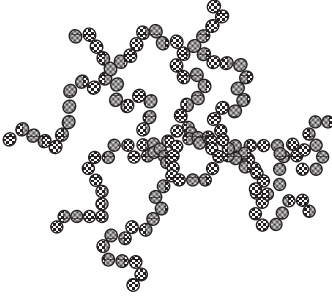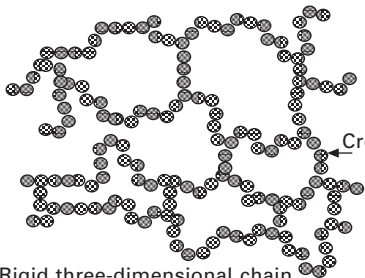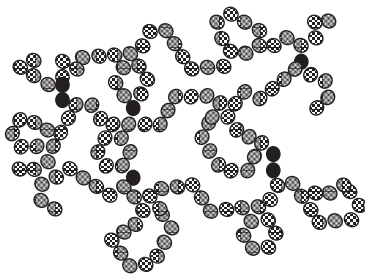# 13

Polymers for aerospace structures

13.1   Introduction

Polymer is a generic term that covers a wide variety and large number of plastics, elastomers and adhesives. The three main groups of polymers are called thermoplastics, thermosetting polymers (or thermosets) and elastomers. The term 'plastic' is often used to describe both thermoplastics and thermosets, although there are important differences between the two. Elastomers are commonly called 'rubbers', although in the aerospace engineering community the former term is the correct one to use. Adhesives are an important sub-group of polymers, and can be thermoplastic, thermoset or elastomer.

The basic chemical properties used to distinguish between thermoplastics, thermosets and elastomers are shown in Fig. 13.1. Thermoplastics consist of long molecular chains made by joining together small organic molecules known as monomers. In effect, monomers are the basic building blocks that are joined end-to-end by chemical reactions to produce a long polymer chain. The property of thermoplastics that distinguishes them from other polymers is that strong covalent bonds join the atoms together along the length of the chain, but no covalent bonding occurs between the chains. Each thermoplastic chain is a discrete molecule. The molecular chains are entangled and intertwined in a thermoplastic, but the chains are not joined or connected. This structure provides thermoplastics with useful engineering properties, including high ductility, fracture toughness and impact resistance. The lack of bonding between the molecular chains causes thermoplastics to soften and melt when heated which allows them to be recycled.

Thermosetting polymers are also long molecular chains made by joining together smaller molecules, although the chemical reactions produce covalent bonds both along the chain and bridging across the chains. The bonding between the chains is known as crosslinking, and it produces a rigid three-dimensional molecular structure. It is the crosslinking of thermosets that distinguishes them from thermoplastics. The crosslinks generally provide thermosets with higher elastic modulus and tensile strength than thermoplastics, but they are more brittle and have lower toughness. Thermosets do not have a melting point because the crosslinks do not allow the chains to flow like a liquid at high temperature and, therefore, these polymers cannot be recycled.

268

Thermoplastic • moderate stiffness • moderate strength • high ductility • high impact resistance • poor creep resistance • recyclable	Flexible linear chains with no crosslinking
Thermoset polymer • high stiffness • high strength • high creep resistance • low/moderate ductility • poor impact resistance • cannot be recycled	← Crosslinks Rigid three-dimensional chain structure with crosslinking
Elastomer • very low stiffness • low strength • very high elasticity • excellent impact resistance • not easily recycled	Linear coiled chains with some crosslinking

13.1 Basic properties of thermoplastics, thermoset polymers and elastomers.

Elastomers are natural and synthetic rubbers with a molecular structure that is somewhere between thermoplastics and thermosets. Some crosslinking occurs between elastomer chains, but to a lesser amount than with thermosets. The elastomer chains are coiled somewhat like a spring, and this allows them to be stretched over many times their original length without being permanently deformed. Elastomers are characterised by low stiffness and low strength as well as good impact resistance and toughness.

In this chapter, the polymers, elastomers and structural adhesives used in aerospace structures are described. These materials lack the stiffness and

strength to be used on their own in aircraft structures, but they are useful when used in combination with other materials such as fibre–polymer composites. The different types of polymers, viz. thermoplastics, thermosets, elastomers and adhesives, are examined. The polymerisation processes and chemical composition of polymers are studied. In addition, the mechanical and thermal properties of polymers, and their applications to aircraft, helicopters and spacecraft are discussed.

13.2   Aerospace applications of polymers

The most common use for polymers is the matrix phase of fibre composites. Polymers are the 'glue' used to hold together the high-stiffness, high-strength fibres in fibre–polymer composites, and these materials are described in chapters 14 and 15. Composites are used in the airframe and engine components of modern military and civilian aircraft, with polymers accounting for 40–45% of the total volume of the material. Moulded plastics and fibre–polymer composites are used extensively in the internal fittings and furniture of passenger aircraft.

Another important application of polymers is as an adhesive for joining aircraft components. It is possible to produce high strength, durable joints using polymer adhesives without the need for fasteners such as rivets and screws. Adhesives are used to join metal-to-metal, composite-to-composite and metal-to-composite components. For example, adhesives are used to bond ribs, spars and stringers to the skins of structural panels used throughout the airframe. Adhesives are also used to bond face sheets to the core of sandwich composite materials and to bond repairs to composite and metal components damaged during service. Thin layers of adhesive are used to bond together the aluminium and fibre–polymer composite sheets that produce the fibre–metal laminate called GLARE, which is used in the Airbus 380 fuselage. The use of elastomers is usually confined to nonstructural aircraft parts that require high flexibility and elasticity, such as seals and gaskets.

13.3   Advantages and disadvantages of polymers for aerospace applications

Polymers possess several properties that make them useful as aircraft materials, including low density (1.2–1.4 g cm^{-3}), moderate cost, excellent corrosion resistance, and high ductility (except thermosets). Some polymers are tough and transparent which makes them suitable for aircraft windows and canopies. However, polymers cannot be used on their own as structural materials because of their low stiffness, strength, creep properties and working temperature. Table 13.1 summarises the main advantages and disadvantages of thermoplastics, thermosets and elastomers whereas Table 13.2 gives the

Table 13.1 Comparison of the advantages and disadvantages of polymers for aircraft structural applications

Thermoplastic	Thermoset	Elastomer
Advantages		
• Non-reacting; no cure required	• Low processing temperature	• Low processing temperature
• Rapid processing	• Low viscosity	• High ductility and flexibility
• High ductility	• Good compression properties	• High fracture toughness
• High fracture toughness	• Good fatigue resistance	• High impact resistance
• High impact resistance	• Good creep resistance	
• Absorbs little moisture	• Highly resistant to solvents	
• Can be recycled	• Good fibre wetting for composites	
Disadvantages		
• Very high viscosity	• Long processing time	• Long processing times
• High processing temperature (300–400 °C)	• Low ductility	• Poor creep resistance
• High processing pressures	• Low fracture toughness	• Low Young's modulus
• Poor creep resistance	• Low impact resistance	• Low tensile strength
	• Absorb moisture	
	• Limited shelf life	
	• Cannot be recycled	

Table 13.2 Comparison of the typical properties of a structural polymer (epoxy resin) against aerospace structural materials

Materials	Average specific gravity (g cm^{-3})	Young's modulus (GPa)	Specific modulus (MPa m^3 kg^{-1})	Yield strength (MPa)	Specific strength (kPa m^3 kg^{-1})
Polymer (epoxy)	1.2	3	2.5	100	83
Aluminium (7075-T76)	2.7	70	25.9	470	174
Magnesium	1.7	45	26.5	200	115
α+β-Ti alloy	4.6	110	23.9	1000	217
Carbon/epoxy composite*	1.7	50	29.4	760	450

*[0/±45/90] carbon/epoxy; fibre volume content = 60%.

typical properties of polymers compared with several types of aerospace metals, and shows that the polymers are structurally inferior.
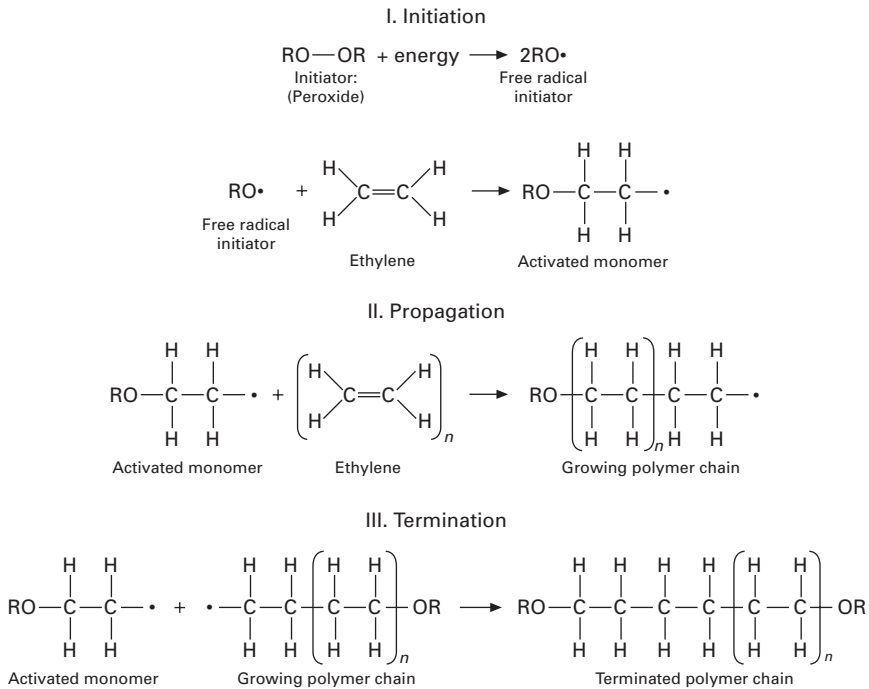
13.4   Polymerisation

13.4.1 Polymerisation processes

Polymerisation is the chemical process by which polymers are made into long chain-like molecules from smaller molecules. Polymerisation is the

process by which small molecules, known as monomers, are joined to create macromolecules. The polymerisation process is used to make thermoplastics, thermosets and elastomers, although the reaction processes are different. The chemistry of polymerisation is a complex topic, and only the basics are described here.

