament material. The modulus of the yarn thus decreases with increasing α_m, that is, with increasing twist. Furthermore, if we assume that rupture occurs as soon as the central filament reaches its breaking extension, the tensile strength of the yarn will similarly decrease with increasing twist.

This very simple model predicts in a general way the well-known fall in both modulus and tensile strength with increasing twist, though quantitative discrepancies, which become more pronounced with increasing values of the strain, are observed. An illustration of these discrepancies in the case of the modulus is shown in figure 2 (colored curve). Possible reasons for the discrepancies have been discussed in detail by J. W. S. Hearle;[1] of these the most important are the following:

- Effects of transverse stresses in the yarn are neglected,
- The properties of the material are not consistent with Hooke's law, except at very small strains, and
- Changes in yarn diameter in extension are neglected.

Of these, the most difficult to deal with in general mathematical terms is the second, owing to the fact that different filament materials have widely different types of stress–strain relations (figure 3). More complex analyses, incorporating approximate expressions for the stress–strain relations and taking into account the effects of lateral stresses and changes in yarn diameter, have been developed, particularly by Hearle. A further step was taken when G. Riding, in collaboration with me,[2] introduced a numerical computation technique to calculate the total energy in the stressed yarn, the changes in yarn diameter being derived on the assumption of constancy of yarn volume. From the total energy so calculated, the yarn stress is then immediately obtained by differentiation with respect to the axial length (that is, yarn strain). This method has the advantages of being applicable to any form of filament stress–strain relation and to any magnitude of strain. A typical example of the application of this theory is shown in figure 2.

Despite the apparent success of the coaxial-helix model for the prediction of yarn properties, direct observation of the paths of filaments in actual yarns by means of a single colored "tracer" filament do not substantiate this simple type of structure. In practice the path of the individual filament does not correspond to a helix of constant radius; instead the radial position of the filament varies irregularly from point to point along the length of the yarn. A typical example, taken from the work of Riding,[3] is reproduced in figure 4; from the projections of the tracer filament in two perpendicular directions the radial position of the filament with respect to the yarn axis at any point in the yarn may be directly obtained. The path of the filament may be described as a helix of varying radius. The reason for this "filament migration," as it is called, is obvious on reflection. According to the theoretical model the length of a filament in the twisted yarn increases with increasing distance from the yarn axis. But before twisting the filaments are all of equal length. The necessary increase in length of the outer filaments (with respect to the axial fila-

ment) could only be brought about by introducing large permanent strains into these filaments, which it is easy to show experimentally are not present. The difficulty can only be evaded by allowing every filament to migrate in a more or less random manner from one radial position to another position.

Migration of this kind occurs also in corded structures made up by the twisting of, say, seven separate strands of yarn. If one of these strands is colored this strand is found to disappear periodically from view in accordance with the requirement that each of the component plies must occupy the central or core position in the cord for the same proportion of its length.

Rope-making technology, in which it is important to avoid irregularities of this kind, employs an entirely different process. Here the separate strands are fed to the twisting zone at rates appropriate to their position in the structure.

Reverting now to the single-yarn problem, the question may be asked whether the presence of filament migration necessitates the abandonment of the coaxial-helix model for the calculation of yarn properties. The answer, fortunately, is that so long as the rate of migration is not too fast the effect of the migration on the system of stresses, and hence on the properties of the yarn, is negligibly small.

Single yarns are mechanically unsymmetrical structures. The presence of twist is liable to give rise to a torsional couple, which can lead to snarling or other unwanted effects. Consequently in systems subjected to high mechanical stresses a multi-ply structure consisting of two or more strands of yarn twisted together in the opposite sense to the original yarn twist is adopted. The two twists (the initial yarn twist and the subsequent cord twist) are related in such a way that the resultant cord is approximately "balanced," which means that it has no inherent tendency to twist or untwist on application or removal of a load.

In the case of a symmetrical cord structure, such as a typical tire cord containing two or three plies, the axis of each ply describes an identical helix about the axis of the cord. The helical paths of the individual filaments in the original single yarns are converted into coiled helices by the cord-twisting operation (see the insert to figure 5). The geometry of this system is somewhat complex. From the purely mathematical standpoint the helix itself may be described as a "twisted" curve, the amount of twist—or "tortuosity," to use the technical term—being measured by the rate of rotation of the plane of curvature on progressing along the curve; for a helix of radius a and angle α it is given by $(1/a)\sin\alpha\cos\alpha$. The implication of this is that the formation of the cord itself introduces an additional amount of twist corresponding to the tortuosity of the ply axis. This description, however, does not dispose of the problem, because any change in the state of twist of a yarn (or of a ply in a cord) alters the length of the yarn axis. If ψ_0 is the original yarn twist, the final twist in the ply after the cording operation must therefore be expressed in the form

