

MATERIALS SCIENCE

EFFECT OF STRUCTURE AND RELAXATION STATE ON THE PROPERTIES AND PROCESSING OF CHEMICAL FIBRES FOR INDUSTRIAL APPLICATIONS

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The features and differences in the structure, physical (relaxation) state, and properties of the basic types of industrial fibres that are important in processing them into textile and composite materials and articles are briefly examined. Fundamental recommendations are given on optimizing processing and increasing the degree of realization of the mechanical properties of the high-modulus industrial fibres in articles.

Approximately 25% of the total textiles manufactured now are industrial textiles. The precise amount is difficult to estimate, since the concept of “industrial textiles” includes different types of materials and articles used in many areas of engineering, agriculture, transportation, sports, tourism, medicine, etc., in different countries. Highly loaded textile articles, fibre construction composites, and rubber textile articles are the most important types [1, 2]. Fibres made of aliphatic, aromatic, carbon, silicate, and inorganic (ceramic) polymers are used to manufacture industrial articles. However, the features of the structure and properties of some types of fibres cause important problems in processing, which requires special approaches in constructing the articles to ensure stability of processing (continuity) and attaining the highest level of the mechanical properties. It should be noted that ordinary types of complex textile fibres for widely used articles do not cause such problems, since they have relatively high deformability.

In publications on fibre processing, the fibres are usually considered as polymer rods of low cross section, i.e., as a united whole, usually with no analysis of the structural dependence of their mechanical properties [3, 4]. This approach is valid, but does not allow completely evaluating the role of the macrostructure of the fibres and properties of the individual filaments in processing the fibres. This is very important for optimizing the technology and properties of the fibres, materials, and articles obtained.

In previous studies, the important role of both the morphological and energetic characteristics of the structure and the physical (relaxation) state in formation of the properties of fibres/filaments in examining the structural features of chemical fibres and filaments [5-7]. We will expand the examination of the role of the structure in the “behavior” of fibres in processing and formation of some of the macroproperties of fibre materials/articles. Let us consider the features of the structure and properties of chemical fibres important for optimizing processing and attaining maximum realization of their mechanical properties in articles.

BASIC TYPES OF CHEMICAL FIBRES FOR INDUSTRIAL USE

The wide range of industrial articles makes it necessary to use the most varied types of fibres for manufacturing them — from hyperelastic to highly brittle (Table 1). At ordinary temperature, they are in different relaxation (physical) states. For this reason, the corresponding process conditions are required for each type of fibre. Processing of hyperelastic

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TABLE 1. Range of the Properties of Chemical Fibres/Filaments

Fibres/filaments	Deformation modulus, GPa	Strength, MPa	Elongation at break, %	Relaxation state at 20°C	Glass transition temperature, °C
Elastomeric polyurethane	$(2-5) \cdot 10^{-2}$	50-100*	700-900	Hyperelastic, $t \gg t_g$	30-40
High-strength and high-modulus carbon	300-700	2000-5000	0.3-1.0	Brittle, $t \ll t_g$	1500

*In terms of the initial section.

TABLE 2. Fundamental Physicomechanical Properties of Industrial Fibres

Fibres/filaments	Density, g/cm ³	Modulus of elasticity (static), GPa	Strength, GPa	Elongation at break, %	Initial Decomposition temperature, °C
Polyurethane (elastomeric)		$(2-5) \cdot 10^{-2}$	0.6-1.2	500-900	70-100*
Polypropylene	0.92-0.94	4.5-6	0.4-0.8	20-30	176***
Polyacrylonitrile		4.5-8	0.5-0.75	10-17	160-17*
Polycaproamide		4.5-6	0.65-1	15-20	215***
Polyhexamethylene adipamide					265***
Polyvinyl alcohol (Vinol MVM, Vinalon NM)	1.3-1.32	30-60	0.6-1.2	3-5	170-200*
Polyester (Lavsan, Dacron, Trevira)	1.38-1.39	12-18	0.65-0.8	6-12	180-200*
Hydrated cellulose	1.52-1.54	6.5-12	0.35-0.45	9-15	160-180*
Thermosable aromatic (Arelon, Fenilon, Nomex, etc.)	1.4-1.45	5-15	0.5-0.8	6-16	250-300*
Superstrong and high-modulus para-aramid (SVM, Rusar, Armos, Twaron, Kevlar, etc.)	1.43-1.45	70-120	3-5	2.5-4	250-300*
Carbon (low-modulus and medium-modulus)	1.4-1.8	30-180	0.4-1.5	1-1.5	300-400**
Graphitized carbon (high-strength and high-modulus)	1.7-1.9	200-500	2.5-5	0.5-1	300-400**
Glass, basalt	2.55	50-90	1.5-4	2-4	300-400***
Inorganic (ceramic — boron, oxide, carbide, etc.)	2.4-3.2	300-480	1.3-3.5	1-2	1600-2800***

*In air. **In inert medium. ***Softening, melting point.