The polymerisation process can be divided into two types of chemical reaction: addition polymerisation and condensation polymerisation. Addition polymerisation involves the linking of monomers into the polymer chain by a chemical reaction that does not produce molecular by-products. For example, the major steps in the addition polymerisation reaction for polyethylene is shown in Fig. 13.2, which involves the joining of ethylene monomers (C_2H_4) into a long polyethylene chain $(CH_2)_{2n}$ where n is the number of ethylene monomers in the chain. A catalyst, also known as the 'initiator' because it starts the reaction, is added to the monomers. The catalyst splits the double covalent bond within the ethylene monomer to produce unpaired electrons. Each unpaired electron needs to immediately pair with another electron, so it joins with an unpaired electron at the neighbouring monomer. The pairing forms a single covalent bond that binds the two monomer units, and the process is repeated many, many times to produce a long molecular chain. A polymer
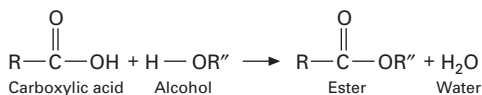
13.2 Addition polymerisation.

chain is built-up from hundreds to many hundreds of thousands of monomer units, which are called mer units when joined into a chain. The addition of monomers to a chain continues until the supply of monomer units or catalyst is exhausted or a special chemical called a terminator is used to stop the reaction process, or there is self-termination when a chain end connects to the end of another chain growing independently. In addition to polyethylene, other examples of polymers produced by addition polymerisation are polyvinyl chloride (PVC), polystyrene and polytetrafluroethylene (Teflon).

Condensation polymerisation is a process involving two or more different types of molecules that react to produce a molecular chain made of combinations of the starting molecules. Figure 13.3 shows a simple example of a condensation reaction between carboxylic acid and alcohol. A feature of the condensation reaction is that small molecules are produced as a by-product. These by-product molecules do not form part of the polymer chain. Water is a by-product of many condensation reactions and, when possible, it should be extracted from the polymer before use in aircraft. Examples of aerospace polymers produced by condensation reactions are epoxy resin, which is used as the matrix phase of carbon-fibre composite structures and as a structural adhesive, and phenolic resin which is used inside aircraft cabins for fire resistance.

Polymerisation reactions for most of the polymers used in aircraft involve just one type of monomer. When the polymer chain is made using just one monomer type it is known as a homopolymer. Polymers can also be produced by the polymerisation of two types of monomers, which is called a copolymer. Although copolymers are not used extensively in plastic aircraft parts, they are sometimes used as elastomers in seals. The two monomer types can be arranged in various ways along the chain, as illustrated in Fig. 13.4, thus resulting in different material properties. When the two different monomers are distributed randomly along the chain it is called a random copolymer. Under controlled processing conditions, the two monomer types may alternate as single mer units along the chain, and this is known as a regular copolymer. If, however, a long sequence of one type of mer units is followed by a long sequence of another type of mer units, it is termed a block copolymer. This latter type is called a graft copolymer when the chains produced from one type of monomer are attached (or grafted) to the chain created from the other monomer.

Addition and condensation reactions are started using a chemical catalyst,

13.3 Condensation polymerisation.
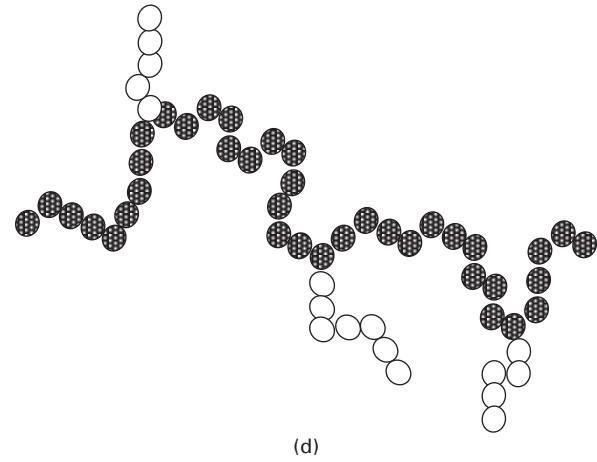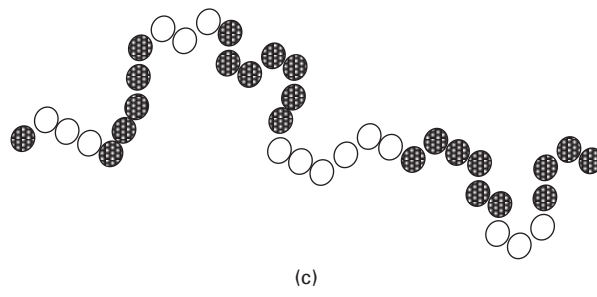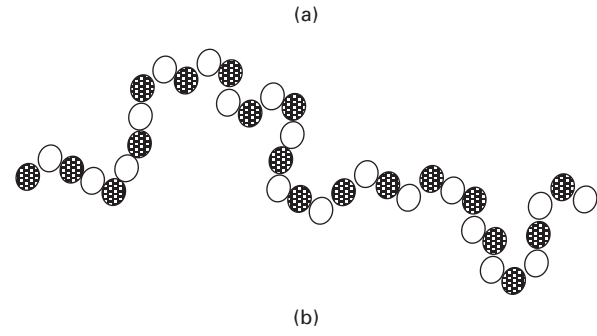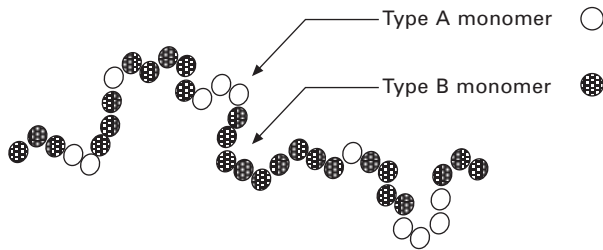
13.4 Structural types of copolymers: (a) random, (b) alternate, (c) block and (d) graft.

and the polymerisation rate is controlled by the amount of catalyst and the temperature. Increasing the catalyst content and temperature accelerates the reaction rate. However, other methods can be used to drive the polymerisation process, most notably electrons (e-beam) and ultraviolet (UV) radiation. E-beam curing is a process that involves irradiating the polymer with an electron beam to split the double covalent bonds in the monomer to produce unpaired electrons. Irradiating the polymer with UV radiation is another method for producing unpaired electrons. The unpaired electrons then bond with unpaired electrons from other monomer units to produce long polymer chains. These methods are gaining importance in the aircraft industry because they eliminate the need to use corrosive and toxic catalysts, although at the moment the use of catalysts remains the most common way of curing most types of polymer.

13.4.2 Polymer structure

The structural arrangement of the chain-like molecules has a major impact on the mechanical properties of a polymer. Thermoplastics can be polymerised by both addition and condensation reactions, although the monomers that make up thermoplastics are always bifunctional. This means they have two sites in the molecule where pairing can occur with other molecules. As a result, the polymer can only grow as a linear chain. Thermosetting polymers are also produced by addition and condensation reactions, but are formed from trifunctional monomers which have three reaction sites, and this allows the polymer to grow with covalent bonds along the chain and covalent (crosslink) bonds bridging across the chains. Elastomers contain a mixture of bifunctional and trifunctional monomers, which produces long linear segments in the chain from the bifunctional units, and widely spaced crosslinks from the trifunctional units.

Structural variations can occur within the chain during the polymerisation process that may significantly alter the engineering properties. The three major types of polymer structures are called atactic, isotactic and syndiotactic, and they are shown in Fig. 13.5. The chemical composition of the three types of polymer structure is the same; with the only difference being the location of atoms and small compounds ('R' groups) attached as side groups to the chain. When the side groups are located randomly along the chain, this is called an atactic structure. When the side groups are placed on the chain in the same location in each mer, it is called an isotactic structure. Syndiotactic refers to a structure with the R groups placed on the chain in a more or less regular pattern, but having alternate positions on either side of the chain.