$$\psi = \psi_0(l_0/l) + (1/a)\sin\alpha\cos\alpha \quad (2)$$

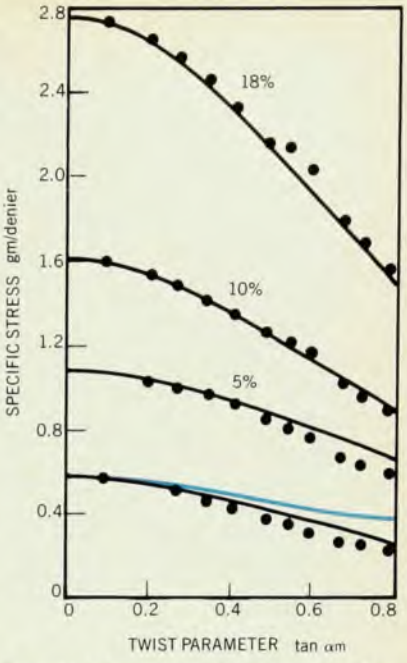
in which the factor l_0/l represents the change in length of the ply axis due to the change in tortuosity. On the basis of this equation the geometry of the final cord may be completely specified. By methods essentially similar to those applied in the case of a single yarn it is then not difficult to calculate the mechanical properties (the stress–strain relation) for the cord. A comparison of theoretical and experimental curves[4] for typical three-ply cords (figure 5) shows rather larger discrepancies than for single yarns; these discrepancies probably arise from the distortion of the cross section of the plies due to the mutual pressure between them in the contact region, and from the consequent disturbance of the yarn geometry and of the uniformity of packing of the filaments.

These examples of the application of theoretical models to the calculation of the mechanical properties of yarns and cords have undoubtedly led to a better understanding of the industrial processes of yarn formation. Such discrepancies as have arisen may reasonably be attributed to the inevitable lack of precision in defining the geometry of the practical system. On the basis of these studies we may proceed with some confidence to attack the more complex problems of fabric structure and fabric properties.

Fabric properties

The bulk of fabric structures are produced either by weaving or by knitting, both of which processes rely on purely geometrical constraints for the formation and maintenance of the structure. In addition there are felts and non-woven fabrics, consisting of randomized fiber assemblies held together by mechanical entanglements that may be reinforced by some form of stitching or by the incorporation of an adhesive element. These materials, particularly when highly compressed or adhesive-bonded, lack the flexibility of woven or knitted fabrics and find applications mainly where a relatively high flexural rigidity is required.

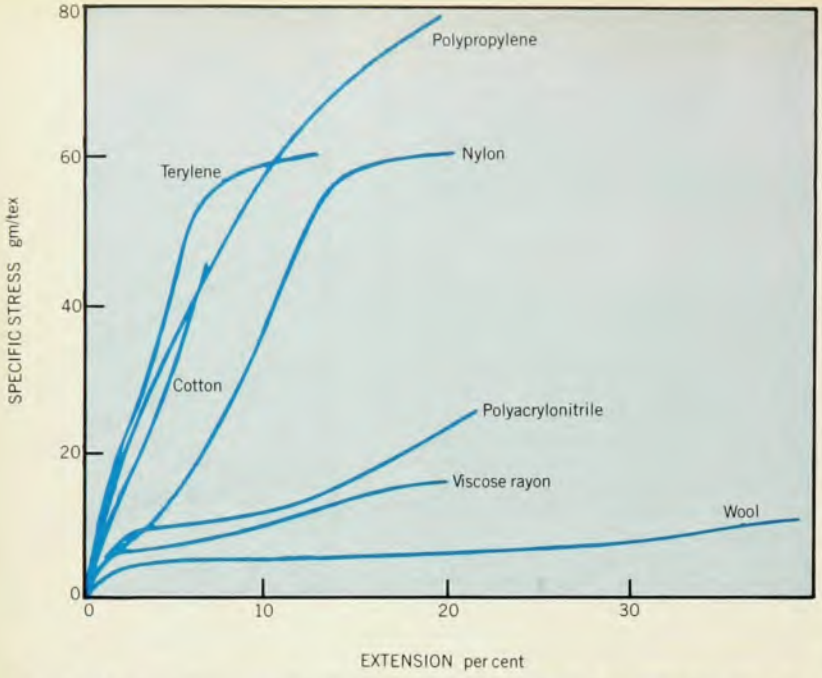
Both woven and knitted fabrics are available in a wide variety of constructions to produce the desired physical properties, which may include tensile strength and abrasion resistance, extensibility, flexural rigidity, retention of creases, optical appearance (for example hairyness or gloss) and thermal transmission. All such properties are complex



Relation between specific stress and twist for high-tenacity rayon (Tenasco) yarns at different values of axial extension. The points are experimental. Black lines are from the theory of L. R. G. Treloar and G. Riding (reference 2) and the colored line is from simplified theory (see equation 1 in the text). Figure 2

