

## Chapter 1

# INTRODUCTION

### 1.1. Structural materials

Materials are the basic elements of all natural and man-made structures. Figuratively speaking, these materialize the structural conception. Technological progress is associated with continuous improvement of existing material properties as well as with the expansion of structural material classes and types. Usually, new materials emerge due to the necessity to improve structural efficiency and performance. In addition, new materials themselves as a rule, in turn provide new opportunities to develop updated structures and technology, while the latter challenges materials science with new problems and tasks. One of the best manifestations of this interrelated process in the development of materials, structures, and technology is associated with composite materials, to which this book is devoted.

Structural materials possess a great number of physical, chemical and other types of properties, but at least two principal characteristics are of primary importance. These characteristics are the stiffness and strength that provide the structure with the ability to maintain its shape and dimensions under loading or any other external action.

High stiffness means that material exhibits low deformation under loading. However, by saying that stiffness is an important property we do not mean that it should be necessarily high. The ability of a structure to have controlled deformation (compliance) can also be important for some applications (e.g., springs; shock absorbers; pressure, force, and displacement gauges).

Lack of material strength causes an uncontrolled compliance, i.e., in failure after which a structure does not exist any more. Usually, we need to have as high strength as possible, but there are some exceptions (e.g., controlled failure of explosive bolts is used to separate rocket stages).

Thus, without controlled stiffness and strength the structure cannot exist. Naturally, both properties depend greatly on the structure's design but are determined by the stiffness and strength of the structural material because a good design is only a proper utilization of material properties.

To evaluate material stiffness and strength, consider the simplest test – a bar with cross-sectional area  $A$  loaded with tensile force  $F$  as shown in Fig. 1.1. Obviously, the higher the force causing the bar rupture, the higher is the bar's strength. However, this strength does not only depend on the material properties – it is proportional to the cross-sectional area  $A$ .

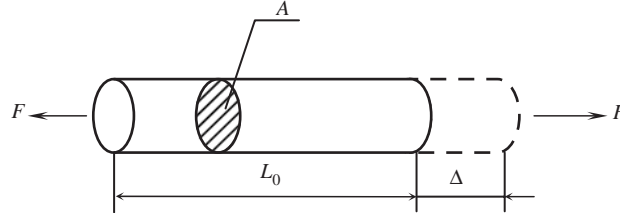


Fig. 1.1. A bar under tension.

Thus, it is natural to characterize material strength by the ultimate stress

$$\bar{\sigma} = \frac{\bar{F}}{A} \quad (1.1)$$

where  $\bar{F}$  is the force causing the bar failure (here and subsequently we use the overbar notation to indicate the ultimate characteristics). As follows from Eq. (1.1), stress is measured as force divided by area, i.e., according to international (SI) units, in pascals (Pa) so that  $1 \text{ Pa} = 1 \text{ N/m}^2$ . Because the loading of real structures induces relatively high stresses, we also use kilopascals ( $1 \text{ kPa} = 10^3 \text{ Pa}$ ), megapascals ( $1 \text{ MPa} = 10^6 \text{ Pa}$ ), and gigapascals ( $1 \text{ GPa} = 10^9 \text{ Pa}$ ). Conversion of old metric (kilogram per square centimeter) and English (pound per square inch) units to pascals can be done using the following relations:  $1 \text{ kg/cm}^2 = 98 \text{ kPa}$  and  $1 \text{ psi} = 6.89 \text{ kPa}$ .

For some special (e.g., aerospace or marine) applications, i.e., for which material density,  $\rho$ , is also important, a normalized characteristic

$$k_\sigma = \frac{\bar{\sigma}}{\rho} \quad (1.2)$$

is also used to describe the material. This characteristic is called the ‘specific strength’ of a material. If we use old metric units, i.e., measure force and mass in kilograms and dimensions in meters, substitution of Eq. (1.1) into Eq. (1.2) yields  $k_\sigma$  in meters. This result has a simple physical sense, namely  $k_\sigma$  is the length of the vertically hanging fiber under which the fiber will be broken by its own weight.

The stiffness of the bar shown in Fig. 1.1 can be characterized by an elongation  $\Delta$  corresponding to the applied force  $F$  or acting stress  $\sigma = F/A$ . However,  $\Delta$  is proportional to the bar’s length  $L_0$ . To evaluate material stiffness, we introduce strain

$$\varepsilon = \frac{\Delta}{L_0} \quad (1.3)$$

Since  $\varepsilon$  is very small for structural materials the ratio in Eq. (1.3) is normally multiplied by 100, and  $\varepsilon$  is expressed as a percentage.

Naturally, for any material, there should be some interrelation between stress and strain, i.e.,

$$\varepsilon = f(\sigma) \quad \text{or} \quad \sigma = \varphi(\varepsilon) \quad (1.4)$$

These equations specify the so-called constitutive law and are referred to as constitutive equations. They allow us to introduce an important concept of the material model which represents some idealized object possessing only those features of the real material that are essential for the problem under study. The point is that in performing design or analysis we always operate with models rather than with real materials. Particularly, for strength and stiffness analysis, such a model is described by constitutive equations, Eqs. (1.4), and is specified by the form of the function  $f(\sigma)$  or  $\varphi(\varepsilon)$ .

The simplest is the elastic model which implies that  $f(0) = 0$ ,  $\varphi(0) = 0$  and that Eqs. (1.4) are the same for the processes of an active loading and an unloading. The corresponding stress–strain diagram (or curve) is presented in Fig. 1.2. The elastic model (or elastic material) is characterized by two important features. First, the corresponding constitutive equations, Eqs. (1.4), do not include time as a parameter. This means that the form of the curve shown in Fig. 1.2 does not depend on the rate of loading (naturally, it should be low enough to neglect inertial and dynamic effects). Second, the active loading and the unloading follow one and the same stress–strain curve as in Fig. 1.2. The work performed by force  $F$  in Fig. 1.1 is accumulated in the bar as potential energy, which is also referred to as strain energy or elastic energy. Consider some infinitesimal elongation  $d\Delta$  and calculate the elementary work performed by the force  $F$  in Fig. 1.1 as  $dW = Fd\Delta$ . Then, work corresponding to point 1 of the curve in Fig. 1.2 is

$$W = \int_0^{\Delta_1} F d\Delta$$

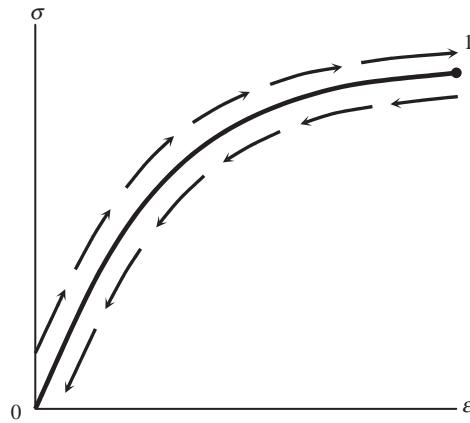


Fig. 1.2. Stress–strain curve for an elastic material.

where  $\Delta_1$  is the elongation of the bar corresponding to point 1 of the curve. The work  $W$  is equal to elastic energy of the bar which is proportional to the bar's volume and can be presented as

$$E = L_0 A \int_0^{\varepsilon_1} \sigma d\varepsilon$$

where  $\sigma = F/A$ ,  $\varepsilon = \Delta/L_0$ , and  $\varepsilon_1 = \Delta_1/L_0$ . Integral

$$U = \int_0^{\varepsilon_1} \sigma d\varepsilon = \int_0^{\varepsilon_1} \varphi(\varepsilon) d\varepsilon \quad (1.5)$$

is a specific elastic energy (energy accumulated in a unit volume of the bar) that is referred to as an elastic potential. It is important that  $U$  does not depend on the history of loading. This means that irrespective of the way we reach point 1 of the curve in Fig. 1.2 (e.g., by means of continuous loading, increasing force  $F$  step by step, or using any other loading program), the final value of  $U$  will be the same and will depend only on the value of final strain  $\varepsilon_1$  for the given material.

A very important particular case of the elastic model is the linear elastic model described by the well-known Hooke's law (see Fig. 1.3)

$$\sigma = E\varepsilon \quad (1.6)$$

Here,  $E$  is the modulus of elasticity. It follows from Eqs. (1.3) and (1.6), that  $E = \sigma$  if  $\varepsilon = 1$ , i.e., if  $\Delta = L_0$ . Thus, the modulus can be interpreted as the stress causing elongation of the bar in Fig. 1.1 to be the same as the initial length. Since the majority of structural materials fail before such a high elongation can occur, the modulus is usually much higher than the ultimate stress  $\bar{\sigma}$ .

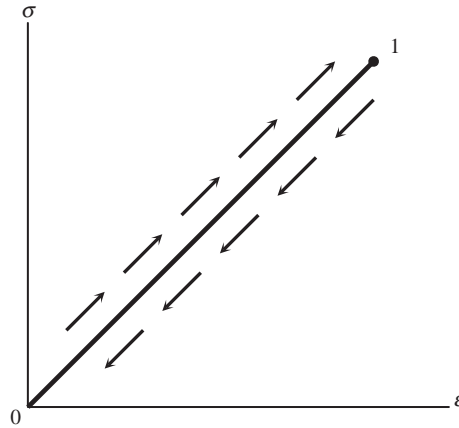


Fig. 1.3. Stress-strain diagram for a linear elastic material.