The arrangement of the molecular chains at the end of the polymerisation process is complex, and simplified illustrations of the most common forms are shown in Fig. 13.6. The four most common structures are called linear,
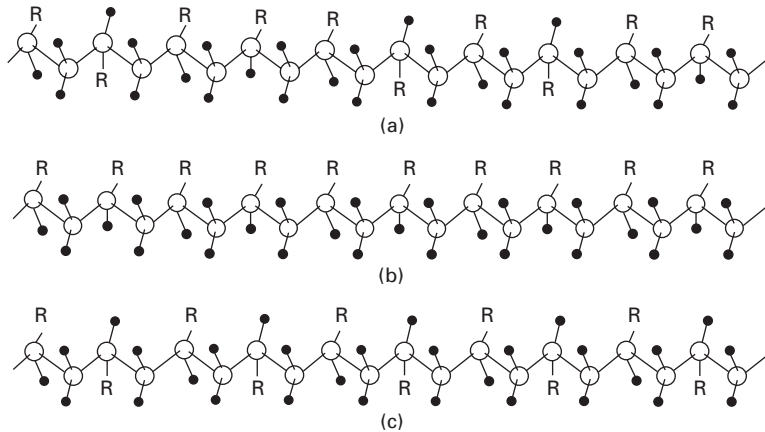
13.5 Models of polymer chains with (a) atactic, (b) isotactic and (c) syndiotactic structures.
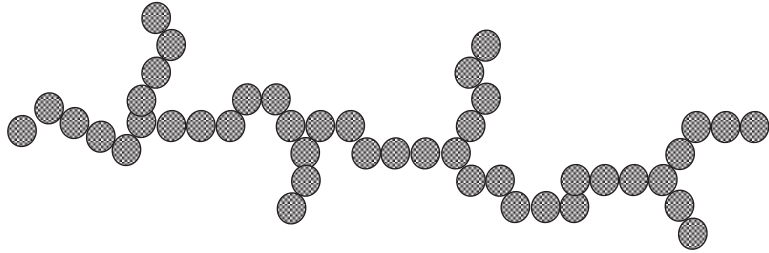
crosslinked, branched and ladder. Polymer chains are never straight, even over very short distances, and instead twist and turn along their length and become intertwined with other chains. Entanglement and intertwining of the chains is an important mechanism for providing stiffness and strength to polymers. This mechanism is particularly important for thermoplastics because they do not have crosslinking to resist sliding of the chains under an applied force. However, thermoplastics do have weak attraction forces between the chains. These are known as van der Waals bonds, also called 'secondary bonds', which is an electrostatic force between atoms owing to the nonsymmetric distribution of electrons around the atomic nucleus. These bonds are much weaker than the covalent bonds that form crosslinks between thermosets and, therefore, are less effective at resisting chain sliding.

13.5   Thermosetting polymers

Thermosetting polymers are crosslinked polymers that have a three-dimensional network structure with covalent bonds linking the chains. Thermosets are produced by mixing a liquid resin consisting of monomers and oligomers (several monomer units joined together) with a liquid hardener, which can be another resin or catalyst. The resin and hardener react in a process that joins the monomers and oligomers into long polymer chains and forms crosslinks between the chains. Heat is often used to accelerate the reaction process and pressure is applied to squeeze out volatile by-products. When the crosslinks are formed they resist rotation and sliding of the chains under load, and this provides thermosets with better strength, stiffness and hardness than thermoplastics.
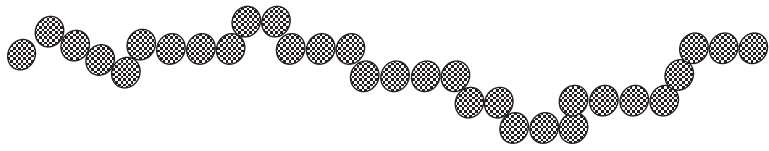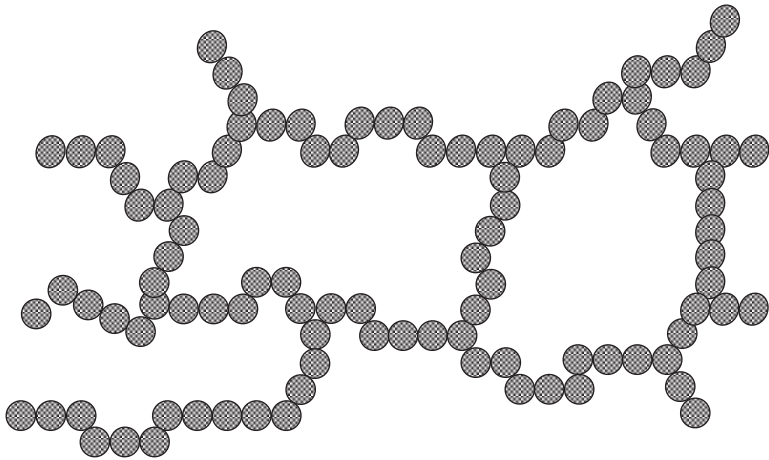
13.6 Schematic illustration of the molecular structure of (a) linear, (b) branched, (c) crosslinked, and (d) ladder polymers.

13.5.1 Epoxy resin

Epoxy resin is the most common thermosetting polymer used in aircraft structures. Epoxy resin is used as the matrix phase in carbon-fibr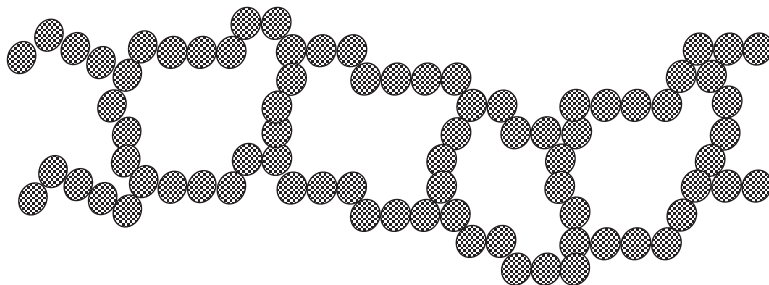e composites for aircraft structures and as an adhesive in aircraft structural joints and repairs. There are many types of epoxy resins, and the chemical structure of an epoxy resin often used in aerospace composite materials is shown in Fig. 13.7. Epoxy resin is a chemical compound containing two or more epoxide groups per monomer, and this molecule contains a tight C—O—C ring structure. During polymerisation, the hardener opens the C—O—C rings, and the bonds are rearranged to join the monomers into a three-dimensional network of crosslinked chain-like molecules. The cure reaction for certain types of epoxy resins occurs rapidly at room temperature, although many of the high-strength epoxies used in aircraft need to be cured at an elevated temperature (120–180 °C). Epoxy resins are the polymer of choice in many aircraft applications because of their low shrinkage and low release of volatiles during curing, high strength, and good durability in hot and moist environments.

13.5.2 Phenolic resin

Epoxy resin is used extensively in aircraft composite structures, but cannot be safely used inside cabins because of its poor fire performance. Most epoxy resins easily ignite when exposed to fire, and release copious amounts of heat, smoke and fumes. Federal Aviation Administration (FAA) regulations specify the maximum limits on heat release and smoke produced by cabin materials in the event of fire, and most structural-grade epoxy resins fail to meet the specifications. Phenolic resins meet the fire regulations, and most of the internal fittings, components and furniture in passenger aircraft are made of fibreglass–phenolic composite and moulded phenolic resin.

13.5.3 Polyimide, bismaleimide and cyanate

Thermosetting polymers that are also used in structural fibre composites are polyimides, bismaleimides and cyanate esters. These polymers are used in aircraft composite structures required to operate at temperatures above the performance limit of epoxy resin, which is usually in the upper range
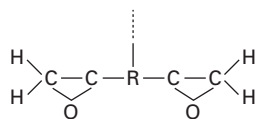
13.7 Functional unit of epoxy resins used in aircraft composite materials.

of 160–180 °C. Polyimides can operate continuously at temperatures up to 175 °C and have an operating limit of about 300 °C. The polyimide called PMR-15 is the most common, and is used as the matrix phase of carbon-fibre composites in high-speed military aircraft and jet engine components. The down-side of using polyimides is their high cost. Bismaleimide (BMI) is also used in fibre composites required to operate at temperature, with an upper service temperature of about 180 °C. Carbon–BMI composites are used in the F-35 *Lightning II* fighter along with carbon–epoxy materials. Cyanate resins, which are also known as cyanate esters, cyanic esters or triazine resins, have good strength and toughness at high temperature, and their maximum operating temperature is approximately 200 °C. However, cyanate resins pose a safety risk because they produce poisonous hydrogen cyanide during the cure reaction process.
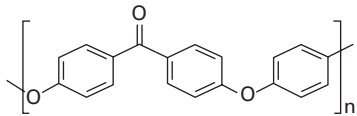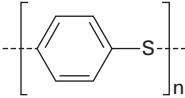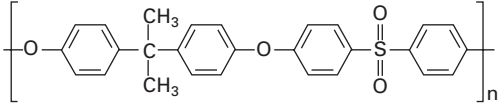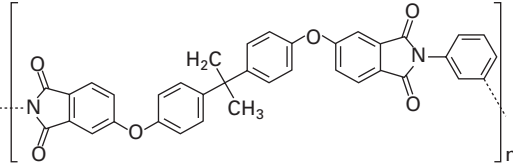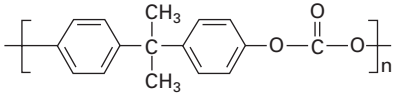
13.6   Thermoplastics

13.6.1 Aerospace thermoplastics

The use of thermoplastics in aircraft, whether as the matrix phase of fibre–polymer composites or as a structural adhesive, is small compared with the much greater use of thermosets. Some sectors of the aerospace industry are keen to increase the use of thermoplastics in composite materials, and the number of applications is gradually increasing. Thermoplastics provide several important advantages over thermosets when used in composite materials, most notably better impact damage resistance, higher fracture toughness and higher operating temperatures. However, thermoplastics must be processed at high temperature that makes them expensive to manufacture into aircraft composite components.