(elastomeric) fibres, due to the high stretchability, and on the other hand, high-modulus fibres in the brittle state (carbon and inorganic) is especially difficult.

Industrial fibres are made from initial polymers of very different structure and properties:

- linear organic polymers (polyurethane, polypropylene, aliphatic polycaproamide, polyacrylonitrile, polyvinyl alcohol, polyester, para-aramid, etc.);
- carbon polymers;
- silicates (glass, basalt, quartz);
- inorganic (ceramic) — boron, oxide, carbide, etc.).

The fundamental physicomechanical properties of these fibres summarized in Table 2 [5-15] are the result of tensile tests in standard conditions — at 20°C for ~10 sec. However, the conditions of processing the fibres differ significantly from the conditions of standard tensile tests.

As these data show, the different deformability, which is a function of the relaxation (physical) state, is an important feature of these fibres [5-15], which causes large differences in the approaches in constructing articles and selecting processing conditions.

Fibres with a high glass-transition temperature t_g are in the glassy or brittle state during processing and in articles so that relaxation processes take place in them at a low rate and internal stresses persist for a long time.

Note that high-strength, high-modulus fibres have structural features and properties that textile specialists frequently do not pay due attention to, although they are determining in constructing articles during processing into textile structures

TABLE 3. Characteristics of Industrial Fibres/Filaments with Different Structures [7]

Fibres/filaments	Molecular structure (shape of macromolecules)	Statistical segment (A), nm	Polar groups	Supra-molecular (nano) structure	Temperature, °C		Deformation modulus, GPa	Strength, GPa	Bending strength, thousands of cycles	Moisture content, %
					glass transition	melting				
Polypropylene	Spiral	2.1	None	Highly oriented, anisotropic - crystalline	-(12-20)	175-176	4.5-6	0.4-0.8	> 100	0
Polyamide (Capron, PA 6)	Linear	1.7	-CONH-		45-55	215-217	4.5-6	0.6-1	500-1000	4-5
Polyester (PET)	Same	3.5-3.6	-COO-		80-90	265-267	12-18	0.6-0.8	7-15	0.3-0.4
Para-aramid	" "	30-50	-CONH-		280-370	> 550	70-120	3-5	0.05-0.3	3-4
Carbon	Laminar (ribbon)	→ ∞	> CO, -OH (on surface)	Amorphous	> 1500	3600 (sublimation)	200-500	2.5-5	Brittle failure	0.05-0.1
Glass	Three-dimensional	→ ∞	-OH (on surface)		350-500	700-1000 (softening)	50-90	1.5-4	Same	0.03-0.05

TABLE 4. Temperature Characteristics Important in Evaluating and Predicting the Properties of Fibres/Filaments

Polymers, fibres	T_m	T_g	Θ_1	Θ_2
Polymers, fibres with low glass transition temperature, $T_m \ll 293$ K. In the hyperelastic state at 273 K ($\Theta_2 \gg 1$)				
Polyurethane (elastomeric)	—	233-243	—	1.21-1.25
Polyethylene	411	193-203	0.71	1.44-1.7
Polypropylene	449	253-261	0.65	1.12-1.16
Polymers, fibres with medium glass transition temperature, $T_g \gg 293$ K. In beginning of region of glassy state at 273 K ($\Theta_2 \sim 1$)				
Polyacrylonitrile	593	348-373	0.49	0.79-0.84
Polyvinyl alcohol	498	348-363	0.59	0.81-0.84
Polycapromide	488	313-333	0.60	0.88-0.94
Polyhexamethylene adipamide	537	318-333	0.55	0.87-0.95
Poly(ethylene terephthalate)	538	353-373	0.54	0.79-0.83
Polymers, fibres with high glass transition temperature, $T_m \gg 293$ K. In brittle state at 273 K ($\Theta_2 \ll 1$)				
Cellulose	Decompose	493-543	—	0.58-0.59
Cellulose triacetate	Decompose	443-453	—	0.64-0.66
Aromatic	—	553-623	—	0.47-0.53
Silicate	Softening 1000-1200	650-750	—	0.39-0.45
Carbon	3900-4000	1800	~0.07	~0.15

* $T = 293$ K was used as the normalizing temperature.