Similar to specific strength  $k_\sigma$  in Eq. (1.2), we can introduce the corresponding specific modulus

$$k_E = \frac{E}{\rho} \quad (1.7)$$

which describes a material's stiffness with respect to its material density.

Absolute and specific values of mechanical characteristics for typical materials discussed in this book are listed in Table 1.1.

After some generalization, the modulus can be used to describe nonlinear material behavior of the type shown in Fig. 1.4. For this purpose, the so-called secant,  $E_s$ , and tangent,  $E_t$ , moduli are introduced as

$$E_s = \frac{\sigma}{\varepsilon} = \frac{\sigma}{f(\sigma)} \quad E_t = \frac{d\sigma}{d\varepsilon} = \frac{d\varphi(\varepsilon)}{d\varepsilon} \quad (1.8)$$

While the slope  $\alpha$  in Fig. 1.4 determines the conventional modulus  $E$ , the slopes  $\beta$  and  $\gamma$  determine  $E_s$  and  $E_t$ , respectively. As can be seen,  $E_s$  and  $E_t$ , in contrast to  $E$ , depend on the level of loading, i.e., on  $\sigma$  or  $\varepsilon$ . For a linear elastic material (see Fig. 1.3),  $E_s = E_t = E$ .

Hooke's law, Eq. (1.6), describes rather well the initial part of stress–strain diagram for the majority of structural materials. However, under a relatively high level of stress or strain, materials exhibit nonlinear behavior.

One of the existing models is the nonlinear elastic material model introduced above (see Fig. 1.2). This model allows us to describe the behavior of highly deformable rubber-type materials.

Another model developed to describe metals is the so-called elastic–plastic material model. The corresponding stress–strain diagram is shown in Fig. 1.5. In contrast to an elastic material (see Fig. 1.2), the processes of active loading and unloading are described with different laws in this case. In addition to elastic strain,  $\varepsilon_e$ , which disappears after the load is taken off, the residual strain (for the bar shown in Fig. 1.1, it is plastic strain,  $\varepsilon_p$ ) remains in the material. As for an elastic material, the stress–strain curve in Fig. 1.5 does not depend on the rate of loading (or time of loading). However, in contrast to an elastic material, the final strain of an elastic–plastic material can depend on the history of loading, i.e., on the law according to which the final value of stress was reached.

Thus, for elastic or elastic–plastic materials, constitutive equations, Eqs. (1.4), do not include time. However, under relatively high temperature practically all the materials demonstrate time-dependent behavior (some of them do it even under room temperature). If we apply some force  $F$  to the bar shown in Fig. 1.1 and keep it constant, we can see that for a time-sensitive material the strain increases under a constant force. This phenomenon is called the creep of the material.

So, the most general material model that is used in this book can be described with a constitutive equation of the following type:

$$\varepsilon = f(\sigma, t, T) \quad (1.9)$$

Table 1.1  
Mechanical properties of structural materials and fibers.

Material	Ultimate tensile stress, $\bar{\sigma}$ (MPa)	Modulus, $E$ (GPa)	Specific gravity	Maximum specific strength, $k_{\sigma} \times 10^3$ (m)	Maximum specific modulus, $k_E \times 10^3$ (m)
Metal alloys					
Steel	400–2200	180–210	7.8–7.85	28.8	2750
Aluminum	140–700	69–72	2.7–2.85	26.5	2670
Titanium	420–1200	110	4.5	26.7	2440
Magnesium	220–320	40	1.8	14.4	2220
Beryllium	620	320	1.85	33.5	17,300
Nickel	400–500	200	8.9	5.6	2250
Metal wires (diameter, $\mu\text{m}$ )					
Steel (20–1500)	1500–4400	180–200	7.8	56.4	2560
Aluminum (150)	290	69	2.7	10.7	2550
Titanium (100–800)	1400–1500	120	4.5	33.3	2670
Beryllium (50–500)	1100–1450	240–310	1.8–1.85	80.5	17,200
Tungsten (20–50)	3300–4000	410	19–19.3	21.1	2160
Molybdenum (25–250)	1800–2200	360	10.2	21.5	3500
Thermoset polymeric resins					
Epoxy	60–90	2.4–4.2	1.2–1.3	7.5	350
Polyester	30–70	2.8–3.8	1.2–1.35	5.8	310
Phenol-formaldehyde	40–70	7–11	1.2–1.3	5.8	910
Organosilicone	25–50	6.8–10	1.35–1.4	3.7	740
Polyimide	55–110	3.2	1.3–1.43	8.5	240
Bismaleimide	80	4.2	1.2	6.7	350
Thermoplastic polymers					
Polyethylene	20–45	6–8.5	0.95	4.7	890
Polystyrene	35–45	30	1.05	4.3	2860
Teflon	15–35	3.5	2.3	1.5	150
Nylon	80	2.8	1.14	7.0	240
Polyester (PC)	60	2.5	1.32	4.5	190
Polysulfone (PSU)	70	2.7	1.24	5.6	220
Polyamide-imide (PAI)	90–190	2.8–4.4	1.42	13.4	360
Polyetheretherketone (PEEK)	90–100	3.1–3.8	1.3	7.7	300
Polyphenylene sulfide (PPS)	80	3.5	1.36	5.9	250
Synthetic fibers					
Capron	680–780	4.4	1.1	70	400
Dacron	390–880	4.9–15.7	1.4	60	1430
Teflon	340–440	2.9	2.3	190	130
Nitron	390–880	4.9–8.8	1.2	70	730
Polypropylene	730–930	4.4	0.9	100	480
Viscose	930	20	1.52	60	1300
Fibers for advanced composites (diameter, $\mu\text{m}$ )					
Glass (3–19)	3100–5000	72–95	2.4–2.6	200	3960
Quartz (10)	6000	74	2.2	270	3360

Table 1.1 (Contd.)

Material	Ultimate tensile stress, $\bar{\sigma}$ (MPa)	Modulus, $E$ (GPa)	Specific gravity	Maximum specific strength, $k_{\sigma} \times 10^3$ (m)	Maximum specific modulus, $k_E \times 10^3$ (m)
Basalt (9–13)	3000–3500	90	2.7–3.0	130	3300
Aramid (12–15)	3500–5500	140–180	1.4–1.47	390	12,800
Polyethylene (20–40)	2600–3300	120–170	0.97	310	17,500
Carbon (5–11)					
High-strength	7000	300	1.75	400	17,100
High-modulus	2700	850	1.78	150	47,700
Boron (100–200)	2500–3700	390–420	2.5–2.6	150	16,800
Alumina – $\text{Al}_2\text{O}_3$ (20–500)	2400–4100	470–530	3.96	100	13,300
Silicon Carbide – SiC (10–15)	2700	185	2.4–2.7	110	7700
Titanium Carbide – TiC (280)	1500	450	4.9	30	9100
Boron Carbide – $\text{B}_4\text{C}$ (50)	2100–2500	480	2.5	100	10,000
Boron Nitride – BN (7)	1400	90	1.9	70	4700

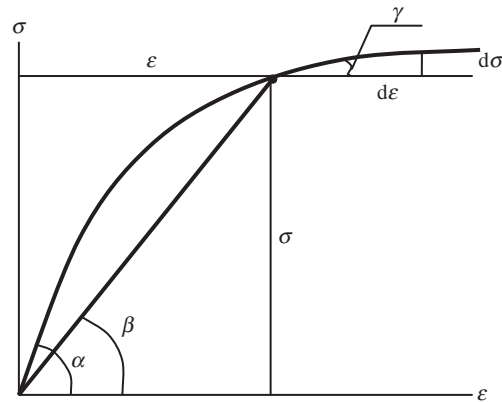


Fig. 1.4. Introduction of secant and tangent moduli.

where  $t$  indicates the time moment, whereas  $\sigma$  and  $T$  are stress and temperature, corresponding to this moment. In the general case, constitutive equation, Eq. (1.9), specifies strain that can be decomposed into three constituents corresponding to elastic, plastic and creep deformation, i.e.,

$$\varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_c \quad (1.10)$$

However, in application to particular problems, this model can be usually substantially simplified. To show this, consider the bar in Fig. 1.1 and assume that a force  $F$  is applied at the moment  $t = 0$  and is taken off at moment  $t = t_1$  as shown in Fig. 1.6a. At the

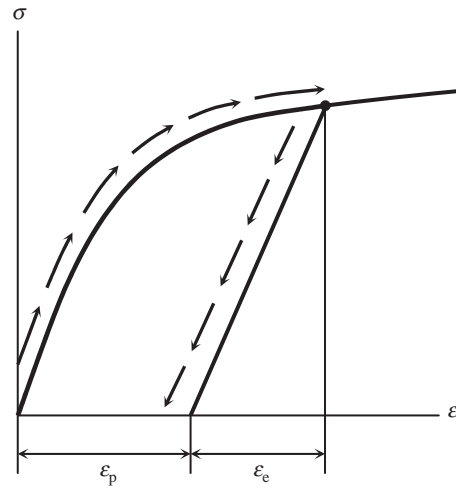
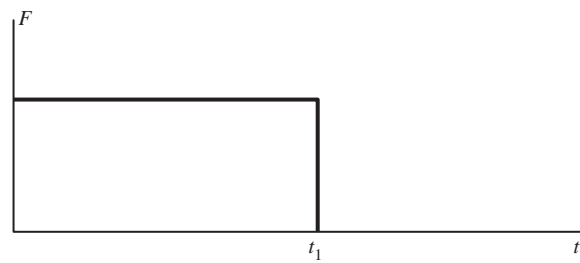
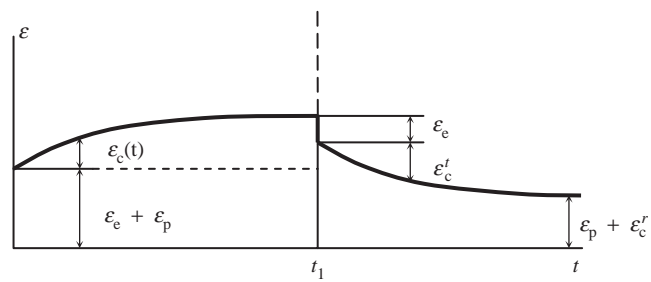


Fig. 1.5. Stress-strain diagram for elastic-plastic material.