The group of thermoplastics that are most used in aircraft composite structures are called polyketones, and include polyether ketone (PEK), polyether ketone ketone (PEKK) and, the most common, polyether ether ketone (PEEK). The main types of thermoplastics used in aircraft are given in Fig. 13.8.

Several types of thermoplastics are transparent, tough and impact resistant which makes them well suited for aircraft windows and canopies. The thermoplastics most often used in aircraft windows are acrylic plastics and polycarbonates. Acrylic plastics are any polymer or copolymer of acrylic acid or variants thereof. An example of acrylic plastic used in aircraft windows is polymethyl methacrylate (PMMA), which is sold under commercial names such as Plexiglas and Perspex. Acrylic plastics are lighter, stronger and tougher than window glass. Polycarbonates get their name because they are polymers having functional groups linked together by carbonate groups (—O—(C=O)—O—) in the long molecular chain. Polycarbonates are stronger

Polyether ether ketone (PEEK)	
Polyphenylene sulfide (PPS)	
Polysulfone (PSU)	
Polyetherimide (PEI)	
Polycarbonate	

13.8 Thermoplastics used in aircraft.

and tougher than acrylic plastics and are used when high-impact resistance is needed, such as cockpit windows and canopies. In these applications, the material must have high impact resistance because of the risk of collision with birds. Although bird strikes do not occur at cruise altitudes, they present a serious risk at low altitudes, particularly during take-off and landing. Polycarbonate windscreens are also resistant to damage by large hailstones. Figures 13.9 and 13.10 show examples of damage caused to aircraft windows by bird strike or hail, respectively. Although the polycarbonate windows are damaged, they were impacted under severe conditions that would have caused most other polymer materials to rupture leading to cabin depressurisation. A large bird hit the window shown in Fig. 13.9 when the aircraft was flying at several hundred kilometres per hour and hailstones larger than golf balls caused the damage shown in Fig. 13.10. Had these windows been made with glass the bird and hailstones would almost certainly have punctured through and entered the cockpit. Polycarbonate windows offer good safety to the flight crew against severe impact events.

13.6.2 Crystallisation of thermoplastics

A unique property of thermoplastics is the ability of their polymer chains to be amorphous or crystalline (Fig. 13.11). Amorphous polymers consist of
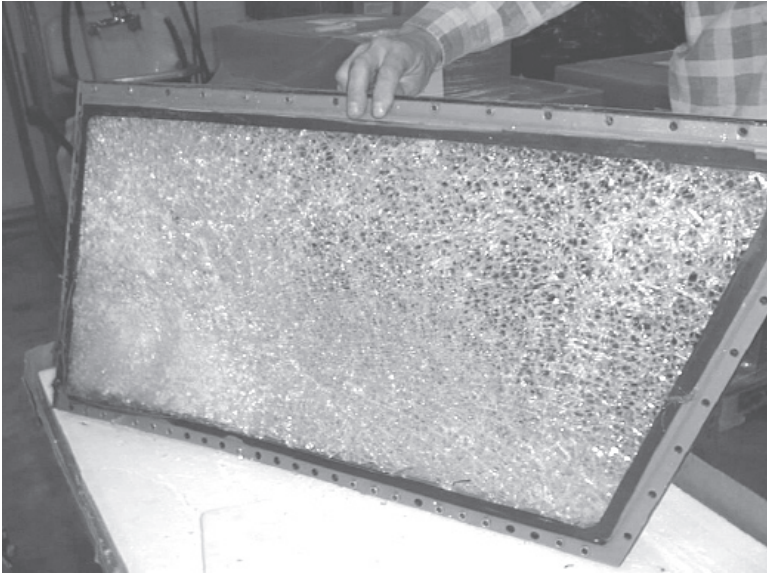
13.9 Bird strike damage to a cockpit window. Photograph reproduced with permission from AirSafe.com.

13.10 Hail damage to a cockpit window.

long chains that are randomly shaped and disordered along their length. Each chain twists and turns along its length without order, and there is no pattern with the other chains. In comparison, crystalline polymers consist of chains with a well-ordered structure. Thermosets and elastomers always occur in

the amorphous condition; crystallinity is a property unique to thermoplastics. The ability of thermoplastics to crystallise is important for their use in aircraft because crystalline polymers generally have better resistance to paint strippers, hydraulic fluids and aviation fuels, which can degrade amorphous polymers. A crystalline polymer also has higher elastic modulus and tensile strength than the same polymer in the amorphous condition.

Crystallisation occurs when a thermoplastic is cooled slowly from its melting temperature, which allows sufficient time for segments of the polymer chains to take an ordered structure. The folded chain model depicted in Fig. 13.11 is one representation of a crystallised polymer. A single chain folds back and forth over a distance of 50–200 carbon atoms, and the folded chains extend in three dimensions producing thin plates or lamellae. It is virtually impossible for thermoplastics to be completely crystalline because the entanglement and twisting of the chains stops them folding into an ordered pattern over large distances. Instead, thermoplastics can have both the amorphous and crystalline phases present together in the same material, and these are called semicrystalline thermoplastics. The crystalline phase occurs in tiny regions, typically only a few hundred angstroms wide, in which the chains are aligned. In some polymers these crystalline regions cluster into small groups known as spherulites. Surrounding these crystalline regions is the amorphous thermoplastic.

The percentage volume fraction of crystallised material within a thermoplastic typically varies from 30% to 90%, with the actual amount being determined by several factors. Crystallisation occurs more easily for linear polymers that have small side groups attached to the main chain. Thermoplastics that have large side groups or have extensive chain branching are more difficult to crystallise. For example, linear polyethylene can be crystallised to 90%

Amorphous region
Semicrystalline region
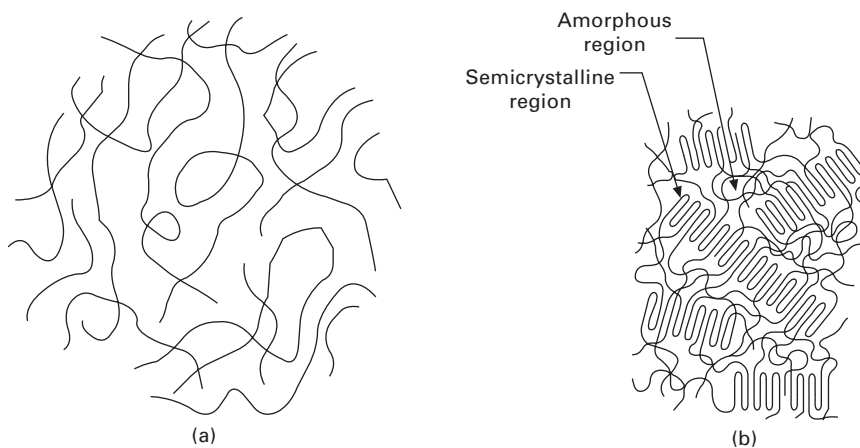
13.11 (a) Amorphous and (b) semicrystalline polymer structures.

by volume, whereas branched polyethylene can be crystallised to only 65%. This occurs because the branches interfere with the chain-folding process, thereby limiting the growth of crystalline zones. The length of the polymer chain also controls the amount of crystallisation. Crystallisation occurs more easily with shorter chains because the entanglement, which hinders crystallisation, is less.

The most common method to control the amount of crystallinity is careful management of the polymer processing conditions. Cooling a thermoplastic slowly from its melting temperature increases the amount of crystallisation because more time is given for the chains to move into an ordered pattern. Slowly deforming a thermoplastic at high temperature (but below the melting temperature) also increases crystallinity by allowing the chains to straighten in the direction of the applied stress. Lastly, the process of annealing, which involves holding the polymer at high temperature for a period of time, increases crystallinity. Often two or more of these methods are used to control the amount of crystallisation to ensure the thermoplastic has the properties best suited for a specific application.

13.7   Elastomers

13.7.1 Aerospace applications of elastomers

Elastomers are not suitable for use in aircraft structures because they lack stiffness and strength, but they do have exceptionally high elasticity with elongation values between one hundred and several thousand percent. This makes elastomers suitable when low stiffness and high elasticity is required, such as aircraft tyres, seals and gaskets. Many aircraft components that require a tight seal, such as window and door seals, use elastomers. These materials are used for their excellent elasticity; they can be easily compressed to make a tight seal without being damaged or permanently deformed. Although elastomers usually work well as seals and gaskets, they can gradually erode and degrade in harsh operating conditions, such as high temperatures. The most dramatic example of failure of an elastomer was the space shuttle *Challenger* accident. This accident is described in more detail in the case study in Section 13.15 at the end of the chapter.

### 13.7.2 Structure of elastomers

The molecular structure of elastomers is characterised by coiling of their chains. The coiled structure occurs because the chain is not balanced along its length owing to the bonding pattern and the location of side groups along the chain. Curvature of the chain is produced by the arrangement of atoms and side groups along the chain. An atom or side group R can be placed in

either the *cis* or *trans* position along the carbon chain, as shown in Fig. 13.12. The unsaturated segment of the chain is where there are C=C double bonds. In the *trans* position, the unsaturated bonds are on opposite sides, whereas in the *cis* position the unsaturated bonds are on the same side of the chain and the R groups are on the opposite side. The location of the R groups on the same side of the chain causes it to become unbalanced, and this forces the chain to coil until it finds an equilibrium position. Elastomers usually have the unsaturated bonds in the *cis* position, which causes the chain to coil like a spring. It is the coiled structure of elastomers that distinguishes them from other polymers, and gives them their very high elasticity. Coiling allows the chains to stretch like a spring and, under an applied tensile force, they can elongate to many times their original length without permanently deforming. The chains spring back into their original coiled structure when the applied load is removed.