** T_g decreases significantly in the wet state for hydrophilic fibres (polycapromide, cellulose, polyvinyl alcohol, etc.) [5-7].

and composites (Table 3). Such features include the specific bending behavior of the fibres, the varying length of the filaments, and the presence of different defects that affect the strength and deformation properties, etc. [16-18].

TEMPERATURE CHARACTERISTICS AND COMPARISON OF FIBRE-FORMING POLYMERS AND FIBRES IN AN EQUIVALENT PHYSICAL (RELAXATION) STATE. CORRELATION WITH MECHANICAL PROPERTIES

All types of fibres made of linear organic, carbon, silicate, and other polymers have different temperature characteristics on which their mechanical properties and processing conditions are greatly dependent [5-7]. T_{br} , t_{br} are the brittleness temperature; T_g , t_g are the glass transition/devitrification temperature; T_m , t_m are the melting point; T_d , t_d are the initial decomposition temperature.

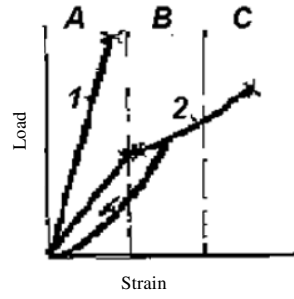


Fig. 1.

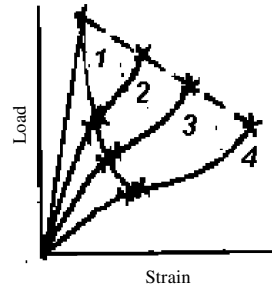


Fig. 2.

Fig. 1. Stress-strain diagram of high-strength fibres: 1) at $T < T_{br}$ (carbon, silicate, and ceramic fibres); 2) at $T_{br} < T < T_g$ (highly oriented fibres from linear polymers: polyester, para-aramid, etc.). Basic deformation regions for fibres from linear polymers: A) small (reversible); B) medium (partially reversible); C) ultimate.

Fig. 2. Stress-strain diagram of fibres from linear polymers as a function of the temperature. $T_1(T_{br}) < T_2 < T_3 < (T_4 = T_g)$.

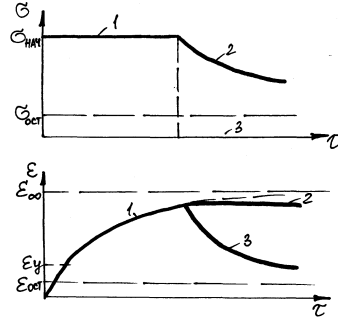


Fig. 3. Relaxation properties of fibres at average loads and after removal of loads: 1) creep at $\sigma = \text{const}$; $e = e_e + e_r - \exp - t/t_{r1}$; 2) stress relaxation at $e = \text{const}$; $\sigma = \sigma_{in} \exp - t/t_{r,2} + \sigma_{res}$; 3) strain relaxation (recovery) at $\sigma = 0$; $e = e_{in} \exp - t/t_{r,3} + e_{res}$. Here $t/t_r = k_r$; τ is the time; τ_r is the relaxation time; σ is the stress; ϵ is the strain.

Some temperature characteristics of these types of fibres are reported in Table 4. They are examined in more detail in [5-7] and are summarized in Table 3.

In assessing the properties of the fibres and processing features, it is useful to compare them at the same standardized heat-content level, and this also means the intensity of molecular motion with respect to the thermal fluctuation energies at the temperatures of phase transitions of the first (melting) and second kind (glass transition) [7, 19]:

$$\Theta_1 = \frac{E}{E_m(\text{at } T_m)} = \frac{nkT}{nkT_m} = \frac{T}{T_m}$$

and

$$\Theta_2 = \frac{E}{E_g(\text{at } T_g)} = \frac{nkT}{nkT_g} = \frac{T}{T_g},$$

where Θ_1 and Θ_2 are the standardized (relative) values of the temperatures corresponding to the melting point and glass transition temperature; $E = nkT$, $E_m = nkT_m$, and $E_g = nkT_g$ are the energies of the thermal oscillatory motion of the structural elements of the macromolecules at the testing (temperature) temperature, melting point, and glass transition temperature.