(a)



(b)

Fig. 1.6. Dependence of force (a) and strain (b) on time.



moment  $t = 0$ , elastic and plastic strains that do not depend on time appear, and while time is running, the creep strain is developed. At the moment  $t = t_1$ , the elastic strain disappears, while the reversible part of the creep strain,  $\varepsilon_c^t$ , disappears with time. Residual strain consists of the plastic strain,  $\varepsilon_p$ , and residual part of the creep strain,  $\varepsilon_c^r$ .

Now assume that  $\varepsilon_p \ll \varepsilon_e$  which means that either the material is elastic or the applied load does not induce high stress and, hence, plastic strain. Then we can neglect  $\varepsilon_p$  in Eq. (1.10) and simplify the model. Furthermore, let  $\varepsilon_c \ll \varepsilon_e$  which in turn means that either the material is not susceptible to creep or the force acts for a short time ( $t_1$  is close to zero). Thus, we arrive at the simplest elastic model, which is the case for the majority of practical applications. It is important that the proper choice of the material model depends not only on the material nature and properties but also on the operational conditions of the structure. For example, a shell-type structure made of aramid–epoxy composite material, that is susceptible to creep, and designed to withstand the internal gas pressure should be analyzed with due regard to the creep, if this structure is a pressure vessel for long term gas storage. At the same time for a solid propellant rocket motor case working for seconds, the creep strain can be ignored.

A very important feature of material models under consideration is their phenomenological nature. This means that these models ignore the actual material microstructure (e.g., crystalline structure of metals or molecular structure of polymers) and represent the material as some uniform continuum possessing some effective properties that are the same irrespective of how small the material volume is. This allows us, first, to determine material properties testing material samples (as in Fig. 1.1). Second, this formally enables us to apply methods of Mechanics of Solids that deal with equations derived for infinitesimal volumes of material. And third, this allows us to simplify the strength and stiffness evaluation problem and to reduce it to a reasonable practical level not going into analysis of the actual mechanisms of material deformation and fracture.

## 1.2. Composite materials

This book is devoted to composite materials that emerged in the middle of the 20th century as a promising class of engineering materials providing new prospects for modern technology. Generally speaking any material consisting of two or more components with different properties and distinct boundaries between the components can be referred to as a composite material. Moreover, the idea of combining several components to produce a material with properties that are not attainable with the individual components has been used by man for thousands of years. Correspondingly, the majority of natural materials that have emerged as a result of a prolonged evolution process can be treated as composite materials.

With respect to the problems covered in this book we can classify existing composite materials (composites) into two main groups.

The first group comprises composites that are known as ‘filled materials.’ The main feature of these materials is the existence of some basic or matrix material whose properties are improved by filling it with some particles. Usually the matrix volume fraction is more than 50% in such materials, and material properties, being naturally modified by the

fillers, are governed mainly by the matrix. As a rule, filled materials can be treated as homogeneous and isotropic, i.e., traditional models of mechanics of materials developed for metals and other conventional materials can be used to describe their behavior. This group of composites is not touched on in the book.

The second group of composite materials that is under study here involves composites that are called 'reinforced materials.' The basic components of these materials (sometimes referred to as 'advanced composites') are long and thin fibers possessing high strength and stiffness. The fibers are bound with a matrix material whose volume fraction in a composite is usually less than 50%. The main properties of advanced composites, due to which these materials find a wide application in engineering, are governed by fibers whose types and characteristics are considered below. The following sections provide a concise description of typical matrix materials and fiber-matrix compositions. Two comments should be made with respect to the data presented in these sections. First, only brief information concerning material properties that are essential for the problems covered in this book is presented there, and, second, the given data are of a broad nature and are not expected to be used in design or analysis of particular composite structures. More complete description of composite materials and their components including the history of development and advancement, chemical compositions, physical characteristics, manufacturing, and applications can be found elsewhere (Peters, 1998).

### *1.2.1. Fibers for advanced composites*

Continuous glass fibers (the first type of fibers used in advanced composites) are made by pulling molten glass (at a temperature about 1300°C) through 0.8–3.0 mm diameter dies and further high-speed stretching to a diameter of 3–19  $\mu\text{m}$ . Usually glass fibers have solid circular cross sections. However there exist fibers with rectangular (square or plane), triangular, and hexagonal cross sections, as well as hollow circular fibers. Typical mechanical characteristics and density of glass fibers are listed in Table 1.1, whereas a typical stress–strain diagram is shown in Fig. 1.7.

Important properties of glass fibers as components of advanced composites for engineering applications are their high strength, which is maintained in humid environments but degrades under elevated temperatures (see Fig. 1.8), relatively low stiffness (about 40% of the stiffness of steel), high chemical and biological resistance, and low cost. Being actually elements of monolithic glass, the fibers do not absorb water and do not change their dimensions in water. For the same reason, they are brittle and sensitive to surface damage.

Quartz fibers are similar to glass fibers and are obtained by high-speed stretching of quartz rods made of (under temperature of about 2200°C) fused quartz crystals or sand. The original process developed for manufacturing glass fibers cannot be used because the viscosity of molten quartz is too high to make thin fibers directly. However, this more complicated process results in fibers with higher thermal resistance than glass fibers.

The same process that is used for glass fibers can be employed to manufacture mineral fibers, e.g., basalt fibers made of molten basalt rocks. Having relatively low strength and high density (see Table 1.1) basalt fibers are not used for high-performance, e.g.,

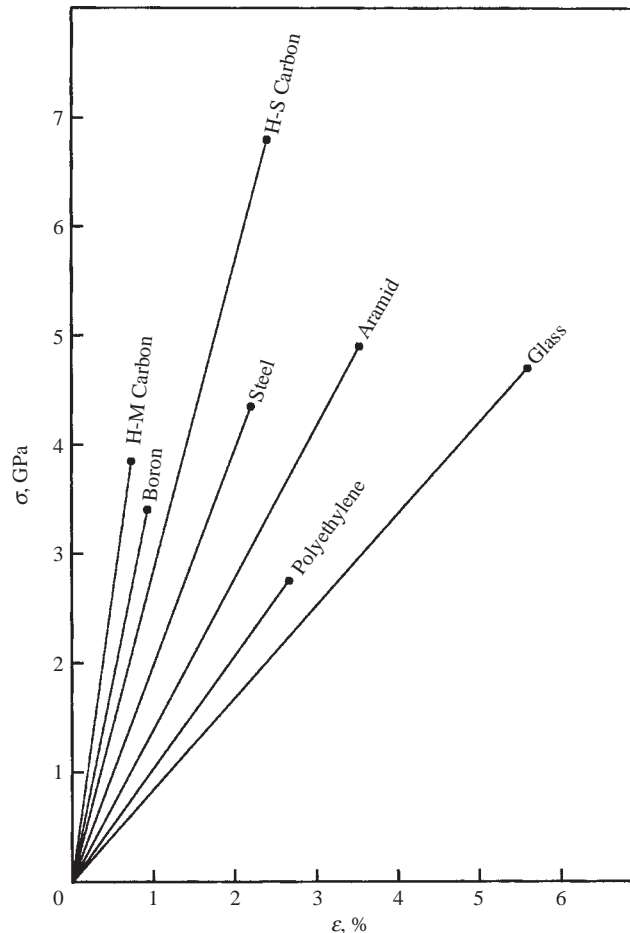


Fig. 1.7. Stress-strain diagrams for typical fibers of advanced composites.

aerospace structures, but are promising reinforcing elements for pre-stressed reinforced concrete structures in civil engineering.

Substantial improvement of a fiber's stiffness in comparison with glass fibers has been achieved with the development of carbon (or graphite) fibers. Modern high-modulus carbon fibers have a modulus that is a factor of about four higher than the modulus of steel, whereas the fiber density is lower by the same factor. Although the first carbon fibers had lower strength than glass fibers, modern high-strength fibers have a 40% higher tensile strength compared to the strength of the best glass fibers, whereas the density of carbon fibers is 30% less than that of glass fibers.