Elastomers have some crosslinking between the chains that provides a small amount of resistance to elastic stretching. The amount of crosslinking is much less than found in the heavily crosslinked thermosets. The crosslinks in elastomers are widely spaced along the coiled polymer chains. The crosslinks between the elastomer chains are created in a process called vulcanisation. The most common vulcanisation process involves heating rubber with sulfur to temperatures of about 120 to 180 °C. Without vulcanisation, elastomers behave like a very soft solid under load. When vulcanisation is carried too far, however, the chains are too tightly bound to one another by excessive crosslinking and the elastomer is very brittle. The crosslinks also improve the wear resistance and stiffness, which is important when elastomers are to be used in aircraft tyres. These properties improve with the amount of crosslinking, but the amount of sulfur present in the elastomer should not exceed about 5% otherwise the material becomes too brittle.

Not all elastomers are crosslinked; a special group known as thermoplastic elastomers are not crosslinked but still have the elasticity of a conventional
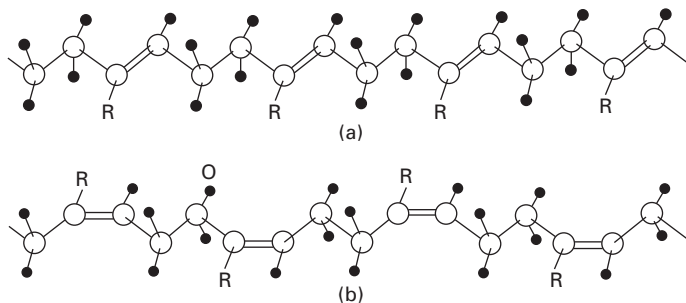
13.12 (a) *cis* and (b) *trans* structures of the polymer chain.

elastomer. As mentioned, the chain in a block copolymer is made using two types of monomers, with a long sequence of one type of monomer followed by a sequence of the other monomer type. An elastomer copolymer is made with thermoplastic and elastomer monomers, and the chains consist of long coiled lengths of the elastomer joined to shorter sections of thermoplastic. A common thermoplastic elastomer is styrene–butadiene–styrene (SBS), where the styrene is the thermoplastic-based monomer and butadiene the elastomer monomer. The SBS chains are made of short linear segments of styrene bonded to longer coiled segments of butadiene. The styrene units from a number of chains clump together, and this stops chains from sliding freely pass each other when the material is under load. The rubbery butadiene units uncoil under load providing SBS with high elasticity.

13.8   Structural adhesives

13.8.1 Aerospace applications of structural adhesives

A structural adhesive can be simply described a 'high-strength glue' that bonds together components in a load-bearing structure. Structural adhesives are used extensively in aircraft for bonding metal-to-metal, metal-to-composite and composite-to-composite parts. Adhesives are most commonly used in joints of thin aerostructures with a well-defined load path. Adhesives are also used to join thick airframe structures with complex, multidirectional load paths, although the joint is usually reinforced with fasteners such as bolts, rivets or screws for added strength and safety. Adhesives are also used to bond repair patches to damaged aircraft structures.

13.8.2 Performance of structural adhesives

Thermosets, thermoplastics and elastomers have adhesive properties, but specially formulated thermosets are used most often for bonding aircraft structures. There are many advantages of using adhesives for joining aircraft components, rather than relying solely on mechanical fasteners for strength. Adhesive bonding eliminates some, or all, of the cost and weight of fasteners in certain aircraft components. Another advantage of bonding is the reduced incidence of fatigue cracking in metal connections. Drilled holes for fasteners are potential sites for the start of fatigue cracks, and removing the need for holes by bonding reduces this particular problem. Adhesive bonding has the advantage of providing a more uniform stress distribution in the connection by eliminating the individual stress concentrations at fastener holes. Bonded joints are usually lighter than mechanically fastened joints and enable the design of smooth external surfaces. In addition to joining structural components, adhesives are used for bonding the skins and core

in sandwich composites. Figure 13.13 shows the application of adhesively bonded sandwich composites in an aircraft.

The adhesive must have high elastic modulus, strength and toughness. Toughening agents (such as tiny rubber particles) are often blended into the adhesive to increase fracture toughness. Structural adhesives must have low shrinkage properties when cured to avoid the development of residual stresses in the joint. Adhesives must also be resistant to attack or degradation in the operating environment. Water and liquids such as solvents (paint strippers), hydraulic fluids and aviation fuel can attack the bond between the adhesive and substrate, and therefore durable adhesive systems must be used.

Structural adhesives with the best mechanical properties and durability are useless unless they can bond strongly to the substrate. The type of adhesive

Kevlar–honeycomb sandwich

Graphite–honeycomb sandwich

Adhesive bonded skins, doublers, stringers, ribs and frames

Adhesive bonded skins and doublers

Fibreglass

Aluminium skin–honeycomb core

Kevlar

13.13 Application of adhesively bonded sandwich composites in the *Citation* III aircraft.

used is critical to ensure strong adhesion. However, surface preparation of the substrate is the keystone upon which the adhesive bond is formed. The substrate must be grit blasted or lightly abraded, cleaned, dried, and then treated with a chemical coupling agent to ensure good adhesion. If the substrate surface is not suitably prepared, the adhesive fails owing to poor bonding.

13.8.3 Types of structural adhesives

The thermosetting adhesives used in aircraft structures are crosslinked polymers that are cured using heat, pressure or a combination of heat and pressure. Heat-curing adhesives are cured at temperatures close to (or preferably slightly over) the maximum-use temperature of the structure. Adhesives are available as films or pastes. Film adhesives are often used in bonding aircraft structures because they usually provide higher strength than paste adhesives. The film is simply placed between the substrates and then heated and pressurised to form a strong bond. Adhesive pastes can be a one-part system that is simply spread on the substrates and cured by heat and/or pressure. Alternatively, two-part systems consisting of resin and hardener are mixed together into an adhesive paste, which is then applied to the substrates.

The polymer most often used as a structural adhesive is epoxy resin because of its ability to adhere to most surfaces (including aircraft-grade aluminium alloys and fibre composites), high strength, and long-term durability over a wide range of temperatures and environments. Silicone is often used when a high toughness adhesive is needed, whereas bismaleimide and polyimide are used when a high-temperature adhesive is required. Other types of adhesives include urethanes, phenolic resins, acrylic resins and inorganic cements, although they are rarely used for bonding aircraft structures. Hot-melt adhesives are used occasionally, although not in highly-loaded aircraft structures. Hot-melt adhesives are thermoplastics or thermoplastic elastomers that melt when heated. On cooling the polymer solidifies and forms a bond with the substrate. Most commercial hot-melt adhesives soften at 80 to 110 °C, which makes them unsuitable as a high-temperature adhesive. Pressure sensitive adhesives (PSA) are usually elastomers or elastomer copolymers that are not crosslinked or are only slightly crosslinked and they bond strongly with a substrate. PSAs adhere simply by the application of pressure, and the most common (but obviously non-aerospace type) is Scotch® tape. Most PSAs are not suitable for joining aircraft structures because of their low strength at elevated temperature.

13.9   Mechanical properties of polymers

13.9.1 Deformation and failure of polymers

Polymers deform elastically and plastically when under load, much like metals. However, the deformation processes for polymers are different to those for metals. The elastic deformation of metals involves elastic stretching of the bonds in the crystal structure and plastic deformation involves dislocation slip. Polymers do not have crystal structures as found in metals nor do they contain dislocations, and so the processes responsible for deformation are different from those for metals.

Tensile stress–strain curves for a thermoplastic, thermosetting polymer and elastomer are presented in Fig. 13.14. These curves are representative of the stress response of these different types of polymers, where the elongation-to-failure increases in the order: thermoset, thermoplastic, elastomer. The curves can be divided into three regimes that are controlled by different deformation processes: elastic, plastic and fracture regimes.

Elastic deformation

When an elastic stress is applied to a polymer, the chains are stretched in the loading direction. Elastic stretching occurs in the covalent bonds between the atoms along the chain backbone. Stretching also involves some straightening of twisted segments of the chain. The stretching of the bonds and the twisted segments of the polymer chains increases with the applied stress. However,
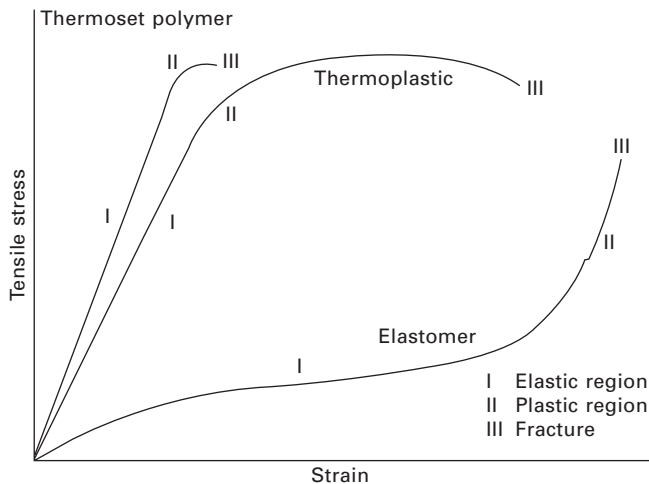
13.14 Typical stress–strain curves for a thermoplastic, thermoset polymer and elastomer.

when the load is removed the chains relax back into their original position. The slope of the stress–strain curve in the elastic regime is rectilinear for thermoplastics and thermosets, and is used to calculate material stiffness, i.e. Young's modulus.