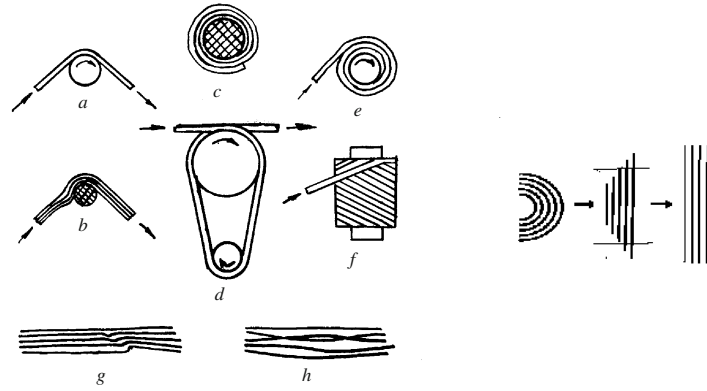


Fig. 4. Diagrams of appearance of variable length of filaments in high-modulus fibres (on left) and in unbending of previously bent fibre (on right): a, b) in bending round roller and thread guide; c, d, e) in processing in pack, in winding or continuous processing on cylinder; f) in takeup into pack; g, h) two types of variable length: local and distributed. The figure was prepared by A. S. Andreev.

The testing (processing) temperature is usually set equal to 20°C (293 K). It is also useful to use 293 K as the normalizing temperature.

The method of comparing the properties at $\Theta_{A1} = \Theta_{B1}$ or $\Theta_{A2} = \Theta_{B2}$ (where A and B refer to different fibre samples) is suitable for analyzing the processing conditions of different fibres and filaments, since it allows selecting the conditions for processing and/or additional relaxation (thermal or thermoplasticizing) treatment of materials and articles and manufacturing them with a stable structure. The values of the standardized (relative) temperatures of the different types of fibres/filaments are reported in Table 4.

The glass transition temperature range of the fibres used in industrial articles is very wide — from negative values for polyurethane and polyolefin fibres to very high values for aromatic, silicate, and carbon fibres. For this reason, at ordinary temperature, the fibres are in a different physical (relaxation) state. A comparison of the data in Tables 2-4 clearly demonstrates the correlation between their glass transition temperatures and deformation properties. Fibres at a temperature above T_g (for $\Theta_2 \gg 1$) have comparatively high deformation characteristics (low modulus of elasticity, high elongation at break); at a glass transition temperature close to room temperature (for $\Theta_2 \sim 1$), the deformation characteristics have average values, while at a temperature much lower than T_g (for $\Theta_2 \ll 1$), these characteristics are minimal (high modulus of elasticity and very low elongation).

EFFECT OF THE RELAXATION STATE ON TENSILE STRAIN

The properties of filaments and fibres in axial deformation are usually characterized by the stress-strain diagram in load—strain coordinates, as shown in Fig. 1 for high-strength industrial fibres [7, 14-15]. The total strain of fibres in the general case included three components:

$$e = e_e + e_{el} + e_{pl} \text{ viscous,}$$

where e_e is the elastic deformation; e_{el} is the elastic; e_{pl} (viscous) is the plastic (viscous) strain.

The relationship of the constituent parts of the strain is essentially a function of the relaxation (physical) state of the fibres, and this means also the temperature:

– in the elastic state, at $T_g < T < T_m$

$$e \gg e_{el} + e_{pl}; e_{el} = e_{el, rev},$$

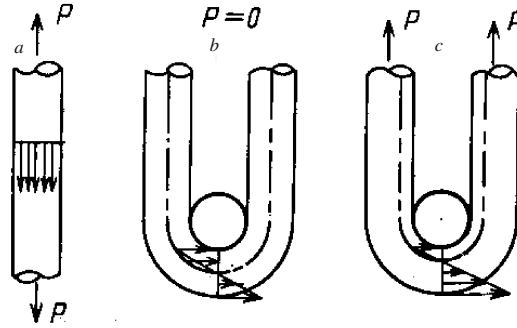


Fig. 5. Diagram of the effect of forces and stress diagram in filaments in stretching (a), bending (b), and bending and stretching (c) of high-modulus fibres.

– in the glassy state, at $T_{br} < T < T_g$

$$e \gg e_e + e_{el} = e_e + e_{el, in} + e_{el, rev},$$

where $e_{el, in}$ is the induced elastic strain that only relaxes at $T > T_g$; $e_{el, rev}$ is the reversible elastic strain,

– in the brittle state, at $T < T_{br}$

$$e \gg e_e; e_{el} \gg 0; e_{pl} \gg 0,$$

where T_{br} is the brittleness temperature at which $e_{el} = 0$; $e_{pl} = 0$.

