Chapter 26
Elastomers and Adhesives for Aerospace Applications

C.M. Bhuvaneswari, Shirish S. Kale, G. Gouda, P. Jayapal and K. Tamilmani

Abstract This chapter deals with the varieties and characteristics of elastomers and adhesives used in the aerospace industry. The key terms, various grades, structure and properties of each elastomer are discussed. An outline of rubber compounding and vulcanisation is presented. Significant elastomer properties for aerospace applications are highlighted. Further, an adhesives section includes the varieties of adhesives, mechanism of adhesive bonding, surface preparation, and joint designs for some loading conditions. Applications of elastomers and adhesives in the aerospace field are also surveyed.

Keywords Elastomers · Adhesives · Mechanical properties · Fluid resistance · Adhesive bonding · Applications

26.1 Elastomers

26.1.1 Introduction

Elastomers are elastic materials that recover to almost their original shape after complete release of the applied force [1]. Elastomers are characterized by large deformability, low shape rigidity, large energy storage capacity, nonlinear stress–strain curves, high hysteresis and a large variation of stiffness with temperature and

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rate of loading [1]. Particular combinations of these properties make elastomers suitable for aerospace applications.

Many aircraft components use elastomers as O rings, gaskets, canopy window or door seals, firewall seals, lip seals and T seals. Elastomers can be compressed to make a tight seal owing to their excellent elasticity without damage or permanent deformation. Characteristics like superior tear strength and excellent resistance to heat build-up make elastomers well-suited for high-performance aircraft tyres. The high damping capacity of elastomers solves dynamic problems in many fields, including space applications. For example, elastomeric shock absorbers and passive dampers are mounted onboard launchers and satellites [2].

26.1.2 Varieties of Elastomers

Natural rubber was the only source of rubber until the advent of synthetic polymers in the early part of the twentieth century. The natural and synthetic rubbers are the two classes of commercial rubber products. The source of natural rubber is the latex obtained from rubber trees. The purified form of natural rubber is the chemical polyisoprene, which can also be produced synthetically. Synthetic rubbers are produced by two important stages: the primary step is the production of monomers, followed by polymerization of monomers. Some of the most important synthetic rubbers are acrylonitrile butadiene, polychloroprene, chlorosulphonated polyethylene, butyl, polybutadiene, silicone, ethylene propylene and fluoropolymers.

The basic chemical structure of each elastomer dictates most of the properties such as oil and fuel resistance, ozone, heat and weathering resistance. The fuel resistance of acrylonitrile butadiene rubber (NBR), weathering resistance of ethylene propylene diene monomer (EPDM), or the high resilience of natural rubber significantly determine the suitability of an elastomer for any given application.

26.1.3 Elastomer Compounding

Compounding is the process of mixing elastomers with various additives and curatives to enhance the properties. Compounding is carried out to tailor the properties of elastomers according to the functional requirements [3]. According to the nature of the additives, properties like increases of modulus, ozone resistance, flame resistance, and electrical conductivity can be achieved.

The processing method also plays a major role in the product performance. Manufacturing of rubber compounds involves mixing, forming and curing. The two main types of mixing machines are two-roll rubber mixing mills and internal mixers. The latter are extensively used for large quantity mixing. Internal mixers generate high shear forces that disperse and mix the fillers and raw materials into a uniform quality compound. After mixing, the compound is fed into a mill. The

two-roll rubber mixing mill disperses the reinforcing fillers within the polymer by repeated milling. The next manufacturing stage is forming the compound to the required shape by an extrusion process.

Compounding ingredients [4] may be categorized as:

- Base polymer (natural or synthetic rubber)
- Curing or vulcanising agents
- Accelerators, accelerator activators and retarders
- Stabilizer systems (antioxidants and anti-ozonants)
- Processing aids (plasticizers, softeners, tackifiers, etc.)
- Reinforcing fillers (carbon black, silica, mineral fillers) and resins
- Inert fillers and diluents
- Special additives (abrasives, blowing agents, colours, pigments, deodorants, etc.).

26.1.4   Vulcanising

Vulcanising is the process of applying heat for specific temperatures and times. The selection of temperature and time depends on the type of elastomer. The properly mixed elastomer compounds can be vulcanised by one of many processes [5], such as moulding, autoclaving or oven curing, etc. The vulcanising process can be batch or continuous curing. During vulcanising the following changes occur:

- The vulcanising agent reacts with the long chains of the rubber molecules and forms cross-links to form three-dimensional structures as shown in Fig. 26.1. The cross-links resist the large molecular chains slipping past each other under the application of external forces.
- The cross-linked rubber becomes a solid elastomer with improved strength and resistance to degradation.