Comparison of material strengths by area and by mass

Material	Strength T (MN/m^2)	Relative density ρ	T/ρ (MN/m^2)
Carbon fibers	3200	1.9	1700
Nylon, high tenacity	1000	1.15	870
Rayon (cellulose), high tenacity	1000	1.56	640
Flax (cellulose)	900	1.56	580
Steel, piano wire	2000	7.8	260
Glass filaments	1000–3000	2.5	400–1200
Glass, sheet	40–80	2.6	15–30



Stress–strain curves for representative textile materials. Note the widely differing behavior. (The "tex" unit is the mass in grams of 1000 meters of filament.) Figure 3

functions of the fundamental properties of the filament material and the geometry of the final structure, which includes, of course, the structure of the yarn. Furthermore, because the geometry of the final structure is itself determined by the elastic (or visco-elastic) and frictional properties of the filaments, it is apparent that the quantitative elucidation of the various factors involved in the determination of fabric properties presents problems of considerable difficulty to the physicist.

In this short article I can only hint at the way these problems are being tackled, taking as an example the simplest case of a plain-weave fabric in which the yarns are of circular cross section (but not necessarily of equal diameter). For the Peirce model,[5] depicted in figure 6, the structure may be completely specified by five independent parameters: the two yarn diameters, (d_1,d_2) the two thread spacings (p_1,p_2) and one of the two crimp angles (θ_1,θ_2).

The load–extension curve for a structure of this kind, measured in either warp or weft direction, has the general form shown in figure 7, taken from the work of P. Grosberg.[1] The main deformation process is associated with the straightening out of the threads (removal of crimp) in the direction of the stress, which is necessarily accompanied by an increase of crimp in the threads at right angles to this direction. The forces involved in this crimp interchange are determined by the flexural rigidity of the yarn and the frictional forces between fibers, the latter predominating in the early stages of the deformation. At very high stresses, when the corresponding threads are fully extended, the de-crimping process gives way to an actual stretching of the yarns in the direction of the applied stress.

The properties of the fabric in the principal directions thus involve not only the tensile properties of the component yarns, discussed above, but also their bending and frictional properties. Woven fabrics, however, are highly anisotropic systems; for deformations in directions other than the thread directions, very different considerations apply. Thus in the case of a plain-woven fabric with equal warp and weft spacings, deformation takes place most readily in a direction making an angle of 45° to the principal directions. Such a deformation, which is closely related to a simple shear, may be effected by the *rotation* of the warp threads with respect to the weft and involves a strong component of force arising from the friction at cross-over points between these two sets of threads. This kind of deformation, which has been extensively studied,[1] is of great importance in determining the draping properties of fabrics.

Besides these in-plane deformations much work has been devoted to the study of out-of-plane deformations, of which creasing and crease-recovery are familiar examples. Creasing is related to the imperfect elasticity of the fibers, or in other words to the presence of a non-recoverable or plastic component of the deformation. The folding of a fabric involves large bending and torsional strains in the fibers that are only partially recovered on removal of the deforming forces. Considerable stress has been achieved in interpreting these properties on the basis of the observed properties of fibers under comparable conditions.[6]

Fiber structure and properties

With certain exceptions (for example, glass and asbestos), textile fibers are partially crystalline organic polymers in which the molecules are preferentially aligned in a direction parallel to the fiber axis. Their chemical constitution may vary widely, from the cellulose of plant fibers and the protein of animal fibers to the polyesters, polyamides and pure hydrocarbons of the synthetic materials. The two most important considerations from the physical standpoint are that the chains should be of very great length, containing many thousands of atoms in their "backbone" structure, and that the polymer be capable of crystallization by a process involving local ordering of neighboring chain segments to form a three-dimensional lattice.

The general structure of a fiber is shown in a simplified form in figure 8. Since the dimensions of the individual crystallites are considerably less than the average length of the polymer chains, it follows that a single chain may pass successively through several crystallites,