The situation is different for many elastomers, which do not have a rectilinear strain–stress response in the elastic regime. Instead, the apparent elastic modulus for elastomers decreases with increasing strain as the chains begin to uncoil and stretch in the load direction. The elastomer chains are so tightly coiled that they can be stretched many times their original length before there is any significant resistance to loading. As the chains start to straighten, the stiffness begins to increase owing to elastic stretching of the bonds within the chain and the crosslinking bonds between the chains. Because elastomers are not heavily crosslinked, the chains can stretch without a large amount of resistance from the crosslinking bonds. At any point in the elastic regime, the elastomer reverts back to its original shape (in the absence of creep) when the load is removed. Elastic recovery occurs by the bonds along the chains and the crosslinking bonds between the chains relaxing into their original state, allowing the chains to return to their original coiled position.

Plastic deformation

An amorphous polymer plastically deforms when the applied stress exceeds the yield strength. The yielding mechanisms are complicated and involve the stretching, rotation, sliding and disentanglement of the chains under load deformation. Eventually the chains become almost aligned parallel and close together and, at this point, the polymer reaches its ultimate strength. Plastic deformation of thermosets is resisted by the crosslinks and, therefore, the yield strength of these polymers is often higher than thermoplastics. The lack of crosslinks in amorphous thermoplastics allows the chains to stretch, slide and disentangle more readily than in thermosets, which results in greater ductility and toughness.

The yielding process in semicrystalline thermoplastics is a combination of the deformation processes just described for amorphous polymers together with different processes for the crystalline phase. When a tensile load is applied, the crystalline lamellae slide past one another and begin to separate as the chains are stretched. The folds in the lamellae tilt and become aligned in the load direction; at this stage the ultimate strength is reached.

Fracture

The process leading to fracture of polymers starts with the breaking of the weakest or most highly strained segments of the polymer chains. For

thermoplastics, this occurs along the backbone of the chains, whereas in thermosets and elastomers it can start by the breaking of crosslinks. The breaking of the chains continues under increasing strain until micrometre-sized voids develop at the most damaged regions, as shown in Fig. 13.15. These voids grow in size and coalesce into cracks until the polymer eventually breaks.

13.9.2 Engineering properties of polymers

Table 13.3 gives the mechanical properties of thermoplastics, thermosetting polymers and elastomers that have current or potential aerospace applications. The values are the average properties, which can vary owing to changes in the chemical state and processing conditions of the polymer. The Young's modulus of thermoplastics and thermosets is in the range of 2–6 GPa, which is much smaller than the elastic modulus of aluminium alloys (70 GPa), titanium alloys (110 GPa), steels (210 GPa) and other metals used in aircraft. Likewise, the tensile strength of most polymers is under 100 MPa, which is well below the strength of the aerospace alloys. It is because of the low mechanical properties that polymers are not used in heavily loaded aircraft structures.

The tensile strength of polymers can be controlled in several ways:

- Increasing the degree of polymerisation. The strength properties of polymers increase with the length of the chains, which is controlled by the degree of polymerisation. For example, the tensile strength of polyethylene is directly related to the chain length, which is defined by the molecular weight (MW). Low-density polyethylene (MW ~ 200 000
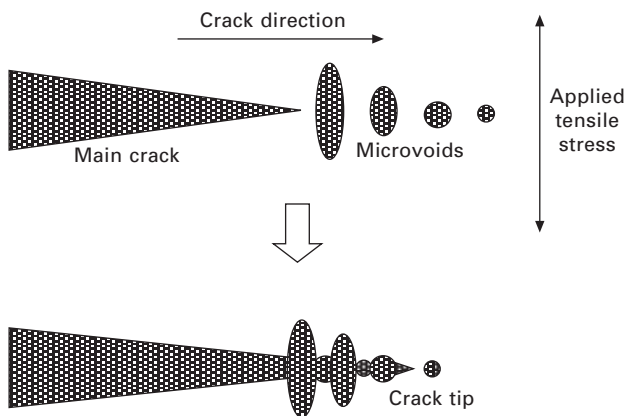
13.15 Schematic showing tensile failure of a polymer by the formation and coalescence of voids.

Table 13.3 Tensile properties of polymers used in aircraft

	Young's modulus (GPa)	Tensile strength (MPa)	Elongation-to-failure (%)
Thermoplastic			
Polyether ether ketone (PEEK)	3.7	96	50
Polyether ketone (PEK)	4.6	110	12
Polyphenylene sulfide (PPS)	6.0	110	12
Polysulfone (PSU)	2.4	68	40
Polyether sulfone (PES)	2.3	81	80
Polyaryl sulfone (PAS)	2.7	75	8
Polyetherimide (PEI)	3.7	100	42
Polycarbonate (PC)	2.7	73	130
Thermoset			
Epoxy	4.5	85	3.0
Phenolic	6	55	1.7
Bismaleimide (524C)	3.3	50	2.9
Polyimide (PMR15)	4.0	65	6.0
Cyanate ester	3.0	80	3.2
Elastomer			
Polyisoprene		20	800
Polybutadiene		23	
Polyisobutylene		27	350
Polychloroprene (Neoprene)		23	800
Butadiene–styrene		30	2000
Thermoplastic elastomer		33	1300
Silicone		7	700

monomer units) has a tensile strength of about 20 MPa, high-density polyethylene (MW ~ 500 000 monomer units) has the strength of 37 MPa, and ultra-high-density polyethylene (MW ~ 4 500 000 monomer units) the strength of 60 MPa. The strength increases with the chain length because they become more tangled and, therefore, a higher stress is needed to stretch and untangle them. The strength increases with the chain length up a limit beyond which further polymerisation does not add extra strength.

- Increasing the size of side groups attached to the main chain. Strength is increased by adding larger atoms or groups to the side of the chain backbone. This makes it more difficult for the chains to rotate, uncoil and disentangle when under load, thereby increasing strength. For example, polyetherimide (PEI) which has relatively large side groups has the tensile strength of about 100 MPa whereas polyphenylene sulfide (PPS) with no large side groups has the strength of only 60 MPa.

- Increasing the amount of chain branching. The strength is increased by extensive chain branching. A high density of branches along the main chain provides resistance against the stretching, sliding and disentanglement of neighbouring chains and, thereby, increases the strength. However,

too much branching can prevent the close packing and crystallisation of the chains and, thereby, reduce the strength.
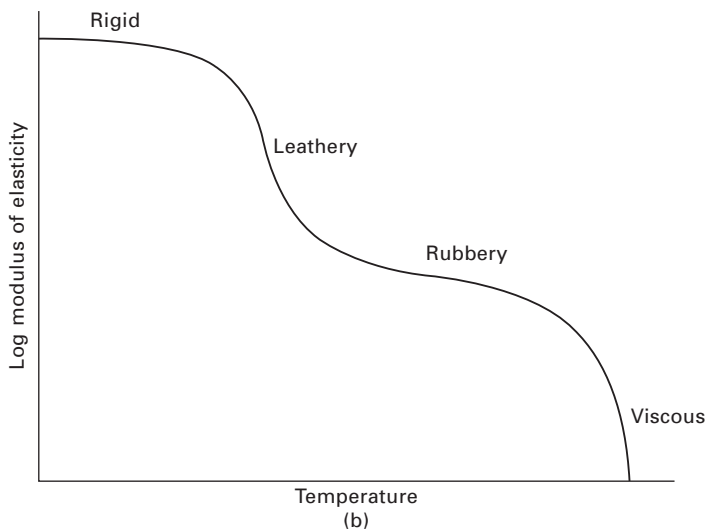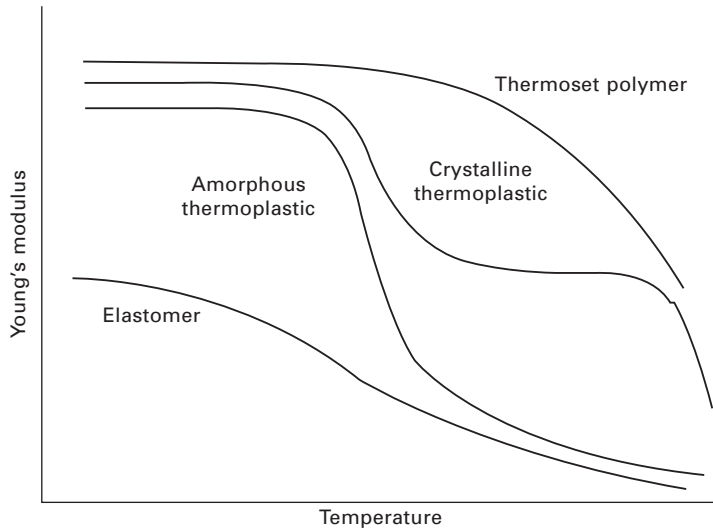
- Increasing the degree of crosslinking (for thermosets and elastomers). The strength increases with the number density of crosslinks between the chains.