Fig. 26.1 Schematic representation of polymer chains before and after vulcanising [7]

Elastomer
No cross-links

Elastomer
Cross-linked
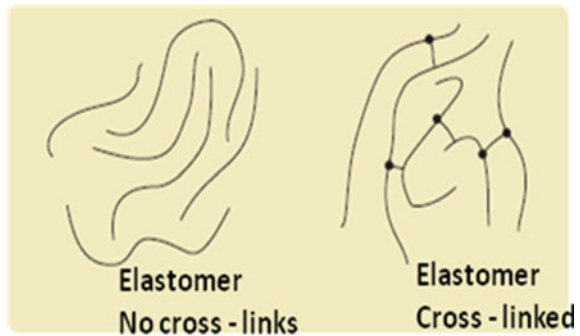
The most common vulcanising agents are sulphur and peroxide [6]. Unsaturated elastomers (with double bonds in the backbones) are vulcanized by sulphur, forming carbon—sulphur—carbon bonds. Saturated elastomers cannot be vulcanised by sulphur and accelerators: organic peroxides are necessary. The peroxides give rise to carbon—carbon bonds, which are quite stable.

26.1.5   Elastomer Types and Properties [8–10]

Elastomers are classified according to chemical composition. ASTM D 1418 classifies elastomers and gives a set of abbreviations as shown in Table 26.1.

For example, elastomers with only carbon atoms in the main chain and no double bonds (reactive areas) are referred to as M-types. If the elastomer main chains contain double bonds, these elastomers are referred as R-types. These are also referred to as unsaturated or diene rubbers.

The main chains containing only alternating silicon and oxygen atoms are called Polysiloxanes. These elastomers are known as silicone rubbers and referred to as Q-types. Table 26.2 clearly illustrates the variety of elastomers and their chemical and trade names. The following paragraphs discuss the important elastomers [8–10] that are useful in the aerospace industry:

(i)   Natural rubber (NR)

The chemical name of NR is cis-1,4 polyisoprene. The molecular structure is given in Fig. 26.2. NR is made by the coagulation and drying of aqueous milky sap from rubber trees (Hevea brasiliensis).

Due to the superior structural regularity and strain crystallization, NR acquires high strength. This property is exploited for applications requiring abrasion or wear resistance, and damping or shock-absorbing. Hence NR is used in large truck tyres, off-road giant tyres and aircraft tyres [11, 12]. It is resistant to acids, alkalis and alcohol, but has poor resistance to atmospheric oxygen, ozone and fuel.
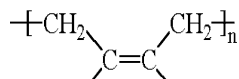
Fig. 26.2 Molecular structure of NR

Table 26.1   Classification of elastomers [10]

| Last letter in the abbreviation: meaning	Examples
M: saturated chains of carbon atoms, no double bonds	EPDM, FKM, FFKM
R: double bonds in the carbon chain (unsaturated)	NR, CR, SR, SBR, IIR, NBR, HNBR
O: oxygen in the polymer chain	Epichlorohydrin rubber
Q: silicon and oxygen in the polymer chain	VMO, FVMQ
T: sulphur in the polymer chain	Polysulphide elastomer
U: carbon, oxygen, and nitrogen in the polymer chain	Polyurethane rubber

Table 26.2 Elastomer chemical and trade names [8]

ASTM D 1418 abbreviation	Chemical names	Trade names
CR	Chloroprene	Neoprene®, Skyprene®, Butclor®, Baypren®, Denka®
CSM	Chlorosulphonyl polyethylene (Chlorosulphonated polyethylene)	Hypalon®, Noralon®
EPD	Ethylene-propylene copolymer	Buna-AP®, Dutral®
EPDM	Ethylene propylene diene terpolymer	Epsyn®, Nordel®, Epcar®, Keltan®, Royalene®, Polysar-EDM®
FEPM	See TFE/P	Aflas®Epsyn®
FFKM/FFPM	Perfluoroelastomer	Perlast®, Kalrez®, Chemraz®
FKM/FPM	Fluoroelastomer	Viton®, Dai-el®, Fluorel®, Tecnoflon®
FVMQ	Fluorosilicone	Silastic LS®, FSE®
HNBR	Hydrogenated nitrile	Therban®, Tornac®, Zetpol®
IIR	Butyl rubber	Exxon Butyl®, Polysar Butyl, ® Esso Butyl®
IR	Isoprene	Shell Isoprene Rubber®
NBR	Nitrile butadiene	Breon, Butakon®, Chemigum®, Hycar®
XNBR	Carboxylated nitrile	Buna-N®, Butacril®, Paracil®, Perbunan®, Krynac®, Europrene-N®, Nipol®
NR	Natural rubber	Nastsyn®
SBR	Styrene butadiene (Buna-S)	Cariflex S®, Plioflex®, Europrene®, Pliolite®, Buna Huls®, Carom®, Solprene®
TFE/P	Tetrafluoroethylene/propylene	Alfas®, Flourel®,Fluoraz®
VMQ PVMQ	Silicone	Silastic®, Siloprene®, Rhodorsil®, Silplus®