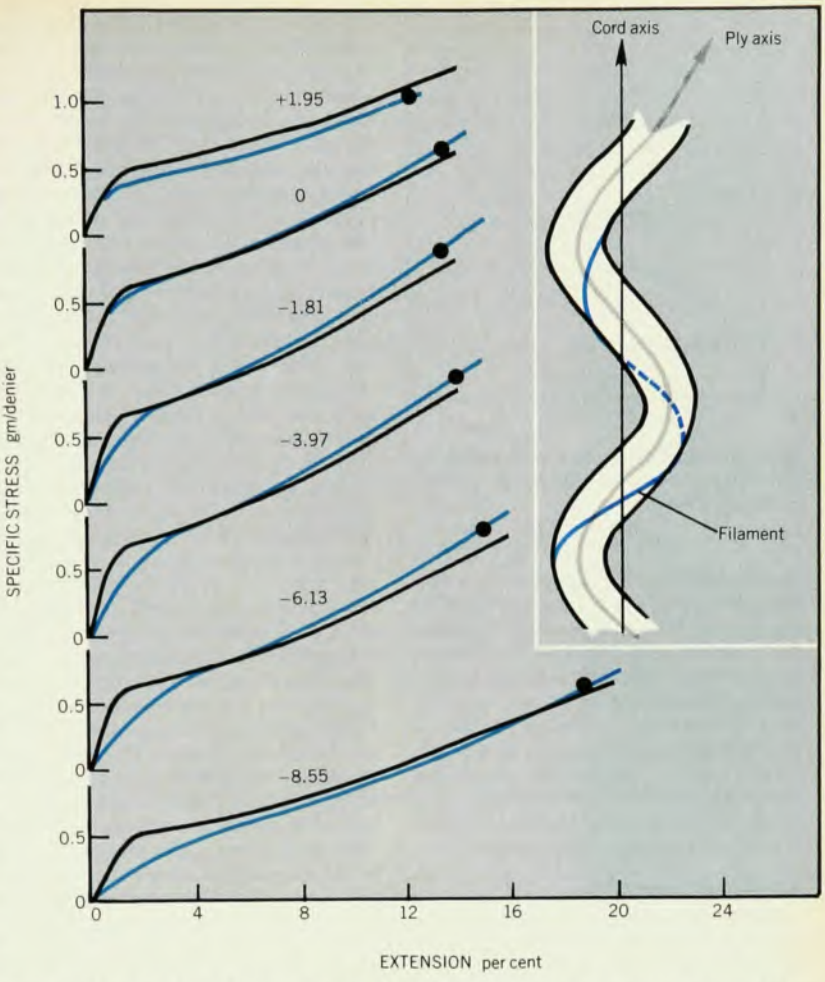
Filament migration in yarn as revealed by tracer filament technique. The photographs represent the same section of yarn viewed from two perpendicular directions. The path of the tracer filament can be described as a helix of varying radius. Figure 4

producing a molecularly interconnected composite structure containing both crystalline and amorphous components. This rather peculiar structure combines the high strength of the crystalline regions with a degree of flexibility or elastic deformability associated with the greater freedom of molecular movement in the amorphous regions, yielding a product of high tenacity and toughness. On a weight basis fibers are among the strongest materials known; the table on page 25 shows some examples of material strengths listed as a function both of area and of mass. A high-tenacity nylon filament, as used for tire cord, for example, has more than three times the strength of a steel wire of the same mass per unit length.

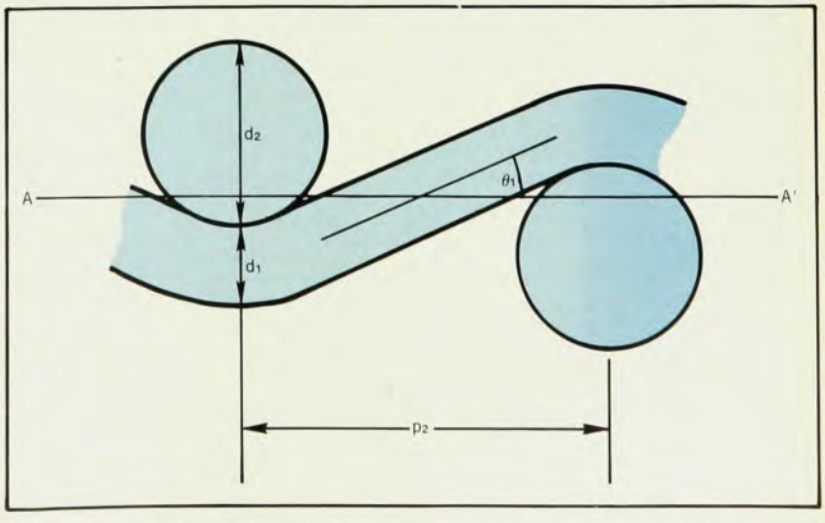
The schematic diagram shown in figure 8 gives a very inadequate picture of the detailed complexities of the structure and morphology of actual fibers. Our ideas on this subject have been profoundly modified by the discovery that polymers such as polyethylene and nylon may be obtained in single-crystal form by precipitation from dilute solution. In these single crystals, which have the form of plates of thickness about 10 nanometers, the individual molecules are found, rather surprisingly, to lie in a direction *perpendicular* to the plane of the plate. For the molecules (whose lengths may be 10 to 100 times as great) to be accommodated within the available dimensions it follows that they must be folded backwards and forwards between the two surfaces of the crystallite.