Carbon fibers are made by pyrolysis of organic fibers of which there exist two main types – PAN-based and pitch-based fibers. For PAN-based fibers the process consists of

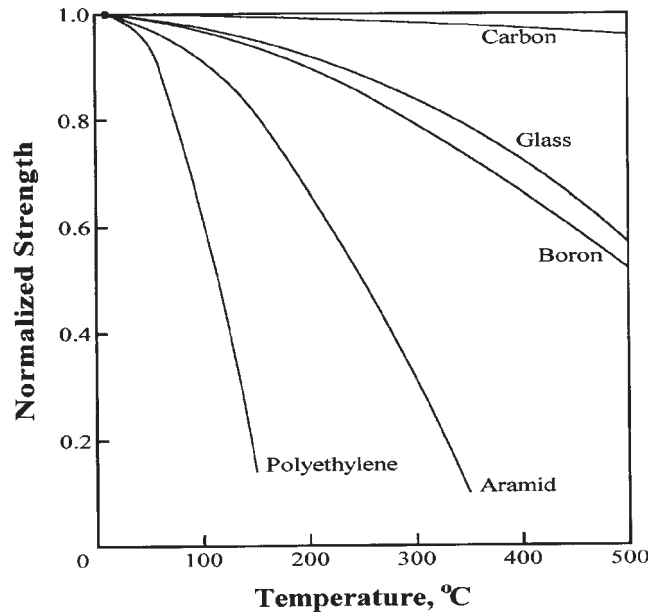


Fig. 1.8. Temperature degradation of fiber strength normalized by the strength at 20°C.

three stages – stabilization, carbonization, and graphitization. In the first step (stabilization), a system of polyacrylonitrile (PAN) filaments is stretched and heated up to about 400°C in an oxidation furnace, while in the subsequent step (carbonization under 900°C in an inert gas media) most elements of the filaments other than carbon are removed or converted into carbon. During the successive heat treatment at a temperature reaching 2800°C (graphitization) a crystalline carbon structure oriented along the fiber's length is formed, resulting in PAN-based carbon fibers. The same process is used for rayon organic filaments (instead of PAN), but results in carbon fibers with lower modulus and strength because rayon contains less carbon than PAN. For pitch-based carbon fibers, the initial organic filaments are made in approximately the same manner as for glass fibers from molten petroleum or coal pitch and pass through carbonization and graphitization processes. Because pyrolysis is accompanied with a loss of material, carbon fibers have a porous structure and their specific gravity (about 1.8) is less than that of graphite (2.26). The properties of carbon fibers are affected by the crystallite size, crystalline orientation, porosity and purity of the carbon structure.

Typical stress–strain diagrams for high-modulus (HM) and high-strength (HS) carbon fibers are plotted in Fig. 1.7. As components of advanced composites for engineering applications, carbon fibers are characterized by very high modulus and strength, high chemical and biological resistance, electric conductivity and very low coefficient of thermal expansion. The strength of carbon fibers practically does not change with temperature up to 1500°C (in an inert media preventing oxidation of the fibers).

The exceptional strength of 7.06 GPa is reached in Toray T-1000 carbon fibers, whereas the highest modulus of 850 GPa is obtained in Carbonic HM-85 fibers. Carbon fibers are anisotropic, very brittle, and sensitive to damage. They do not absorb water and do not change their dimensions in humid environments.

There exist more than 50 types of carbon fibers with a broad spectrum of strength, stiffness and cost, and the process of fiber advancement is not over – one may expect fibers with strength up to 10 GPa and modulus up to 1000 GPa within a few years.

Organic fibers commonly encountered in textile applications can be employed as reinforcing elements of advanced composites. Naturally, only high performance fibers, i.e., fibers possessing high stiffness and strength, can be used for this purpose. The most widely used organic fibers that satisfy these requirements are known as aramid (aromatic polyamide) fibers. They are extruded from a liquid crystalline solution of the corresponding polymer in sulfuric acid with subsequent washing in a cold water bath and stretching under heating. Some properties of typical aramid fibers are listed in Table 1.1, and the corresponding stress–strain diagram is presented in Fig. 1.7. As components of advanced composites for engineering applications, aramid fibers are characterized by low density providing high specific strength and stiffness, low thermal conductivity resulting in high heat insulation, and a negative thermal expansion coefficient allowing us to construct hybrid composite elements that do not change their dimensions under heating. Consisting actually of a system of very thin filaments (fibrils), aramid fibers have very high resistance to damage. Their high strength in the longitudinal direction is accompanied by relatively low strength under tension in the transverse direction. Aramid fibers are characterized with pronounced temperature (see Fig. 1.8) and time dependence for stiffness and strength. Unlike the inorganic fibers discussed above, they absorb water resulting in moisture content up to 7% and degradation of material properties by 15–20%.

The list of organic fibers has been supplemented recently with extended chain polyethylene fibers demonstrating outstanding low density (less than that of water) in conjunction with relatively high stiffness and strength (see Table 1.1 and Fig. 1.7). Polyethylene fibers are extruded from the corresponding polymer melt in a similar manner to glass fibers. They do not absorb water and have high chemical resistance, but demonstrate relatively low temperature and creep resistance (see Fig. 1.8).

Boron fibers were developed to increase the stiffness of composite materials when glass fibers were mainly used to reinforce composites of the day. Being followed by high-modulus carbon fibers with higher stiffness and lower cost, boron fibers have now rather limited application. Boron fibers are manufactured by chemical vapor deposition of boron onto about 12  $\mu\text{m}$  diameter tungsten or carbon fiber (core). Because of this technology, boron fibers have a relatively large diameter, 100–200  $\mu\text{m}$ . They are extremely brittle and sensitive to surface damage. Typical mechanical properties of boron fibers are presented in Table 1.1 and Figs 1.7 and 1.8. Being mainly used in metal matrix composites, boron fibers degrade on contact with aluminum or titanium matrices at the temperature that is necessary for processing (above 500°C). To prevent this degradation, chemical vapor deposition is used to cover the fiber surface with about 5  $\mu\text{m}$  thick layer of silicon carbide, SiC, (such fibers are called Borsic) or boron carbide, B<sub>4</sub>C.

There exists a special class of ceramic fibers for high-temperature applications composed of various combinations of silicon, carbon, nitrogen, aluminum, boron, and titanium. The most commonly encountered are silicon carbide (SiC) and alumina ( $\text{Al}_2\text{O}_3$ ) fibers.

Silicon carbide is deposited on a tungsten or carbon core-fiber by the reaction of a gas mixture of silanes and hydrogen. Thin ( $8\text{--}15\text{ }\mu\text{m}$  in diameter) SiC fibers can be made by pyrolysis of polymeric (polycarbosilane) fibers at temperatures of about  $1400^\circ\text{C}$  in an inert atmosphere. Silicon carbide fibers have high strength and stiffness, moderate density (see Table 1.1) and very high melting temperature ( $2600^\circ\text{C}$ ).

Alumina ( $\text{Al}_2\text{O}_3$ ) fibers are fabricated by sintering of fibers extruded from the viscous alumina slurry with rather complicated composition. Alumina fibers, possessing approximately the same mechanical properties as SiC fibers, have relatively large diameter and high density. The melting temperature is about  $2000^\circ\text{C}$ .

Silicon carbide and alumina fibers are characterized by relatively low reduction in strength at elevated temperatures (see Fig. 1.9).

Promising ceramic fibers for high-temperature applications are boron carbide ( $\text{B}_4\text{C}$ ) fibers that can be obtained either as a result of reaction of a carbon fiber with a mixture of hydrogen and boron chloride at high temperature (around  $1800^\circ\text{C}$ ) or by pyrolysis of cellulosic fibers soaked with boric acid solution. Possessing high stiffness and strength and

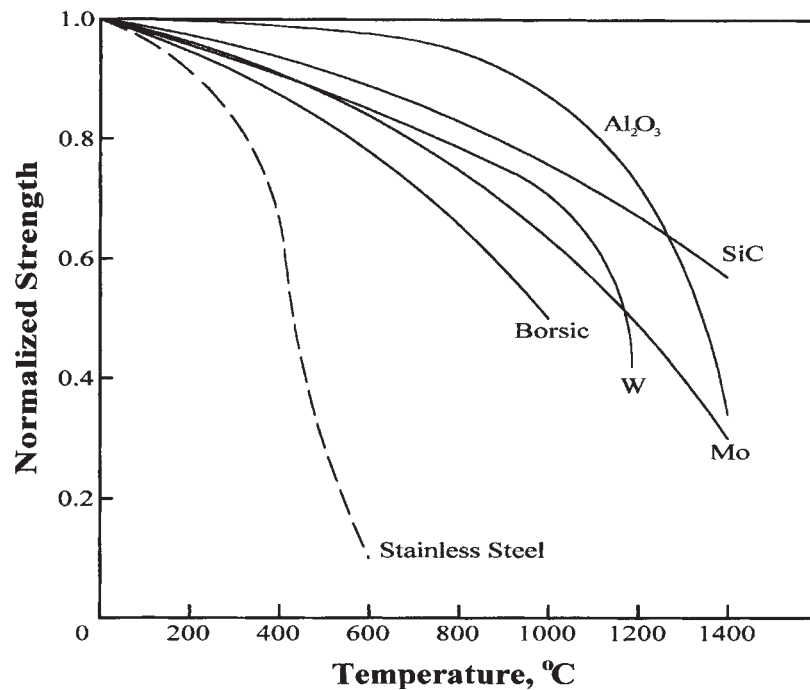


Fig. 1.9. Temperature dependence of high-temperature fibers normalized strength (in comparison with stainless steel).

moderate density (see Table 1.1), boron carbide fibers have very high thermal resistance (up to 2300°C).

Metal fibers (thin wires) made of steel, beryllium, titanium, tungsten, and molybdenum are used for special, e.g., low-temperature and high-temperature applications. Typical characteristics of metal fibers are presented in Table 1.1 and Figs. 1.7 and 1.9.