(ii) Synthetic Polyisoprene (IR)

IR is synthetic natural rubber with the same chemical composition of cis-1,4 polyisoprene. However, IR is inferior in green strength, cure rate, tear and ageing properties compared to natural rubber. IR is mostly used in tyre manufacture and as shock absorbers [13].

Fig. 26.3 Molecular
structure of SBR
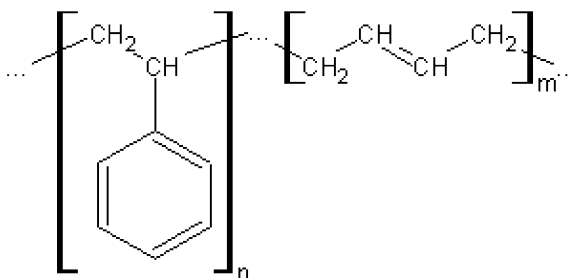
(iii) Styrene butadiene rubbers (SBR)

SBRs are copolymers of styrene and butadiene, with the regular grades containing nearly 23 % styrene. The molecular structure is shown in Fig. 26.3. This rubber was originally developed to replace natural rubber. Absence of strain crystallization in SBR makes it inferior in tensile strength, resilience and abrasion resistance. Owing to backbone unsaturation, SBRs have poor resistance to oxygen and ozone compared to other elastomers. Typical applications are seals for hydraulic braking systems and tyre treads [14].

(iv) Butyl rubbers (IIR)

Isobutene-isoprene rubbers (IIR), or butyl rubbers, are copolymers containing isobutene and isoprene. The molecular structure is shown in Fig. 26.4. These rubbers have an effective long-term temperature range of −50 to +120 °C.

A small percentage of isoprene is introduced to furnish the necessary sites for vulcanising. The densely packed structure of IIR elastomers promotes very low gas permeability and water absorption. Typical applications are in gas retentions such as tyre inner tubes, vacuum seals and membranes [15].

(v) Poly butadiene Rubbers (BR)

BR is a homopolymer of butadiene. The molecular structure is depicted in Fig. 26.5. This rubber contains approximately 97–98 % cis-1,4 Butadiene units, and is an NR substitute with properties generally inferior to those of NR. However, some polybutadienes exhibit better low temperature flexibility than NR.

Hydrogenated polybutadiene is chemically resistant to hydrazine, propyl nitrate and tricresyl phosphate, and is useful for missile applications [16]. Hydroxyl-terminated polybutadiene is used as the polymeric binder in solid rocket propellants [17].

(vi) Ethylene Propylene Diene Rubber (EPDM)

EPDM is a terpolymer of ethylene, propylene and a small percentage of non-conjugated diene, which provides unsaturation in side-chains pendent from the fully saturated backbone. The molecular structure is depicted in Fig. 26.6. EPDM's mechanical properties are inferior to those of NR but it has superior resistance to ageing, swelling and chemicals.
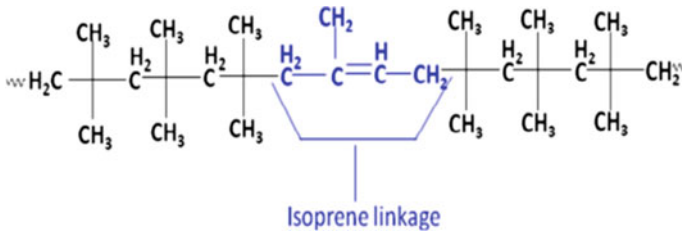
Isoprene linkage