The shape of the stress-strain diagram is essentially a function of the temperature and physical (relaxation) state of the fibres, which is schematically shown in Fig. 2 for high-strength and high-modulus fibres.

The stress-strain diagram of fibres from linear polymers usually has an inflection in the middle part — the “elastic limit” (it is little noticed only in high-strength, high-modulus fibres with high orientation of the structure). Note that at high temperatures, weak inflections are also present in the stress-strain diagram for carbon (low- and medium-modulus) and silicate fibres. “Degeneration” of elastic strain as the temperature decreases from T_g to T_{br} is clearly seen in Fig. 2.

Deformation and relaxation processes take place in fibres and filaments in time. The overall shape of the curves characterizing strain and relaxation processes is shown in Fig. 3. The equations corresponding to these curves are satisfactorily described by exponential functions of the Kohlrausch equation type.

The rates of these processes are a function of the physical (relaxation) state of the fibres, i.e., the relationship of the temperature during the relaxation process and the glass transition temperature (the value of Θ_2):

- in the hyperelastic state, at $T_g < T < T_m$, the rate of relaxation processes is maximum;
- in the glassy state, at $T_{br} < T < T_g$, the rate of relaxation processes is limited;
- in the brittle state, at $T < T_{br}$, relaxation takes place extremely slowly, so that the rate can be set at zero in practice.

VARIABLE LENGTH OF FILAMENTS IN THE FIBRE

Variable length of the filaments in fibres is an important effect that affects the mechanical properties of complex industrial fibres. Variable lengths arise when the fibres are taken up in the pack (spreading and winding), when they move along the thread-guide parts, and in many other cases schematically shown in Fig. 4. The appearance of variable lengths is very pronounced in fibres at temperatures below T_g , especially in fibres in the brittle state (i.e., below T_{br}).

It should be noted that variable length arises in filaments for the reasons indicated above in ordinary types of complex textile fibres as well. However, it rapidly relaxes and actually does not appear in these fibres.

As an example, let us consider variable length in unwinding from the pack and assess its effect on the properties of carbon fibres in the following conditions: elongation of the fibre at break $\epsilon = 0.02 = 2\%$; tensile strength (straight fibre) $\sigma = 2$ GPa; winding diameter of 100 mm (radius of 50 mm); thickness of wound fibre (in radial direction) of 1.0 mm; we will assume that the shape and thickness of the fibre do not change after unwinding.

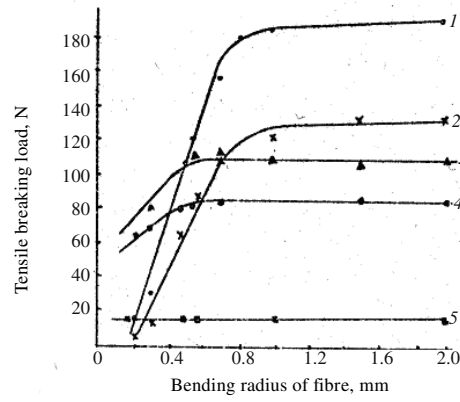


Fig. 6. Breaking tensile force as a function of the fibre bending radius: 1, 2) UKN carbon fibres; 3) SVM fibre; 4) PFTA fibre (Terlon); 5) PAN fibre (for comparison) [20, 21].

TABLE 5. Values of the Critical Bending Radii of Different High-Modulus Fibres

Fibre type	Linear density, tex	Critical bending radius, mm	
		first	second
UKN-2500 and UKN-5000	200-400	0.15-0.2	0.6-1.0
Terlon	29-58	—	0.45-0.55
SVM	29-58	—	0.45-0.5

The variable length between the outer and inner layer is thus:

$$\Delta R/R = 0.01 = 1\%,$$

where R is the winding radius in the pack; ΔR is the thickness of the winding layer (wound fibre).

The variable length that arises decreases the strength of the fibre, since the individual filaments are deformed and do not break simultaneously. The stress-strain diagram of the carbon fibre is a straight line. For this reason, its deformation by $0.01 = 1\%$ corresponds to half of the deformation at break ($0.02 = 2\%$) and half of the tensile breaking stress (1 GPa). Then the strength of the fibre with variable length will be equal to

$$\sigma_b^*/\sigma^* = 1 - 0.5 \cdot 0.01 : 0.02 = 0.75,$$

where σ_v is the strength with consideration of the variable length; coefficient 0.5 characterizes the average value of the length as a result of the appearance of variable length of the filaments (see Fig. 4).