In advanced composites, fibers provide not only high strength and stiffness but also a possibility to tailor the material so that directional dependence of its mechanical properties matches that of the loading environment. The principle of directional properties can be traced in all natural materials that have emerged as a result of a prolonged evolution and, in contrast to man-made metal alloys, are neither isotropic nor homogeneous. Many natural materials have fibrous structures and utilize high strength and stiffness of natural fibers listed in Table 1.2. As can be seen (Tables 1.1 and 1.2), natural fibers, having lower strength and stiffness than man-made fibers, can compete with modern metals and plastics.

Before being used as reinforcing elements of advanced composites, the fibers are subjected to special finish surface treatments, undertaken to prevent any fiber damage under contact with processing equipment, to provide surface wetting when the fibers are combined with matrix materials, and to improve the interface bond between fibers and matrices. The most commonly encountered surface treatments are chemical sizing performed during the basic fiber formation operation and resulting in a thin layer applied to the surface of the fiber, surface etching by acid, plasma, or corona discharge, and coating of the fiber surface with thin metal or ceramic layers.

With only a few exceptions (e.g., metal fibers), individual fibers, being very thin and sensitive to damage, are not used in composite manufacturing directly, but in the form of tows (rovings), yarns, and fabrics.

A unidirectional tow (roving) is a loose assemblage of parallel fibers consisting usually of thousands of elementary fibers. Two main designations are used to indicate the size of

Table 1.2  
Mechanical properties of natural fibers.

Fiber	Diameter ( $\mu\text{m}$ )	Ultimate tensile stress, $\bar{\sigma}$ (MPa)	Modulus, $E$ (GPa)	Specific gravity
Wood	15–20	160	23	1.5
Bamboo	15–30	550	36	0.8
Jute	10–50	580	22	1.5
Cotton	15–40	540	28	1.5
Wool	75	170	5.9	1.32
Coir	10–20	250	5.5	1.5
Bagasse	25	180	9	1.25
Rice	5–15	100	6	1.24
Natural silk	15	400	13	1.35
Spider silk	4	1750	12.7	–
Linen	–	270	–	–
Sisal	–	560	–	–
Asbestos	0.2	1700	160	2.5

the tow, namely the  $K$ -number that gives the number of fibers in the tow (e.g.,  $3K$  tow contains 3000 fibers) and the tex-number which is the mass in grams of 1000 m of the tow. The tow tex-number depends not only on the number of fibers but also on the fiber diameter and density. For example, AS4-6K tow consisting of 6000 AS4 carbon fibers has 430 tex.

A yarn is a fine tow (usually it includes hundreds of fibers) slightly twisted (about 40 turns per meter) to provide the integrity of its structure necessary for textile processing. Yarn size is indicated in tex-numbers or in textile denier-numbers (den) such that  $1 \text{ tex} = 9 \text{ den}$ . Continuous yarns are used to make fabrics with various weave patterns. There exists a wide variety of glass, carbon, aramid, and hybrid fabrics whose nomenclature, structure, and properties are described elsewhere (Chou and Ko, 1989; Tarnopol'skii et al., 1992; Bogdanovich and Pastore, 1996; Peters, 1998).

An important characteristic of fibers is their processability which can be evaluated as the ratio,  $K_p = \bar{\sigma}_s / \bar{\sigma}$ , of the strength demonstrated by fibers in the composite structure,  $\bar{\sigma}_s$ , to the strength of fibers before they were processed,  $\bar{\sigma}$ . This ratio depends on fibers' ultimate elongation, sensitivity to damage, and manufacturing equipment causing damage to the fibers. The most sensitive to operational damage are boron and high-modulus carbon fibers possessing relatively low ultimate elongation  $\bar{\epsilon}$  (less than 1%, see Fig. 1.7). For example, for filament wound pressure vessels,  $K_p = 0.96$  for glass fibers, while for carbon fibers,  $K_p = 0.86$ .

To evaluate fiber processability under real manufacturing conditions, three simple tests are used – tension of a straight dry tow, tension of tows with loops, and tension of a tow with a knot (see Fig. 1.10). Similar tests are used to determine the strength of individual fibers (Fukuda et al., 1997). For carbon tows, normalized strength obtained in these tests is presented in Table 1.3 (for proper comparison, the tows should be of the same size). As follows from this table, the tow processability depends on the fiber ultimate strain (elongation). The best processability is observed for aramid tows whose fibers have high elongation and low sensitivity to damage (they are not monolithic and consist of thin fibrils).

### 1.2.2. Matrix materials

To utilize high strength and stiffness of fibers in a monolithic composite material suitable for engineering applications, fibers are bound with a matrix material whose strength and stiffness are, naturally, much lower than those of fibers (otherwise, no fibers would be necessary). Matrix materials provide the final shape of the composite structure and govern the parameters of the manufacturing process. The optimal combination of fiber and matrix properties should satisfy a set of operational and manufacturing requirements that are sometimes of a contradictory nature, and have not been completely met yet in existing composites.

First of all, the stiffness of the matrix should correspond to the stiffness of the fibers and be sufficient to provide uniform loading of fibers. The fibers are usually characterized by relatively high scatter in strength that may be increased due to damage of the fibers caused by the processing equipment. Naturally, fracture of the weakest or damaged fiber should not result in material failure. Instead, the matrix should evenly redistribute the load from



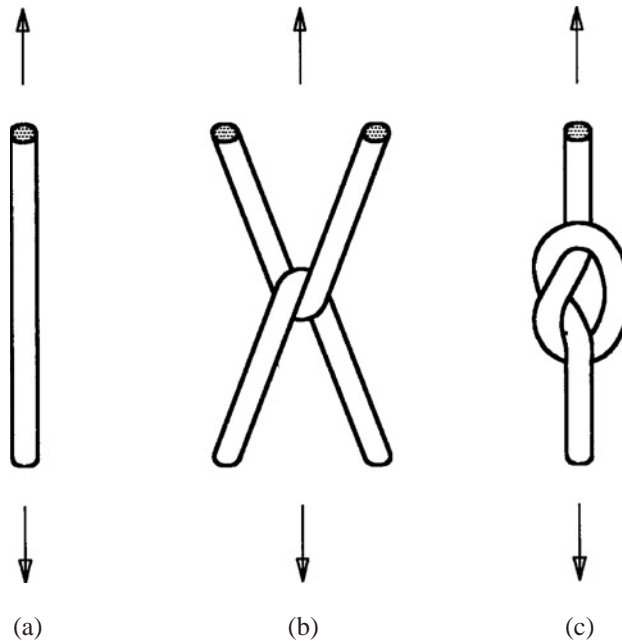


Fig. 1.10. Testing of a straight tow (a), tows with a loop (b), and tow with a knot (c).

Table 1.3  
Normalized strength of carbon tows.

Ultimate strain, $\bar{\epsilon}$ (%)	Normalized strength		
	Straight tow	Tow with a loop	Tow with a knot
0.75	1	0.25	0.15
1.80	1	0.53	0.18

the broken fiber to the adjacent ones and then load the broken fiber at a distance from the cross section at which it failed. The higher the matrix stiffness, the smaller is this distance, and less is the influence of damaged fibers on material strength and stiffness (which should be the case). Moreover, the matrix should provide the proper stress diffusion (this is the term traditionally used for this phenomenon in the analysis of stiffened structures (Goodey, 1946)) in the material at a given operational temperature. That is why this temperature is limited, as a rule, by the matrix rather than by the fibers. But on the other hand, to provide material integrity up to the failure of the fibers, the matrix material should possess high compliance. Obviously, for a linear elastic material (see Fig. 1.3), a combination of high stiffness and high ultimate strain  $\bar{\epsilon}$  results in high strength which is not the case for modern matrix materials. Thus, close to optimal (with respect to the foregoing requirements) and

realistic matrix material should have a nonlinear stress–strain diagram (of the type shown in Fig. 1.5) and possess high initial modulus of elasticity and high ultimate strain.

However, matrix properties, even though being optimal for the corresponding fibers, do not manifest in the composite material if the adhesion (the strength of fiber–matrix interface bonding) is not high enough. High adhesion between fibers and matrices, providing material integrity up to the failure of the fibers, is a necessary condition for high-performance composites. Proper adhesion can be reached for properly selected combinations of fiber and matrix materials under some additional conditions. First, a liquid matrix should have viscosity low enough to allow the matrix to penetrate between the fibers of such dense systems of fibers as tows, yarns, and fabrics. Second, the fiber surface should have good wettability with the matrix. Third, the matrix viscosity should be high enough to retain the liquid matrix in the impregnated tow, yarn, or fabric in the process of fabrication of a composite part. Finally, the manufacturing process providing the proper quality of the resulting material should not require high temperature and pressure to make a composite part.

At present, typical matrices are made from polymeric, metal, carbon, and ceramic materials.

Polymeric matrices are divided into two main types, thermoset and thermoplastic. Thermoset polymers, which are the most widely used matrix materials for advanced composites, include polyester, epoxy, polyimide and other resins (see Table 1.1) cured under elevated or room temperature. A typical stress–strain diagram for a cured epoxy resin is shown in Fig. 1.11. Being cured (polymerized), a thermoset matrix cannot be reset, dissolved, or melted. Heating of a thermoset material results first in degradation of its strength and stiffness, and then in thermal destruction.