A very considerable amount of work has been carried out on the factors that determine the structure and form of these single crystals, notably by P. H. Geil[7] in the US and A. Keller[8] in the UK. There is much evidence also to suggest that in bulk polymers prepared from the melt folded-chain lamellae form the basic elements of the structure. The lamellae may be arranged in more complex morphological forms such as stacked lammellae or spherulitic structures. The precise morphology depends on many factors: the molecular weight and molecular-weight distribution of the molten polymer; its temperature and rate of extrusion, and the temperature gradient in the moving threadline, which determines the rate of solidification. The conditions in the liquid jet proceeding from the spinneret determine the degree of molecular orientation and hence the rate of crystallization and the final morphology of the solidified filament. Subsequent to solidification the "unspun" filament is then subjected to a further drawing process in which the crystal lamellae tend to break down and give way to extended-chain crystallization of the type indicated in figure 8.

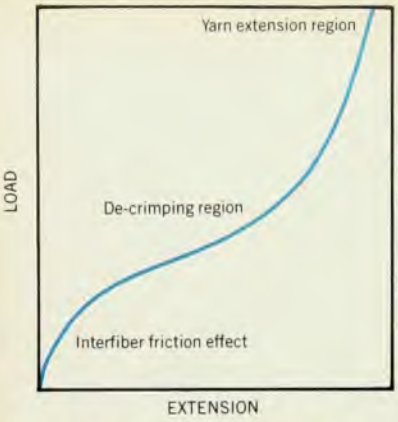
The final properties of the fiber can be varied over a wide range by modifications of the spinning and drawing conditions. In general, the higher the degree of ori-



Three-ply cords are made of three strands of yarn twisted together in the opposite sense to the original yarn twist. The inset shows the path of a filament in such a cord, and the curves in the main part of the figure show the stress–strain relationship for three-ply cords containing different values of cord twist (in turns per cm). The original yarn twist was 11.1 turns per cm. Black lines are calculated; colored lines are experimental; note that the discrepancies are larger than for single yarns. Black dots show mean breaking extension. From reference 4. Figure 5



The Peirce model of plain-weave fabric, seen parallel to the warp threads. The structure is completely specified by five independent parameters: d_1 and d_2, the warp and weft yarn diameters; p_1 and p_2, the yarn spacings, and θ_1, the warp crimp angle. AA′ is the median plane. Figure 6



General form of the load-extension curve for a principal direction of a plain-weave fabric. From reference 1. Figure 7

entation achieved the higher is the tensile strength and the lower the extension to break. For industrial yarns (for example, tire cords), tensile strength is a primary objective; for other purposes (clothing) a higher extensibility and lower modulus may be preferable. The production of any desired properties from widely different types of polymer is an area of technology on which a great deal of effort is now being concentrated, and one which is of great interest to the physicist.