Fig. 26.4 Molecular structure of IIR
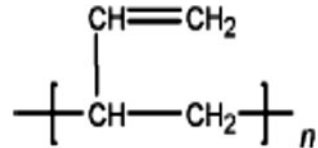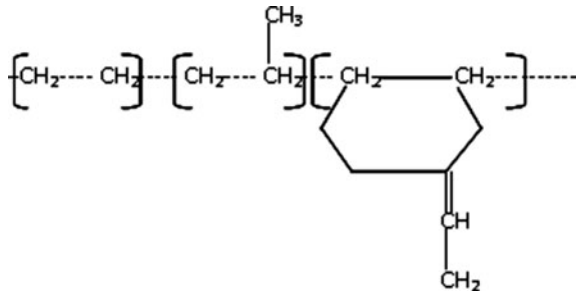
Fig. 26.5 Molecular structure of BR

**Fig. 26.6** Molecular structure of EPDM

Owing to its low density, EPDM is used as the rocket motor insulator for rocket and missile applications [18, 19]. It is also used as elastomeric bushings in aircraft and helicopter applications [20].

(vii) Polychloroprenes (CR)

This type of rubber is a homopolymer of chloroprene (chlorobutadiene). These are also called Neoprene rubbers. The molecular structure is depicted in Fig. 26.7. The backbone chains are of the trans-1,4 configuration, which gives a high degree of stereo-regularity. This property enables CRs to crystallize on stretching.

Neoprene has inferior mechanical properties at room temperature and poorer low temperature flexibility compared to natural rubber. However, neoprene is ozone and

Fig. 26.7 Molecular structure of CR
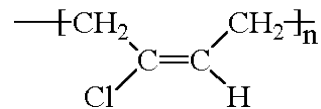
flame resistant, and also has fair resistance to corrosive chemicals and moderate swelling resistance to oils, fuels and solvents.

Owing to its strain-induced crystallization, neoprene is used as rubber pads, elastomeric bushings, seals, O rings and shock mounts [21].

(viii) Nitrile rubbers (NBR)

NBR is a copolymer of acrylonitrile and butadiene rubber. The properties of this copolymer are governed by the ratio of the two monomers acrylonitrile and butadiene. The molecular structure is shown in Fig. 26.8.

Nitrile rubber can be classified as three types based on the acrylonitrile (ACN) content (low, medium and high) as follows:

- High nitrile: >45 % ACN content
- Medium nitrile: 30–45 % ACN content
- Low nitrile: <30 % ACN content

As the ACN content increases, NBRs show superior resistance to aromatic hydrocarbons. This can be attributed to the polarity nature of ACN. However, the lower the ACN content, the better will be the low temperature flexibility. Hence the medium nitrile NBR is widely used for the best overall balance.

NBRs show excellent resistance to aircraft fuel, and hydraulic and lubricating oils. But they are not suitable for strong polar liquids. They are widely used as seals, gaskets and hoses in fuel/hydraulic system of aircraft, helicopters, rockets and aero engines.

Nitrile rubbers are also available as carboXylated (XNBR) and Hydrogenated (HNBR) nitrile rubbers [22]. Compared to regular NBR, XNBR shows increased tensile strength, higher modulus and better abrasion and tear resistance. HNBR gives improved resistance to heat and ozone.

(ix) Chlorosulphonated polyethylene rubbers (CSM)

Polyethylene is converted into CSM by reacting with chlorine and sulphur dioxide. The molecular structure is depicted in Fig. 26.9. Hypalon is a trade name
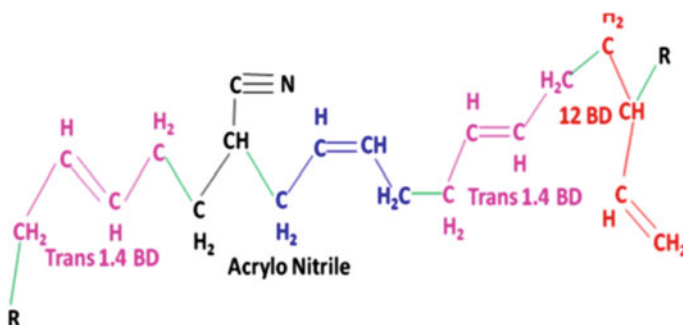