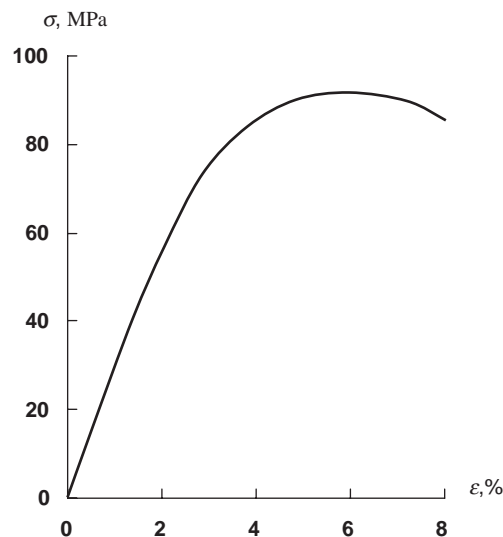


Fig. 1.11. Stress–strain diagram for a typical cured epoxy matrix.

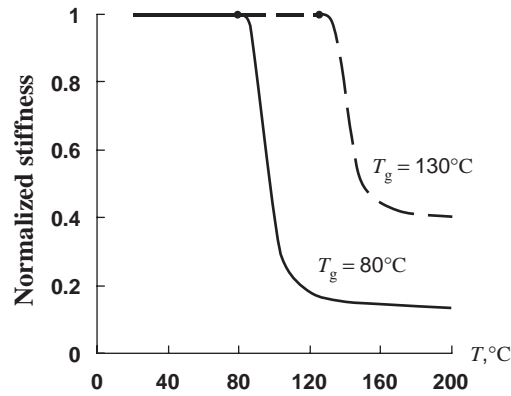


Fig. 1.12. Typical thermo-mechanical diagrams for cured epoxy resins with glass transition temperatures  $80^\circ\text{C}$  (—) and  $130^\circ\text{C}$  (---).

In contrast to thermoset resins, thermoplastic matrices (PSU, PEEK, PPS and others – see Table 1.1) do not require any curing reaction. They melt under heating and convert to a solid state under cooling. The possibility to re-melt and dissolve thermoplastic matrices allows us to reshape composite parts forming them under heating and simplifies their recycling, which is a problem for thermoset materials.

Polymeric matrices can be combined with glass, carbon, organic, or boron fibers to yield a wide class of polymeric composites with high strength and stiffness, low density, high fatigue resistance, and excellent chemical resistance. The main disadvantage of these materials is their relatively low (in comparison with metals) temperature resistance limited by the matrix. The so-called thermo-mechanical curves are plotted to determine this important (for applications) characteristic of the matrix. These curves, presented for typical epoxy resins in Fig. 1.12, show the dependence of some stiffness parameter on the temperature and allow us to find the so-called glass transition temperature,  $T_g$ , which indicates a dramatic reduction in material stiffness. There exist several standard methods to obtain a material's thermo-mechanical diagram. The one used to plot the curves presented in Fig. 1.12 involves compression tests of heated polymeric discs. Naturally, to retain the complete set of properties of polymeric composites, the operating temperature, in general, should not exceed  $T_g$ . However, the actual material behavior depends on the type of loading. As follows from Fig. 1.13, heating above the glass transition temperature only slightly influences material properties under tension in the fiber direction and dramatically reduces its strength in longitudinal compression and transverse bending. The glass transition temperature depends on the processing temperature,  $T_p$ , at which a material is fabricated, and higher  $T_p$  results, as a rule, in higher  $T_g$ . Thermoset epoxy matrices cured at a temperature in the range  $120\text{--}160^\circ\text{C}$  have  $T_g = 60\text{--}140^\circ\text{C}$ . There also exist a number of high temperature thermoset matrices (e.g., organosilicone, polyimide, and bismaleimide resins) with  $T_g = 250\text{--}300^\circ\text{C}$  and curing temperatures up to  $400^\circ\text{C}$ . Thermoplastic matrices are also characterized by a wide range of glass transition temperatures – from  $90^\circ\text{C}$  for PPS and  $140^\circ\text{C}$  for PEEK to  $190^\circ\text{C}$  for PSU and  $270^\circ\text{C}$  for PAI

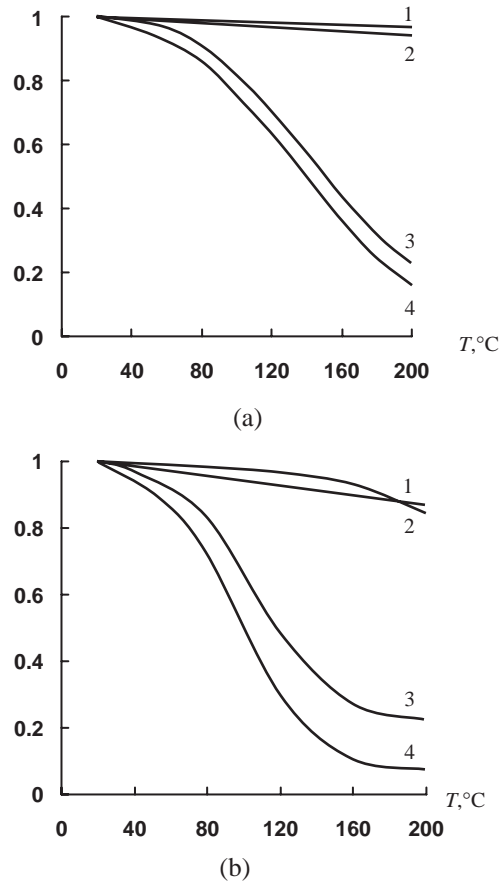


Fig. 1.13. Dependence of normalized longitudinal moduli (1), strength under longitudinal tension (2), bending (3), and compression (4) on temperature for unidirectional carbon composites with epoxy matrices having  $T_g = 130^\circ\text{C}$  (a) and  $T_g = 80^\circ\text{C}$  (b).

(see Table 1.1 for abbreviations). The processing temperature for different thermoplastic matrices varies from 300 to 400°C.

Further enhancement in temperature resistance of composite materials is associated with application of metal matrices in combination with high temperature boron, carbon, ceramic fibers, and metal wires. The most widespread metal matrices are aluminum, magnesium, and titanium alloys possessing high plasticity (see Fig. 1.14), whereas for special applications nickel, copper, niobium, cobalt, and lead matrices can be used. Fiber reinforcement essentially improves the mechanical properties of such metals. For example, carbon fibers increase strength and stiffness of such a soft metal as lead by an order of magnitude.

As noted above, metal matrices allow us to increase operational temperatures for composite structures. The dependencies of longitudinal strength and stiffness of

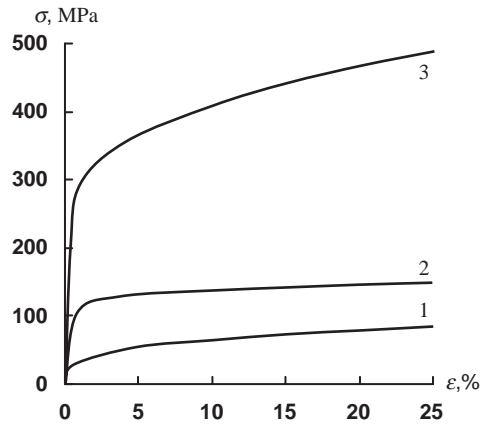


Fig. 1.14. Typical stress–strain curves for aluminum (1), magnesium (2), and titanium (3) matrices.

boron–aluminum unidirectional composite material on temperature, corresponding to the experimental results that can be found in Karpinos (1985) and Vasiliev and Tarnopol'skii (1990), are shown in Fig. 1.15. Naturally, higher temperature resistance requires higher processing temperature,  $T_p$ . Indeed, aluminum matrix composite materials are processed at  $T_p = 550^\circ\text{C}$ , whereas for magnesium, titanium, and nickel matrices the appropriate temperature is about 800, 1000, and  $1200^\circ\text{C}$  respectively. Some processes also require rather high pressure (up to 150 MPa).

In polymeric composites, the matrix materials play an important but secondary role of holding the fibers in place and providing good load dispersion into the fibers, whereas material strength and stiffness are controlled by the reinforcements. In contrast,

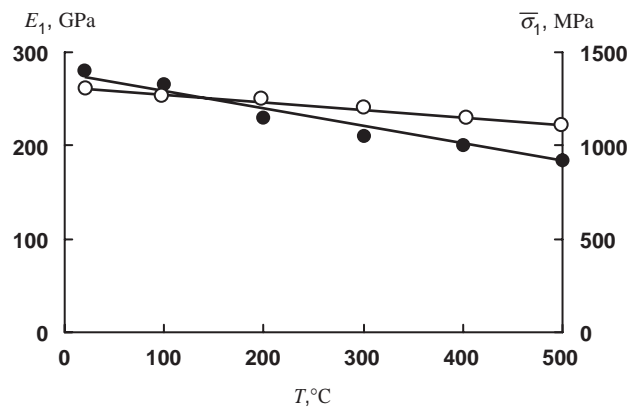


Fig. 1.15. Temperature dependence of tensile strength (●) and stiffness (○) along the fibers for unidirectional boron–aluminum composite.

the mechanical properties of metal matrix composites are controlled by the matrix to a considerably larger extent, though the fibers still provide the major contribution to the strength and stiffness of the material.