- Increasing the degree of crystallisation (for thermoplastics). The strength increases with the volume percentage of thermoplastic that is crystallised. This is because a higher load is needed to permanently deform polymer chains when in a crystallised state rather than the amorphous condition.

Table 13.3 shows that thermosets have low ductility, with elongation-to-failure usually below 5%. This is because the high density of crosslinks between the chains resists extensive plastic deformation of the polymer. Many thermoplastics have high elongation-to-failure (above 50%), although their ductility decreases with increasing crystallinity. Elastomers have exceptionally high elongation-to-failure, in the range of several hundred to several thousand percent, because of their coiled chain structure.

13.9.3 Thermal properties of polymers

An important consideration in the use of polymers is softening that occurs owing to heating effects, such as the frictional heating of aircraft skins at fast flight speeds or the operating temperature of engine components. Polymers lose stiffness, strength and other properties at moderate temperature. Although other aerospace materials, including the metal alloys we have discussed, also lose mechanical performance when heated, the properties of polymers are reduced at much lower temperatures. The mechanical properties of most polymers drop sharply above 100–150 °C, and therefore their use in fibre composite airframe, bonded joints, engine components and other structural applications must be confined to lower temperatures. For high-temperature conditions, several polymer systems can be used, such as bismaleimides, polyimides and cyanates, but even here the maximum operating temperature is below 200–220 °C.

The effect of increasing temperature on the Young's modulus of polymers is shown in Fig. 13.16. At low temperature there is low internal energy within the polymer and, therefore, the chains are 'sluggish' and difficult to move under an applied force. In crystalline polymers, the sluggish behaviour makes it difficult for the chains to unfold and align themselves in the load direction. In amorphous polymers, the chains lack the energy to slide and move through the tangled network in order to align in the load direction. The ability of polymers to undergo large deformations is suppressed at low temperatures and they are more likely to resist the applied load, thus becoming

Young's modulus

Thermoset polymer

Crystalline
thermoplastic

Amorphous
thermoplastic

Elastomer

Temperature
(a)

Log modulus of elasticity

Rigid

Leathery

Rubbery

Viscous

Temperature
(b)

13.16 Variation of (a) Young's modulus with temperature and (b) deformability with temperature.

stiff, strong and brittle. In this condition, polymers are often described as being glassy. When the temperature is raised more energy is available to the polymer chains to move under load. This is observed as a reduction in the elastic modulus and strength and an increase in the ductility (elongation-to-failure). When an amorphous polymer transforms from a rigid, brittle material to a soft, ductile material with increasing temperature it is described as converting from a glassy state to a rubbery state. Crystalline materials

go through two stages of softening: a glassy-to-leathery transformation as the crystalline chains begin to unfold and assume an amorphous state, and a leathery-to-rubbery transformation as the chains are easily deformed under load.

Two properties are used to define the softening temperature of polymers: heat deflection temperature (HDT) and glass transition temperature (T_g). The HDT is a measure of the ability of the polymer to resist deformation under load at elevated temperature. The definition of the HDT is simply the temperature required to deflect a polymer by a certain amount under heat and load. The stress applied to the polymer is usually 0.46 MPa (66 psi) or 1.8 MPa (264 psi). The higher the HDT then the greater is the temperature needed to deform a polymer when under load. The HDT is also sometimes called the 'deflection temperature under load' or 'heat deflection temperature'. A polymer used in an aircraft part should not exceed an operating temperature of about 80% of the HDT to avoid the likelihood of distortion.

The glass transition temperature T_g is used more often than the HDT to define the softening temperature of polymers. The T_g can be defined as the temperature when an amorphous polymer undergoes the glassy-to-rubbery transformation and there is a significant change in properties.

Below the T_g, the polymer is glassy and hard whereas above the T_g it is rubbery and soft. Many physical properties change suddenly around the T_g, including the viscosity, elastic modulus and strength and, therefore, it is considered an important property for defining the temperature operating limit of polymers. The T_g of various aerospace polymers are given in Table 13.4. It is common practice to set the maximum operating temperature of polymers as the glass transition temperature less a certain temperature interval such as 30 °C (i.e. $T_{max} = T_g - 30$ °C). This ensures that polymers do not suffer excessive softening during service. The T_g of elastomers is below room temperature, and therefore they respond as a rubbery and soft material under normal operating conditions. Elastomers with a low T_g are often used in seals because they are soft and compliant at most operating temperatures for aircraft.

Table 13.4 also gives the average melting temperatures for the thermoplastics, which is usually 1.5 to 2 times higher than the glass transition temperature. Thermosets do not have a melting temperature because the crosslinks stop the chains flowing like a liquid, and instead these polymers decompose at high temperature without melting.

13.10   Polymer additives

Additives are often blended into polymers during processing to improve one or more properties. Additives include chemical pigments to give colour;

Table 13.4 Temperature properties of aerospace polymers

	Glass transition temperature (°C)	Melting temperature (°C)
Thermoplastics		
Polyether ether ketone (PEEK)	140	245
Polyphenylene sulfide (PPS)	75	285
Polyetherimide (PEI)	218	220
Polycarbonate (PC)	150	155
Thermosets		
Polyester	110	–
Vinyl ester	120	–
Epoxy	110–220	–
Phenolic	100–180	–
Bismaleimide	220	–
Polyimide	340	–
Cyanate ester	250–290	–
Elastomers		
Polybutadiene	–90	120
Polychloroprene	–50	80
Polyisoprene	–73	30

filler particles to reduce cost, increase mechanical performance and provide dimensional stability; toughening agents and plasticisers to increase fracture toughness and ductility; stabilisers to increase operating temperature or resistance against ultraviolet radiation; and flame retardants. An important class of additives is fibrous fillers, such as glass, carbon, boron and aramid fibres, used as the reinforcement in fibre–polymer composites, which are described in chapters 14 and 15.

Additives are not always used in polymers for aircraft applications, and when they are used it is often for a specific purpose. Additives may be included in the polymer matrix phase of fibre composites to increase flame resistance and environmental durability. Additives are often used in structural adhesives to increase toughness and durability, particularly against hot–wet conditions. Elastomers used for aircraft tyres contain filler particles called carbon black to increase the tensile strength and wear resistance.

Toughening agents are used in thermosets to increase the fracture toughness, ductility and impact hardness. High-strength thermosets, such as epoxy resins, have low ductility with strain-to-failure values as low as a few percent. Adhesives used in aircraft structural joints require high ductility and fracture toughness and, therefore, toughening agents are used to improve fracture toughness. The most common toughening agent comprises small particles of rubber, usually carboxyl-terminated butadiene nitrile (CTBN) rubber. The rubber particles are only a few micrometres in size and are dispersed

through the adhesive to impede crack growth. Fine thermoplastic fillers are also used as toughening agents.

Plasticisers are additives used to increase the toughness of crystalline thermoplastics, in which rubber toughening particles (such as CTBN) are usually ineffective. Plasticisers are low-molecular-weight polymers that increase the spacing between chains of crystalline polymer to make them more flexible and, thereby, tougher.

A safety concern with using polymers and polymer composites in aircraft is fire. Most polymers are flammable and release large amounts of heat, smoke and fumes when they burn. It is often necessary to use flame-retardant additives in polymers to achieve the fire resistant standards specified by safety regulators such as the FAA. Many types of additives are used to improve the flammability resistance of polymers, with the most common containing halogenated or phosphorus compounds. Flame-retardant additives are either discrete particles within the polymer or are chemically incorporated into the polymer chain structure. New and more effective flame retardant additives are being developed, with carbon nanotubes (see chapter 14) offering new possibilities for increased fire resistance combined with improved mechanical performance.

13.11   Polymers for radar-absorbing materials (RAMs)

Radar is the most common technique for the detection and tracking of aircraft. Although radar is an indispensable tool in aviation traffic management, it is a problem in offensive military operations which require aircraft to attack their target and then escape without being detected. Radar involves the transmission of electromagnetic waves into the atmosphere; they are then reflected off the aircraft back to a receiving antenna. Conventional aircraft, such as passenger airliners, are easily detected by radar because of their cylindrical shape together with bumps from the engines and tail plane. Metals used in the aircraft are also strong reflectors of electromagnetic waves, and can be easily detected using radar. Composites are also detected using radar, although usually not as easily as metals.

Radar-absorbing material (RAM) is a specialist class of polymer-based material applied to the surface of stealth military aircraft, such as the F-22 *Raptor* and F-35 *Lightning II* (Fig. 13.19), to reduce the radar cross-section and thereby make them harder to detect by radar. These materials are also applied in stealth versions of tactical unmanned aerial systems, such as the Boeing X-45. RAM is applied over the entire external skin or (more often) to regions of high radar reflection such as surface edges. RAM works on the principle of the aircraft absorbing the electromagnetic wave energy to minimise the intensity of the reflected signal. RAMs are used in combination with other stealth technologies, such as planar design and hidden engines,

(a)

(b)

13.17 Examples of stealth aircraft that use radar-absorbing materials: (a) F-22 *Raptor* and (b) F-35 *Lightning* II. (a) Photograph supplied courtesy of S. Austen. (b) Photograph supplied courtesy of B. Lockett, Air-and-Space.com.

to make military aircraft difficult to detect. It is possible to reduce the radar cross-section of a fighter aircraft to the size of a mid-sized bird through the optimum design and application of stealth technologies.