The strength of the fibre as a result of appearance of variable length is equal to 1.5 GPa, i.e., it decreases to 0.75 of the strength of the initial straight fibre.

The calculation is approximate, but it demonstrates the important role of variable filament length for fibres in the brittle state (much lower than T_g), which is characteristic of most high-strength/high-modulus fibres.

EFFECT OF BENDING AND BENDING WITH STRETCHING ON HIGH-MODULUS FIBRES

When external forces act on the filaments in high-modulus fibres, stresses which are a function of the loading conditions arise in them (Fig. 5) [20, 21].

In simple stretching, the stress distribution is the same in all filaments. When the fibre is simultaneously stretched and bent, the stress distribution in the cross section of the filaments is inhomogeneous and is a function of the ratio of their radius and the bending radius based on the equation:

$$\sigma = \sigma_b \pm E(r/R),$$

where σ is the tensile stress; σ_p is the stress in the peripheral layers of the filament; E is the modulus of elasticity of the filament; r is the radius of the filament; R is the bending radius.

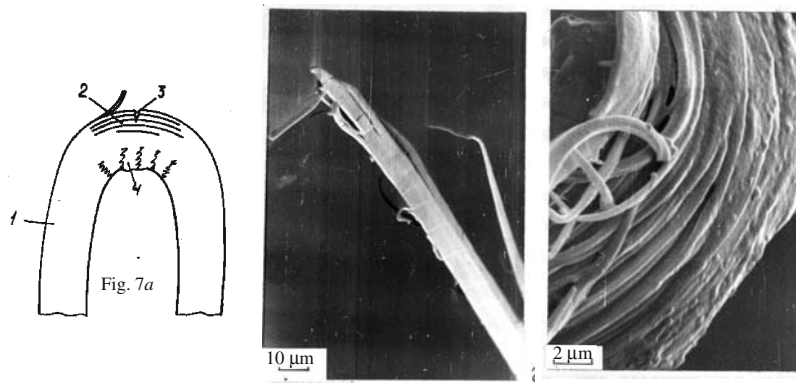


Fig. 7. Type of failure of para-aramid filaments (SVM)) on bending (on left), stretching (Terlon) (in middle), and fibrillation on bending and stretching (on right): 1) filament; 2) fibrillation zone; 3) crack formation; 4) compression zone. Photos by V. N. Kuz'min.

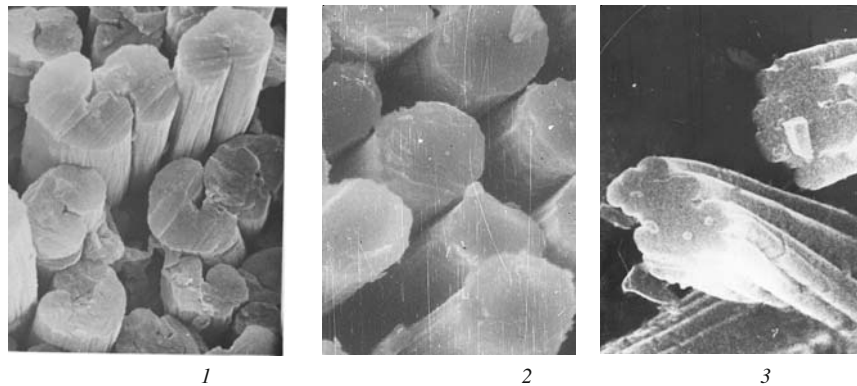


Fig. 8. Character of failure of polyacrylonitrile (1, 2) and hydrated cellulose (3) carbon filaments.

The high stresses that arise in the outer layers of filaments can cause them to fail if they act in a region containing surface defects.

In studies modeling the mechanical effects in processing of high-modulus fibres, dependences of the breaking forces on the bending radius of the filaments were established and they generally have two critical values — a first value below which pure bending causes failure and a second value after which the effect of bending becomes less significant. This is shown in Fig. 6. The results of determining the critical bending radii for three types of high-modulus fibres are reported in Table 5 [20, 21].