The next step in the development of composite materials that can be treated as matrix materials reinforced with fibers rather than fibers bonded with matrix (which is the case for polymeric composites) is associated with ceramic matrix composites possessing very high thermal resistance. The stiffnesses of the fibers which are usually metal (steel, tungsten, molybdenum, niobium), carbon, boron, or ceramic ( $\text{SiC}$ ,  $\text{Al}_2\text{O}_3$ ) and ceramic matrices (oxides, carbides, nitrides, borides, and silicides) are not very different, and the fibers do not carry the main fraction of the load in ceramic composites. The function of the fibers is to provide strength and mainly toughness (resistance to cracks) of the composite, because non-reinforced ceramic materials are very brittle. Ceramic composites can operate under very high temperatures depending on the melting temperature of the matrix that varies from 1200 to 3500°C. Naturally, the higher the temperature, the more complicated is the manufacturing process. The main shortcoming of ceramic composites is associated with a low ultimate tensile elongation of the ceramic matrix resulting in cracks appearing in the matrix under relatively low tensile stress applied to the material.

An outstanding combination of high mechanical characteristics and temperature resistance is demonstrated by carbon–carbon composites in which both components – fibers and matrix are made from one and the same material but with different structure. A carbon matrix is formed as a result of carbonization of an organic resin (phenolic and furfural resin or pitch) with which carbon fibers are impregnated, or of chemical vapor deposition of pyrolytic carbon from a hydrocarbon gas. In an inert atmosphere or in a vacuum, carbon–carbon composites can withstand very high temperatures (more than 3000°C). Moreover, their strength increases under heating up to 2200°C while the modulus degrades at temperatures above 1400°C. However in an oxygen atmosphere, they oxidize and sublime at relatively low temperatures (about 600°C). To use carbon–carbon composite parts in an oxidizing atmosphere, they must have protective coatings, made usually from silicon carbide. Manufacturing of carbon–carbon parts is a very energy- and time-consuming process. To convert an initial carbon–phenolic composite into carbon–carbon, it should receive a thermal treatment at 250°C for 150 h, carbonization at about 800°C for about 100 h and several cycles of densification (one-stage pyrolysis results in high porosity of the material) each including impregnation with resin, curing, and carbonization. To refine the material structure and to provide oxidation resistance, a further high-temperature graphitization at 2700°C and coating (at 1650°C) can be required. Vapor deposition of pyrolytic carbon is also a time-consuming process performed at 900–1200°C under a pressure of 150–2000 kPa.

### 1.2.3. Processing

Composite materials do not exist apart from composite structures and are formed while the structure is fabricated. Being a heterogeneous media, a composite material has two levels of heterogeneity. The first level represents a microheterogeneity induced by at

least two phases (fibers and matrix) that form the material microstructure. At the second level the material is characterized by a macroheterogeneity caused by the laminated or more complicated macrostructure of the material which consists usually of a set of layers with different orientations. A number of technologies have been developed by now to manufacture composite structures. All these technologies involve two basic processes during which material microstructure and macrostructure are formed.

*The first basic process* yielding material microstructure involves the application of a matrix material to the fibers. The simplest way to do it, normally utilized in the manufacturing of composites with thermosetting polymeric matrices, is a direct impregnation of tows, yarns, fabrics, or more complicated fibrous structures with liquid resins. Thermosetting resin has relatively low viscosity (10–100 Pa s), which can be controlled using solvents or heating, and good wetting ability for the majority of fibers. There exist two versions of this process. According to the so-called ‘wet’ process, impregnated fibrous material (tows, fabrics, etc.) is used to fabricate composite parts directly, without any additional treatment or interruption of the process. In contrast to that, in ‘dry’ or ‘prepreg’ processes, impregnated fibrous material is dried (not cured) and thus preimpregnated tapes obtained (prepregs) are stored for further utilization (usually under low temperature to prevent uncontrolled premature polymerization of the resin). An example of a machine for making prepregs is shown in Fig. 1.16. Both processes, having similar advantages and shortcomings, are widely used for composites with thermosetting matrices. For thermoplastic matrices, application of direct impregnation (‘wet’ processing) is limited by the relatively high viscosity (about  $10^{12}$  Pa s) of thermoplastic polymer solutions or melts. For this reason, ‘prepreg’ processes with preliminary fabricated tapes or sheets in which fibers are already combined with the thermoplastic matrix are used to manufacture composite parts. There also exist other processes that involve application of heat and pressure to hybrid materials including reinforcing fibers and a thermoplastic polymer in the form of powder, films, or fibers. A promising process (called fibrous technology) utilizes tows, tapes, or fabrics with two types of fibers – reinforcing and thermoplastic. Under heat and pressure, thermoplastic fibers melt and form the matrix of the composite material. Metal and ceramic matrices are applied to fibers by means of casting, diffusion welding, chemical deposition, plasma spraying, processing by compression molding or with the aid of powder metallurgy methods.

*The second basic process* provides the proper macrostructure of a composite material corresponding to the loading and operational conditions of the composite part that is fabricated. There exist three main types of material macrostructure – linear structure which is appropriate for bars, profiles, and beams, plane laminated structure suitable for thin-walled plates and shells, and spatial structure which is necessary for thick-walled and bulk solid composite parts.

A linear structure is formed by pultrusion, table rolling, or braiding and provides high strength and stiffness in one direction coinciding with the axis of a bar, profile, or a beam. Pultrusion results in a unidirectionally reinforced composite profile made by pulling a bundle of fibers impregnated with resin through a heated die to cure the resin and, to provide the desired shape of the profile cross section. Profiles made by pultrusion and braiding are shown in Fig. 1.17. Table rolling is used to fabricate small diameter tapered tubular bars (e.g., ski poles or fishing rods) by rolling preimpregnated fiber tapes in the form of

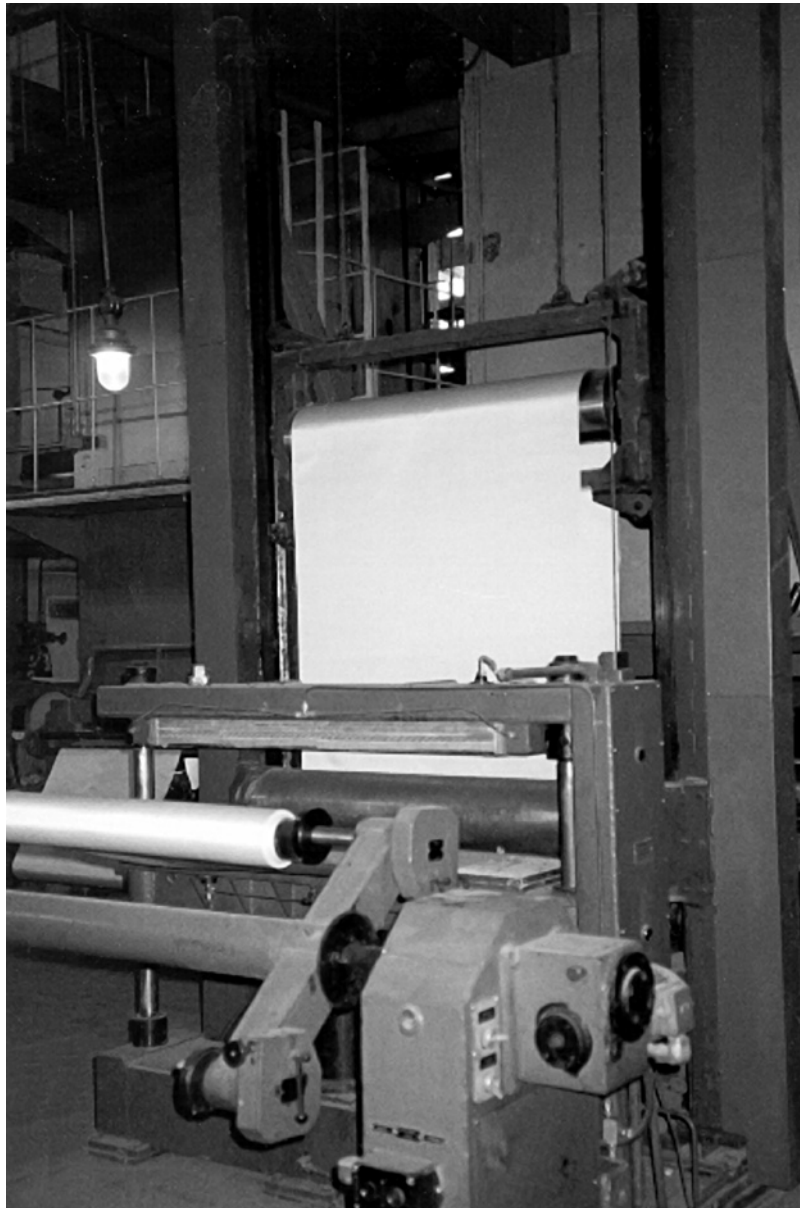


Fig. 1.16. Machine making a prepreg from fiberglass fabric and epoxy resin. Courtesy of CRISM.