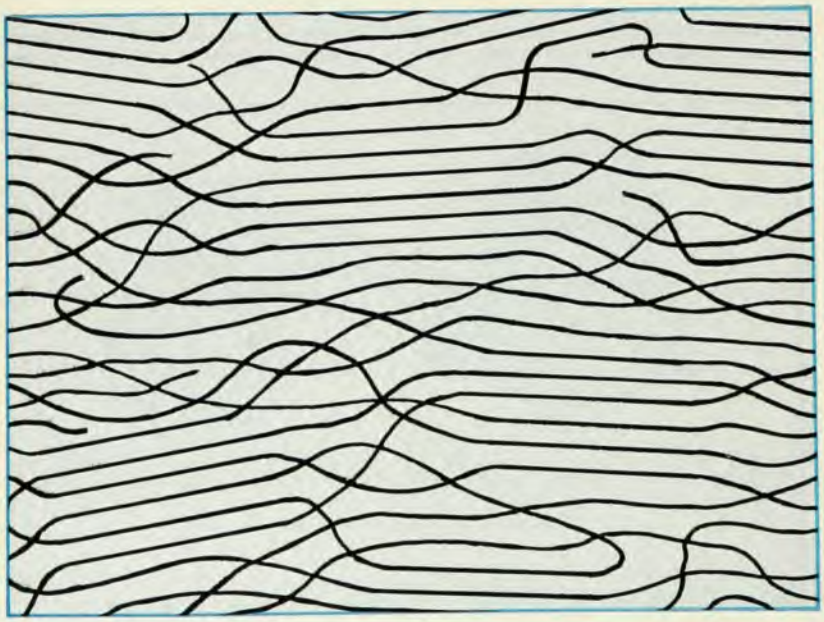
Anisotropic properties

In the previous section our attention has been concentrated on the properties of fibers in the axial direction only. Fibers, however, are highly anisotropic in physical properties; they have a greater strength, and a higher value of Young's modulus, in the direction of drawing than in the transverse direction. This anisotropy arises from the disparity between the strong chemical bonds in the chain backbone structure of the molecule and the relatively weak van der Waals forces operating laterally between a given molecule and its neighbors. On theoretical grounds a difference amounting to a factor of about 50 would be expected between the longitudinal and transverse elastic moduli of a perfectly aligned system (for example, a single polymer crystal). This degree of anisotropy is not realized in a normal fiber, in which the molecules are only imperfectly aligned; nevertheless very significant differences in elastic moduli and fracture properties in the longitudinal and transverse directions have been obtained experimentally. An illustration of the anisotropy of elastic moduli is shown in figure 9a, taken from the work of I. M. Ward and his associates, who have made a special study of this subject.[9] The modulus E_3 corresponding to the direction of drawing (the fiber axis) increases, while the transverse modulus E_1 decreases with increasing draw ratio. A semi-quantitative explanation of these effects may be obtained by treating the system as an aggregate of small elongated anisotropic units that rotate as if embedded in an elastic continuum when the polymer is drawn. The problem cannot be solved exactly because the exact distribution of the stresses and strains is not known, but two extreme cases, corresponding respectively to uniform stress (Reuss average) and uniform strain (Voigt average) may be worked out. By a suitable choice of constants for the structural unit this theory predicts to a reasonable degree of approximation the experimental observations (figure 9b).

These measurements are not in themselves adequate for a complete description of the elastic properties of a fiber. On the basis of the classical theory of elasticity the specification of the most general type of anisotropy requires the introduction of 21 independent elastic constants; for a uniaxially drawn polymer this number is reduced to five. The experimental determination of these five constants necessitates tensile and torsional measurements on specimens cut in different directions with respect to the axis of symmetry. Not all of these are practicable in the case of a fiber, but such measurements have been carried out successfully for a number of oriented polymers in sheet form.[9]

The anisotropic fracture properties of oriented polymers are exemplified by the tendency of such materials (for example, timber) to split or fibrillate in the direction of the orientation. Measurements of the energy for crack propagation—or "fracture surface energy," as defined in terms of the Griffith theory of fracture (see below)—for cleavage parallel to the direction of orientation, show a progressive reduction with increasing orientation for both glassy (amorphous) polymers such as Perspex and Plexiglas and crystalline polymers such as polythene and polyesters. Corresponding measurements for cleavage in a plane transverse to the direction of orientation are virtually impossible, owing to the tendency of the crack to branch out into the longitudinal direction—a tendency that increases rapidly with increasing orientation. This effect is illustrated by observations on transverse impact properties of glassy polymers drawn at temperatures above their softening points and subsequently cooled to room temperature (figure 10). Notched specimens were used, the impact being made on the side of the specimen directly opposite the notch. The amount of double refraction (difference of refractive indices Δn between longitudinal and transverse directions) served as a measure of the degree of molecular orientation.

The tendency of highly drawn polymers to fibrillate is being exploited commercially on a large scale for the production of the coarser grades of yarns and cords, for which purpose polypropylene is eminently suitable. The drawn film may be split either by passing over a drum containing suitably disposed wire pins, or alternatively simply by the twisting of a strip.



Molecular structure of an oriented crystalline polymer, shown in a simplified model. The aligned regions represent crystallites, and a single polymer "chain" (the repeating unit of the molecule) may pass successively through several crystallites. Figure 8

Fracture mechanics

The realizable strength of a typical crystalline or glassy solid is of the order of only $1/100$ of the theoretical strength calculated on the basis of the force fields existing between its constituent atoms,

and this wide discrepancy was attributed by A. A. Griffith in 1921 to the presence of flaws or defects on the surface or within the body of the material. In a specimen subjected to a tensile stress σ an edge crack of length c will propagate in the direction transverse to the stress only if the energy required to create the fresh surface is less than the elastic strain energy released by the further extension of the crack. On this basis the critical stress σ_k for crack propagation is found to be related to the crack length c by the equation