Information about the composition of RAMs is guarded by the military. Most RAMs consist of ferromagnetic particles embedded in a polymer matrix having a high dielectric constant. One of the most common RAMs is called iron ball paint, which contains tiny metal-coated spheres suspended in an epoxy-based paint. The spheres are coated with ferrite or carbonyl iron. When electromagnetic radiation enters iron ball paint it is absorbed by

the ferrite or carbonyl iron molecules which causes them to oscillate. The molecular oscillations then decay with the release of heat, and this is an effective mechanism of damping electromagnetic waves. The small amount of heat generated by the oscillations is conducted into the airframe where it dissipates.

Another type of RAM consists of neoprene sheet containing ferrite or carbon black particles. This material, which was used on early versions of the F-117A *Nighthawk*, works on the same principle as iron ball paint by converting the radar waves to heat. The USAF has introduced radar-absorbent paints made from ferrofluidic and nonmagnetic materials to some of their stealth aircraft. Ferrofluids are colloidal mixtures composed of nano-sized ferromagnetic particles (under 10 nm) suspended in a carrier medium. Ferrofluids are superparamagnetic, which means they are strongly polarised by electromagnetic radiation. When the fluid is subjected to a sufficiently strong electromagnetic field the polarisation causes corrugations to form on the surface. The electromagnetic energy used to form these corrugations weakens or eliminates the energy of the reflected radar signal. RAM cannot absorb radar at all frequencies. The composition and morphology of the material is carefully tailored to absorb radar waves over a specific frequency band.

13.12   Summary

There are three main classes of polymers: thermosets, thermoplastics and elastomers. The polymers most often used in aircraft are thermosets such as epoxy resins and bismaleimides, which are used as the matrix phase in fibre composites and as structural adhesives. The aerospace applications for thermoplastics and elastomers is much less.

The properties of polymers that make them useful aerospace materials are low weight, excellent corrosion resistance and good ductility. Some polymers are also transparent for use in window applications. However, polymers have low stiffness, strength, fatigue life and creep resistance and, therefore, should not be used on their own in structural applications.

Polymers are produced by polymerisation reactions called addition or condensation reactions, which join the monomer units together into long chain-like macromolecules. The chemical and physical structure of the molecular chains has a major influence on the mechanical properties. Thermosets have higher stiffness, strength and creep resistance compared with thermoplastics because the molecular chains are interconnected by crosslinks. These crosslinks resist the sliding of chains under stress and, thereby, increase the mechanical properties.

Epoxy resin is the most used polymer for aerospace, and finds applications in carbon-fibre composites and as a structural adhesive. Epoxy resin has good stiffness, strength and environmental durability and can be cured at moderate

temperatures (under 180 °C) with little shrinkage. Other thermosets used in composite materials include bismaleimide and polyimide, which are suited for high-temperature applications. Phenolic resin has excellent flammability resistance and is used in moulded parts and composites for cabin interiors.

Thermoplastics have high toughness, ductility and impact resistance, but the high cost of processing and low creep resistance limits their use in aerospace. Thermoplastics such as PEEK are used as the matrix phase in fibre composites requiring impact toughness. Polycarbonate is used for aircraft windows because of its high transparency, scratch resistance and impact strength.

Elastomers lack the stiffness and strength needed for aerospace applications, although their high elasticity makes them useful as a sealing material. Elastomers have high elasticity owing to their coiled molecular structure which responds under load in a similar way to a spring.

Adhesives used for bonding aircraft components and sandwich composites are usually thermosets, such as epoxy resin. Adhesives must have low shrinkage during curing to avoid the formation of residual tensile stress in the bond. Correct surface preparation is essential to ensure a high strength and durable bond is achieved with a polymer adhesive.

The mechanical properties of polymers are inferior to aerospace structural metals, and their use is restricted to relatively low-temperature applications. Polymers transform from a hard and glassy condition to a soft and rubbery state during heating, and the maximum working temperature is defined by the heat-deflection temperature or glass transition temperature.

Polymers often contain additives for special functions such as colour, toughness or fire.

Radar-absorbing materials (RAMs) are a special class of polymer that convert radar (electromagnetic) energy to some other form of energy (e.g. heat) and thereby improve the stealth of military aircraft. RAM must be used with other stealth technologies such as design adaptations of the aircraft shape to minimise the radar cross-section.

13.13   Terminology

Addition polymerisation: Polymerisation process where monomer molecules add to a growing polymer chain one at a time.

Amorphous: Amorphous polymer is a material in which there is no long-range order in the positions and arrangement of the molecular chains.

Atactic: Polymer chain configuration in which the side groups are positioned randomly on one or the other side of the polymer back-bone.

Block copolymer: Polymer formed when two different types of monomer are linked in the same polymer chain and occur as alternating sequences (blocks) of each type.

Condensation polymerisation: Polymerisation process involving the reaction of monomer molecules that produces a polymer chain and chemical by-products that do not form part of the chain structure.

Copolymer: A polymer whose chemical structure consists of long chains of two chemically different monomers, which repeat at more or less regular intervals in the chain.

Crosslinks: Covalent bonds linking one polymer chain to another chain.

Crystalline: Polymer with a regular order or pattern of molecular arrangement.

Elastomer: A type of polymer with coiled molecular chains that are crosslinked.

Glass transition temperature: Temperature at which a reversible change occurs in a polymer when it is heated to a certain temperature and undergoes a transition from a hard and glassy to a soft and ductile condition.

Graft copolymer: A special type of branched polymer with the main backbone to the chain composed of one type of monomer while the branches are composed of a chemically different monomer.

Heat deflection temperature: Temperature at which a material begins to soften and deflect (usually by 0.010 inches) under load (usually 264 psi).

Homopolymer: Polymer which is formed from only one type of monomer.

Isotactic: Polymer chain configuration in which the side groups are all located on same side of the polymer back-bone.

Molecular weight: A number defining how heavy one molecule (or unit) of a chemical is compared with the lightest element, hydrogen, which has a weight of 1.

Monomer: Chemical compound that can undergo polymerisation, which is a chemical reaction in which two or more molecules combine to form a larger molecule that contains repeating units.

Polymerisation: Chemical reaction in which small molecules combine to form a larger molecule that contains repeating units of the original molecules. It is a process of reacting monomer molecules together in a chemical reaction to form linear chains or a three-dimensional network of polymer chains.

Radar cross-section: A measure of how detectable an object such as an aircraft or helicopter is with radar. A larger radar cross-section indicates that the object is more easily detected.

Stress rupture: The fracture of a material after carrying a sustained load for an extended period of time; it usually involves viscoelastic deformation and occurs more rapidly at elevated temperature.

Syndiotactic: Polymer chain configuration in which the side groups are located at alternate positions along the polymer backbone.

Thermoplastic: Polymer which may be softened by heat and hardened by cooling in a reversible physical process owing to the lack of crosslinks between the chains.

Thermoset: Thermosetting polymer obtained by crosslinking of the chains that make it an infusible and insoluble material.

Van der Waals bond: A weak attractive force between atoms or nonpolar molecules caused by a temporary change in dipole moment arising from a brief shift of orbital electrons to one side of one atom or molecule, creating a similar shift in adjacent atoms or molecules.

Vulcanisation: Chemical reaction whereby the properties of an elastomer are changed by causing it to react with sulfur or another crosslinking agent.

13.14   Further reading and research

Ebnesajjad, S., *Adhesives technology handbook*, William Andrew Inc., 2008.

May, C. A., *Epoxy resins: chemistry and technology*, Marcel Dekker, 1988.

Powell, P. C. and Ingen Housz, A.J., *Engineering with polymers*, Stanley Thornes, 1998.

Tadmor, Z. and Gogos, C. G., *Principles of polymer processing (2nd edition)*, Wiley Interscience, 2006.

Ward, I. M. and Sweeney, J., *An introduction to the mechanical properties of solid polymers*, John Wiley & Sons, 2004.

13.15   Case study: space shuttle *Challenger* accident

The space shuttle *Challenger* (STS-51) exploded just over one minute after take-off on 28 January 1986, killing seven astronauts. After an exhaustive investigation by NASA and other US agencies the cause of the accident was found. The space shuttle is fitted with two solid rocket boosters that generate an extraordinary amount of thrust during take-off that launches the main vehicle into space. Without the boosters the shuttle cannot generate enough thrust to overcome the gravitational pull of Earth. There is a booster rocket attached to each side of the external fuel tank, and each booster is 36 m long and 7.3 m in diameter (Fig. 13.18). The boosters are constructed from hollow metal cylinders, with the joint connecting the cylinders containing two O-rings made with an elastomer. The elastomer is needed to create a tight seal to prevent hot gases escaping from the rocket motor during take-off.

The *Challenger* accident was caused by several factors, with a critical problem being that one of the elastomer O-rings in a booster rocket did not form a tight seal owing to cold weather during take-off. Elastomers shrink and lose elasticity at low temperature and, at take-off, the O-ring was unable to expand sufficiently to form a seal between two cylinders. This caused hot combustion gases (over 5000 °F) inside the rocket motor to rapidly degrade the elastomer O-ring, thus allowing hundreds of tons of propellant to escape and ignite, thereby causing the space shuttle to explode (Fig. 13.19).

13.18 Rocket boosters on the space shuttle. Photograph reproduced with permission from NASA.

13.19 Explosion of the space shuttle *Challenger* (STS-51).