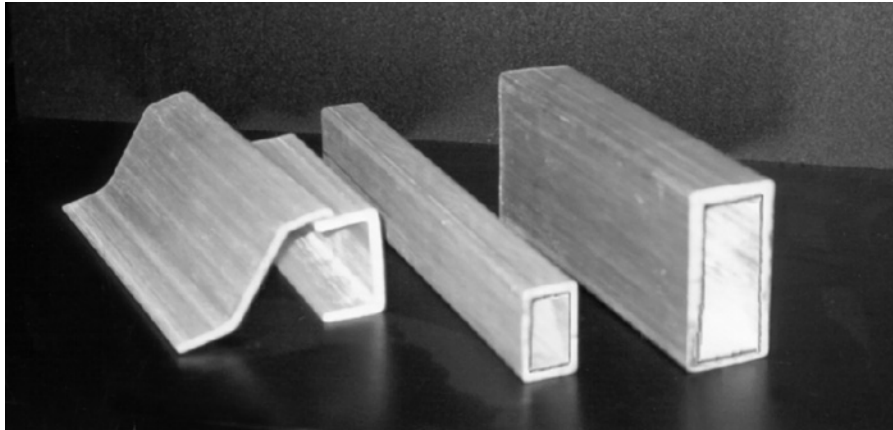


Fig. 1.17. Composite profiles made by pultrusion and braiding. Courtesy of CRISM.

flags around the metal mandrel which is pulled out of the composite bar after the resin is cured. Fibers in the flags are usually oriented along the bar axis or at an angle to the axis thus providing more complicated reinforcement than the unidirectional one typical of pultrusion. Even more complicated fiber placement with orientation angle varying from  $5^\circ$  to  $85^\circ$  along the bar axis can be achieved using two-dimensional (2D) braiding which results in a textile material structure consisting of two layers of yarns or tows interlaced with each other while they are wound onto the mandrel.

A plane-laminated structure consists of a set of composite layers providing the necessary stiffness and strength in at least two orthogonal directions in the plane of the laminate. Such a plane structure would be formed by hand or machine lay-up, fiber placement, or filament winding.

Lay-up and fiber placement technology provides fabrication of thin-walled composite parts of practically arbitrary shape by hand or automated placing of preimpregnated unidirectional or fabric tapes onto a mold. Layers with different fiber orientations (and even with different fibers) are combined to result in the laminated composite material exhibiting the desired strength and stiffness in given directions. Lay-up processes are usually accompanied by pressure applied to compact the material and to remove entrapped air. Depending on the required quality of the material, as well as on the shape and dimensions of a manufactured composite part, compacting pressure can be provided by rolling or vacuum bags, in autoclaves, or by compression molding. A catamaran yacht (length 9.2 m, width 6.8 m, tonnage 2.2 tons) made from carbon-epoxy composite by hand lay-up is shown in Fig. 1.18.

Filament winding is an efficient automated process of placing impregnated tows or tapes onto a rotating mandrel (Fig. 1.19) that is removed after curing of the composite material. Varying the winding angle, it is possible to control the material strength and stiffness within the layer and through the thickness of the laminate. Winding of a pressure vessel is shown in Fig. 1.20. Preliminary tension applied to the tows in the process of winding induces



Fig. 1.18. Catamaran yacht Ivan-30 made from carbon-epoxy composite by hand lay-up. Courtesy of CRISM.

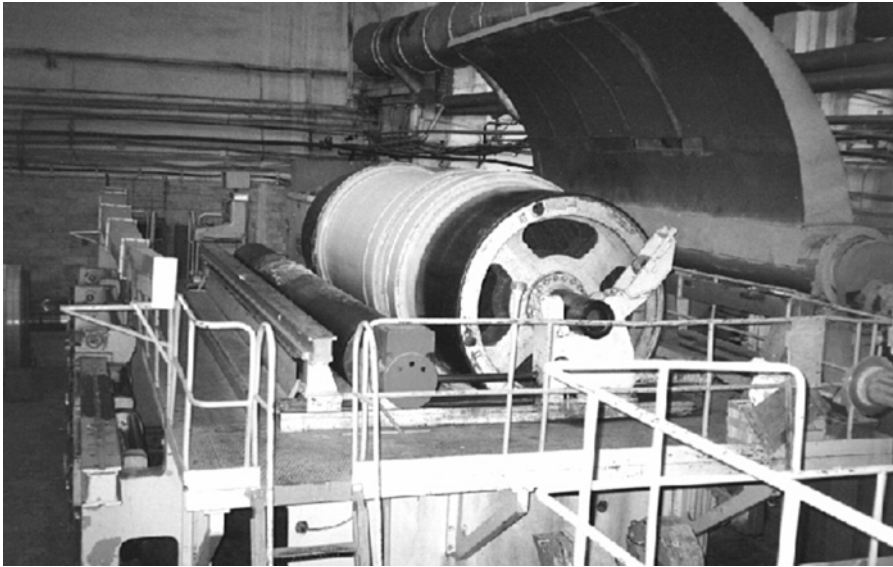


Fig. 1.19. Manufacturing of a pipe by circumferential winding of preimpregnated fiberglass fabric. Courtesy of CRISM.

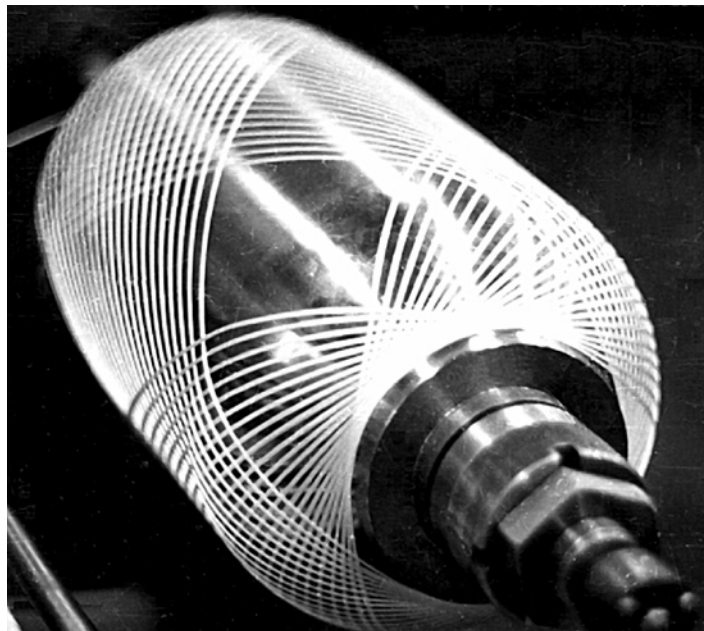


Fig. 1.20. Geodesic winding of a pressure vessel.

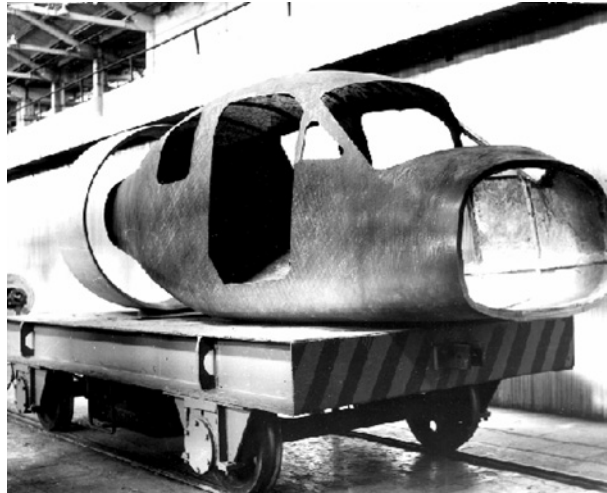


Fig. 1.21. A body of a small plane made by filament winding. Courtesy of CRISM.

pressure between the layers providing compaction of the material. Filament winding is the most advantageous in manufacturing thin-walled shells of revolution though it can also be used in building composite structures with more complicated shapes (Fig. 1.21).

Spatial macrostructure of the composite material that is specific for thick-walled and solid members requiring fiber reinforcement in at least three directions (not lying in one plane) can be formed by 3D braiding (with three interlaced yarns) or using such textile processes as weaving, knitting, or stitching. Spatial (3D, 4D, etc.) structures used in carbon–carbon technology are assembled from thin carbon composite rods fixed in different directions. Such a structure that is prepared for carbonization and deposition of a carbon matrix is shown in Fig. 1.22.

There are two specific manufacturing procedures that have an inverse sequence of the basic processes described above, i.e., first, the macrostructure of the material is formed and then the matrix is applied to fibers.

The first of these procedures is the aforementioned carbon–carbon technology that involves chemical vapor deposition of a pyrolytic carbon matrix on preliminary assembled and sometimes rather complicated structures made from dry carbon fabric. A carbon–carbon shell made by this method is shown in Fig. 1.23.

The second procedure is the well-known resin transfer molding. Fabrication of a composite part starts with a preform that is assembled in the internal cavity of a mold from dry fabrics, tows, yarns, etc., and forms the macrostructure of a composite part. The shape of this part is governed by the shape of the mold cavity into which liquid resin is transferred under pressure through injection ports.

The basic processes described above are always accompanied by a thermal treatment resulting in the solidification of the matrix. Heating is applied to cure thermosetting resins, cooling is used to transfer thermoplastic, metal, and ceramic matrices to a solid phase,



Fig. 1.22. A 4D spatial structure. Courtesy of CRISM.



Fig. 1.23. A carbon-carbon conical shell. Courtesy of CRISM.

whereas a carbon matrix is made by pyrolysis. The final stages of the manufacturing procedure involve removal of mandrels, molds, or other tooling and machining of a composite part.

The fabrication processes are described in more detail elsewhere (e.g., Peters, 1998).

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