$$\sigma_k = \sqrt{\frac{2E\gamma}{\pi c}} \qquad (3)$$

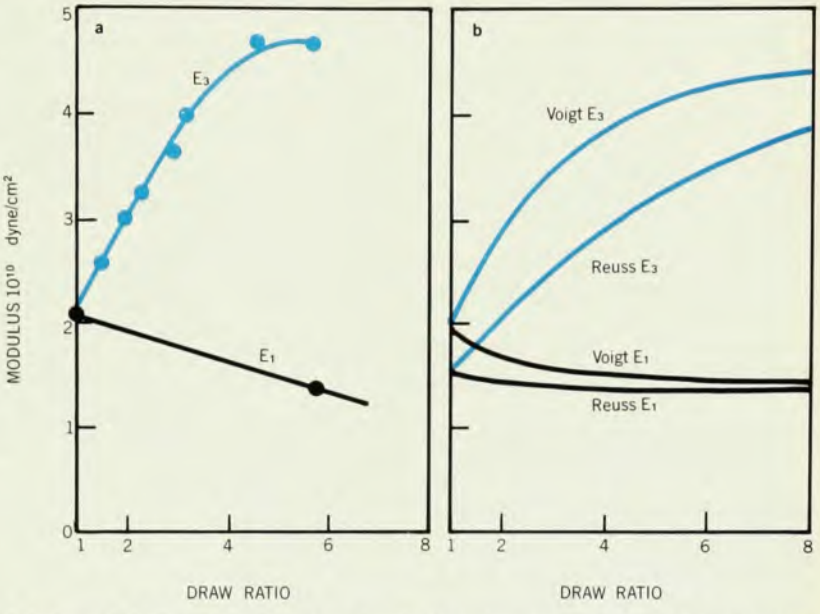
where γ is the energy required to form unit area of fresh surface and E is Young's modulus. Since σ_k falls with increasing c, failure becomes catastrophic when this critical stress is exceeded. From measurements of σ_k as a function of crack length c the value of γ may be derived. In the case of glass this is found to be of the order of 1.0 J/m^2 (1000 erg/cm^2), which is of the same order as the independently estimated surface free energy, as would be expected for a simple cleavage between two planes of atoms. For polymers, however, very much higher values of this characteristic energy are obtained, of the order of 200 J/m^2 for glassy polymers such as Perspex, 10^4 to 10^5 J/m^2 for crystalline polymers (undrawn) and 10^6 J/m^2 for rubbers. These very high values must be interpreted as arising from the fact that the fracture processes in polymers involve plastic or visco-elastic deformations extending over a considerable volume of material in the vicinity of the crack tip, such deformations being made possible by the great lengths of the molecular chains and the comparatively high mobility of local segments of these chains.

In general, the mobility of the chain segments will decrease with decrease in temperature; hence a reduction in the extent of the local plastic deformation and an increase in brittleness is to be expected as the temperature is lowered. Measurements of the temperature dependence of fracture surface energy for polypropylene films[11] containing different amounts of molecular orientation bear out this expectation. Both the magnitude of the fracture surface energy and its sensitivity to temperature decrease with increasing orientation (figure 11).

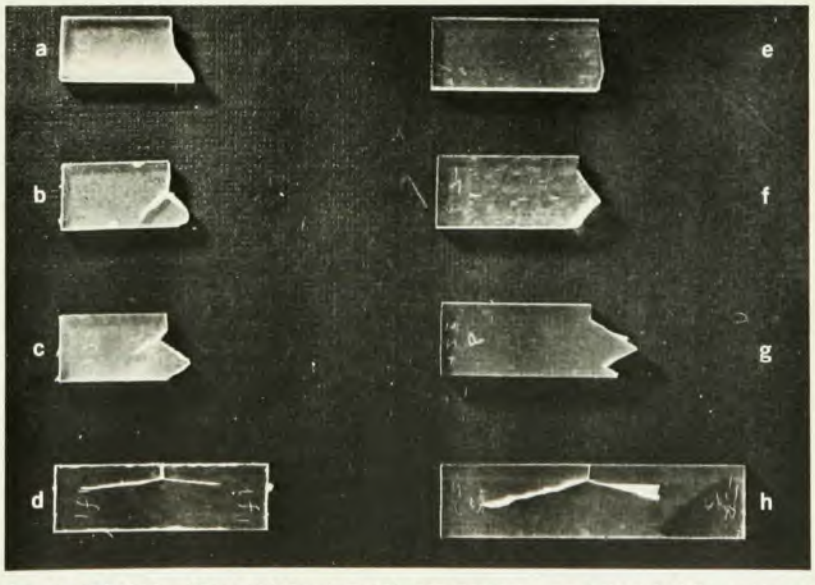
Observations of the morphology of the fracture surfaces of fibers, using the scanning electron microscope, reveal marked variations according to the temperature of testing. Figure 12a shows the appearance of a 15-denier nylon bristle ruptured at room temperature. The relatively smooth zone corresponds to the region of slow crack growth from the point of initiation (front right); the subsequent catastrophic fracture shows massive irregularities suggestive of a plastic or semimolten state. The same material when tested at liquid-nitrogen temperature gives a brittle fibrillar type of fracture, of which the point of initiation is shown in figure 12b.