MACROSTRUCTURE AND TENSILE AND FLEXURAL FAILURE OF HIGH-MODULUS FIBRES

Failure of complex fibres is due to the successive failure of the individual filaments, each of which is initiated by the presence of defects in the macrostructure. The tensile or bending stresses that arise cause the appearance of critical stresses at the sites of the most dangerous defects in the individual filaments. The defects cause cracks to begin to grow, and as a result of growth of the main crack, the filament breaks at the “weakest” site. The character of failure of the filaments is a function of their structure, especially its anisotropy, which produces very different “pictures” of the failure sites. We will give some examples of characteristic failures for two types of high-modulus fibres:

TABLE 6. Stress Distribution and Relaxation in Processing Industrial Fibres

Manufacturing stages	Stresses and stress relaxation for different types of fibres		
	polypropylene, polyamide, $T \gg T_g$	polyvinyl alcohol, polyester, $T \leq T_g$	para-aramid, carbon, silicate, $T \ll T_g$
Fibres in packs	$F_{in} \approx 0$ Fibres in equilibrium (relaxed) state		Variable length possible
Feeding fibres into working zone	$F = F_s + F_{fr}$	$F = F_s + F_{fr}$	$F = F_s + F_{fr}$ Appearance of variable length
Working zone	$F = F_s + F_{fr} + F_{ben} = F_{to} + F_{ben} [1 - \exp(K_r \tau)^q]$ Fast relaxation	$F = F_s + F_{fr} + F_{ben} = F_{to} + F_{ben} [1 - \exp(K_r \tau)^q]$ Slow relaxation	$F = F_s + F_{fr} + F_{ben}$ Relaxation absent
Fabric takeoff zone	Insignificant residual stresses	$F = F_{to} + F_{ben} [1 - \exp(K_r \tau)^q]$ Stresses persist Slow relaxation	$F = F_{to} + F_{ben}$
Finished fabric	Insignificant residual stresses	Residual bending stresses that slowly relax in time	$F_{is} = F_{ufr}$ Bending stresses persist for a long time
Additional thermal relaxation treatment	$F_{is} \rightarrow 0$ (at $T \approx 0.8 T_m$)		Absent

*For standard moisture content.

Notation: F — total stress; F_{is} — internal stresses; F_s — stress in each zone; F_{fr} — friction force (different in each zone); F_{be} — bending force; F_{to} — takeoff force (per fibre); K_r — stress relaxation rate constant (different in each zone); τ — relaxation time; q — supplementary coefficient (refines the character of the relaxation processes, is different in each zone).

– para-aramid filaments primarily fibrillate and only then do the fibrils formed successively break (Fig. 7). The tensile or bending stresses that arise in para-aramid fibres cause fibrillation of the filaments [22]. In bending, the ratio of the bending radii of the fibrils and fibre decrease significantly. In the bending zone, the stresses decrease by many times. This causes the preservation of significant strength on bending of these fibres, which is extremely important in the conditions of processing and utilizing them in articles;

– carbon, glass, and ceramic filaments break with transverse growth of cracks (Fig. 8). Note that carbon fibres have an important number of internal micro- and macrodefects that significantly affect the failure process [7].

In contrast to high-modulus filaments, polyurethane elastomeric filaments fail with formation of thinning and subsequent breaking at the site of the lowest thickness.

APPEARANCE OF THE MECHANICAL PROPERTIES OF HIGH-MODULUS FIBRESIN PROCESSING AND IN FINISHED MATERIALS/ARTICLES

During processing into textile structures (fabrics, woven materials, knits), the fibres are subjected to stretching and bending and the kinks that arise are fixed in the finished material. The greatest stresses and correspondingly breaks are caused by the working parts of the processing equipment [4, 23].

The stresses that arise in the bending zone can partially relax as a function of the physical (relaxation) state of the fibres, more precisely, the relationship between the processing temperature (usually within 20-25°C) and the glass transition temperature (Table 6). Three basic variants can be distinguished here;

– the processing temperature is higher than the glass transition temperature ($T \gg T_g$); the fibres are in the hyperelastic state and relaxation processes take place at a high rate during processing;

– the glass transition temperature is close to or slightly lower than the processing temperature ($T \leq T_g$); relaxation processes take place with a limited rate and in the processing zone: the effects of the working parts cannot be fully exercised and they are completed in the formed cloth takeoff zone;

– the processing temperature is much lower than the glass transition temperature ($T \ll T_g$), relaxation processes take place at an extremely low rate and cannot occur in either the processing zone or the finished cloth takeoff and takeup

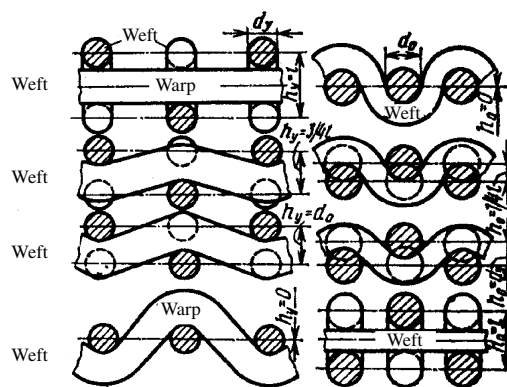


Fig. 9. Bends in fibres in fabrics in different phases of their construction [23].

zone. Internal stresses persist in the finished cloth and reduce the degree of realization of the mechanical properties of the fibres in the material.