Application to fabrics

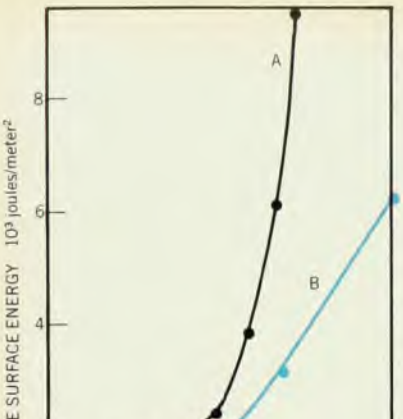
The tear strength of fabrics is a subject of the utmost practical importance particularly in connection with arresting devices or other structures that may be subjected to very high rates of deformation. Up to the present comparatively little fundamental work in this field has been published. In principle the Griffith concept can be applied to such systems, and the work of N. J. Abbott and J. Skelton,[13] for example, gives some indication of the scope for development in this field



Anisotropy of elastic moduli. The curves show the dependence on draw ratio of the elastic moduli E_3 and E_1, respectively parallel and perpendicular to the direction of drawing of nylon filaments. **Curves a** on the left are experimental; **curves b** on the right are calculated from the aggregate model of I. M. Ward and his associates in two extreme cases. From reference 9. Figure 9



Anisotropic fracture. These eight specimens of glassy polymers were first notched, then subjected to transverse impact on the side of the specimen directly opposite the notch. Anisotropy in the specimens was measured by double refraction; Δn is the difference between refractive indices in longitudinal and transverse directions. Specimens a, b, c and d are polystyrene, first unoriented ($\Delta n = 0$) and then with $\Delta n = 2.4$, 5.9 and 17.5×10^{-3} for b, c and d respectively. Specimens e, f, g and h are Perspex with $\Delta n = 0$, 3.0, 6.2 and 9.3×10^{-4} respectively. Photograph from J. W. Curtis and L. R. G. Treloar, reference 10. Figure 10



Temperature dependence of fracture surface energy of polypropylene films having different degrees of drawing. A: $\Delta n = 0.010$; B: $\Delta n = 0.020$; C: $\Delta n = 0.040$. From G. L. A. Sims, reference 11. Figure 11

Fracture surfaces of nylon filaments (15 denier) ruptured in tension, at room temperature at the top and at liquid-nitrogen temperature below. The scale mark corresponds to one micron in each photograph. From B. C. Goswami and J. W. S. Hearle, reference 12. Figure 12

of research. Using a microflash technique, these authors measured the rate of crack propagation in coated nylon fabrics subjected to high tensile stresses, and were able to establish a critical stress beyond which catastrophic failure occurred. Under these conditions the crack was found to propagate with a constant velocity, in the range 300–1000 ft/sec, depending on the conditions. Velocities of this magnitude approach the shear-wave velocity in the fabric, which is a significant parameter in the determination of the rate of release of strain energy near the tip of the advancing crack.

Fundamental studies of this kind can lead to important practical suggestions regarding the most hopeful lines of development to meet specific requirements. The particular study referred to proceeded to demonstrate that a marked increase in resistance to crack propagation could be achieved by the inclusion of "crack barriers" in the form of extra strong reinforcing yarns at regular intervals in the fabric structure. In this way it was possible to raise the stress level for catastrophic failure from 35% to 82% of the (static) breaking stress for the uncut fabric.

It will be clear to the reader that the subject of textiles offers much of interest to the physicist both in the fundamental study of the underlying phenomena of textile fibers and their processing behavior and also in the practical application of the knowledge so gained to the achievement of desirable ends. The last 25 years or so has seen an enormous development of polymeric materials of all kinds; it is unlikely that further developments in the same direction during the next 25 years will be either as significant or as numerous as those that have already taken place. What is much more likely is that the emphasis will change—indeed it is already changing—from the chemical problems associated with the discovery of new polymers, to the physical and engineering problems of making the utmost use of those polymers that already exist, through improvements in the methods of production and technological processing treatments, and by the introduction of new or improved methods of fabrication of textile structures.

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A career in textiles?

Many physicists do not realize that the textile industry is, on a world-wide basis, second only to the food industry when judged by the numbers of man-hours expended. As well as satisfying the basic human need for clothing, textiles are of particular importance in keeping our factories operating, basic to our transportation system, essential in conserving energy—and they also provide comfort and beauty in our homes.

A career in textile physics offers particularly attractive opportunities because physicists have largely ignored this exciting and challenging area. This is largely because our university faculties have little experience with the field and our textile companies have only a limited experience with what physics, as a discipline, can do for them. L. R. G. Treloar points out in his accompanying article that only during the last 25 years have scientists really concerned themselves with the subject. Much of this study has been carried out by individuals whose backgrounds were in fields other than physics. As Treloar also suggests, economic considerations dictate that future development will not be in the discovery of new chemical fibers but rather in a better understanding of how the existing fibers can be used. Physicists with a broad understanding of classical mechanics, viscoelasticity, polymer chemistry and so on will find challenging and rewarding activities in this field.

One question that arises is whether or not a student can find this type of curriculum. I believe the answer is clearly "yes," if the student can first find a faculty member who will respond to his expression of interest in such a program. All of the necessary course work is usually available in existing curricula. What is needed, and today often lacking, is faculty guidance toward a training for industrial careers in physics.

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