To remove internal stresses after textile processing, the cloth or articles usually undergo additional thermal or thermoplasticizing treatment. The optimum temperature of these processes is $T \approx 0.8 T_m$. In the processing conditions and in the finished material during use, the presence of kinks in the article significantly affects the mechanical properties and possibility of filament breaks in high-modulus aromatic, silicate, carbon, and inorganic (ceramic) fibres. The smaller the bending radius, the more important the losses of the strength properties. As the dependences of the stresses on the ratio of the filament and fibre bending radii reported above show, this effect is directly proportional to the modulus of elasticity.

The fibre kinks persist in the structure of the finished material (fabrics, woven or knit material), and stress relaxation is also a function of the relaxation state of the material. The presence of such kinks in cloth structures is shown in Fig. 9 [24].

The effect of bending events becomes marked in processing glass fibres, which have a high glass transition temperature and relatively high modulus of elasticity. Despite the low defectiveness, glass fibres can undergo surface degradation under the effect of atmospheric moisture, and there are frequently breaks in individual filaments.

Carbon fibres, which have a high glass transition temperature and high modulus of elasticity, retain their strength in the finished material to the smallest degree. The significant porosity and presence of defects create important difficulties in processing these fibres and require special attention in constructing articles to increase realization of their mechanical properties.

PRACTICAL ASPECTS OF PROCESSING

In processing high-strength and high-modulus fibres in weaving, braiding, and knitting, tensile and bending forces that affect all filaments in the fibre simultaneously act on the fibres. The stress distribution in filaments was shown in Fig. 4. Simultaneous exposure to tensile and bending stresses increases the possibility of fibre breaks at the sites of defects.

Many methods that reduce defectiveness and breakage and increase the degree of realization of mechanical properties are used in production and processing of high-strength and high-modulus fibres. This sometimes requires a slight change in the design of the equipment, especially the thread-guide and other parts, in contact with the fibres during processing.

In winding high-modulus fibres into packs, cartridges of large diameter must be used to reduce variable length. To optimize processing of high-modulus fibres made of organic polymers (para-aramid, polyvinyl alcohol, etc.), special attention has been focused on the state of the thread-guide and working parts that participate in formation of the textile structure. This is especially important, since high-modulus fibres cause increased wear in these parts.

In processing silicate, carbon, and inorganic (ceramic) high-modulus fibres, different methods are usually used to reduce the possibility of breaking. The basic methods are as follows:

- great caution is required in transport of the fibres over the thread-guide and working parts of the equipment. All thread-guide parts that cause kinks in the fibres in fabrication of materials and articles should have the maximum possible

radius of curvature to reduce variable length and high surface hardness. The radius of curvature should be greater than those that cause mechanical stresses in the filaments which are closing to the breaking stresses:

$$R = Er/(\sigma - \sigma_b)$$

at $\sigma < \sigma^*$;

– to facilitate processing of the fibres, coatings (finishes) are often applied on them which are removed in the finished material or article. The layer of finish plays a dual role: it increases the bending radius of the fibre and “heals” defects in the fibres — filament breaks, thickening, etc. Easily soluble or hydrolyzable polymers, polyvinyl alcohol (containing 10-15% acetate groups) and carboxymethylcellulose, for example, are used as finishing agents [10, 25]. The high-modulus fibre must not be damaged during removal of the layer of finish;

– processing the high-modulus fibre with an auxiliary accessory fibre subsequently easily removed from the finished material or article is used to facilitate passage of high-modulus fibres over the thread-guide parts. Water-soluble polyvinyl alcohol fibres, sodium alginate fibres (soluble in aqueous base), and hydrated cellulose (viscose) fibres (easily hydrolyzed in acid media) are used as the accessory [10, 25]. The conditions of removing the accessory fibre should not affect the properties of the basic high-modulus fibre;

– use of an accessory fibre which can remain in the binder matrix in a reinforced composite is a special case. When several types of thermosetting resin (polyacetals, modified epoxy, phenol) are used as the matrix (binder), polyvinyl alcohol accessory fibres that react with the components of the binder and thus are integrated in the binder, can be used.

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