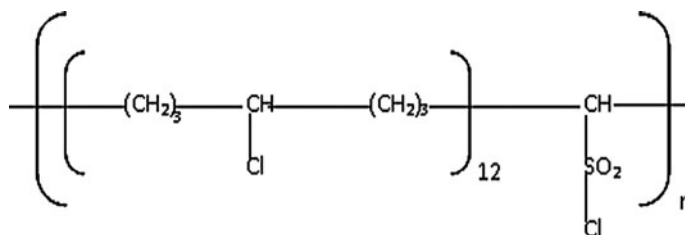Fig. 26.8 Molecular structure of NBR

Fig. 26.9 Molecular structure of CSM

for a CSM. It is resistant to chemicals, temperature extremes and ultraviolet light. Hypalon also has fair mechanical properties and excellent resistance to heat, fatigue, chemicals, ozone and weather. Its major uses are to blend [23] with other elastomers, and for chemical barrier elements and static seals.

(x) Silicone elastomers (VMQ)

Silicone rubber is a polymer with a backbone of silicone-oxygen linkages as depicted in Fig. 26.10. While the backbone of silicone rubber is silicone-oxygen, the pendent groups can be methyl (MQ, most popular), Vinyl methyl (VMQ, higher peroxide cross-linking efficiency), phenyl vinyl methyl (PVMQ, crystallization inhibition, low temperature flexibility), and trifluoropropyl (FSR or FVMQ, solvent/fuel resistance).

According to ASTM D 1418 there are various classes of silicone rubbers [10], see Table 26.3. VMQs have excellent resistance to ozone and weathering, and good resistance to compression set at high temperatures. Due to the flexible backbone of Si–O–Si linkages, they have poor tensile strength, low tear and abrasion resistance, and high gas permeability.

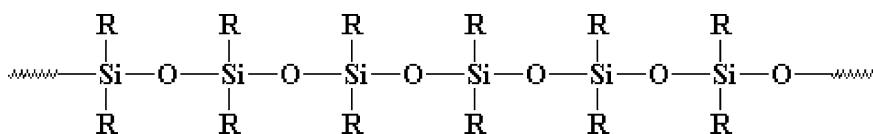**Fig. 26.10** Molecular structure of VMQ

Table 26.3 Classes of silicone elastomers [26]

Class	Substituent in polymer chain	Applications
MQ	Methyl	Not commonly used
VMQ	Vinyl	General purpose
PMQ	Phenyl	Extremely low temperature
PVMQ	Methyl, phenyl and vinyl	Extremely low temperature
FVMQ	Trifluoropropyl	Fuel, oil and solvent resistance

The saturated backbone and flexible chain find wide application in aircraft as weather resistant canopy seals. The properties like inertness and lack of toxicity make these elastomers suitable for pilots' oxygen masks. They are also widely used in the aerospace industry as pneumatic seals [24, 25].

(xi) Fluorosilicone elastomers (FVMQ)

The FVMQ elastomer is a modified silicone rubber. The molecular structure is as shown in Fig. 26.11. The trifluoropropyl substitution in the polymer chain induces the polarity in an FVMQ. This elastomer overcomes the disadvantages of silicone in terms of fuel resistance without compromising the weathering resistance and low temperature flexibility.

These rubbers have a very wide service temperature range and low chemical reactivity. However, they have low tensile strength, and poor tear and abrasion resistance compared to fluorocarbon rubbers. Typical uses include sealing systems [27, 28] requiring wide temperature exposure and resistance to aerospace fuels and oils.

(xii) Fluorocarbon elastomers (FKM or FPM)

Fluorocarbon gums are prepared by copolymerizing monomers such as vinylidene fluoride (VF) and hexafluoropropylene (HFP). The type of monomer determines the fluorine content, and there are three different types of FKM, see Table 26.4. The molecular structures of all three types are shown in Fig. 26.12.

The high strength of FKMs can be attributed to the C–F bond compared to the C–H bond. General properties of FKMs include excellent resistance to heat,
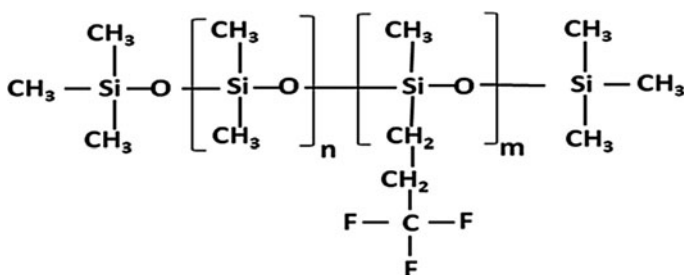
Fig. 26.11 Molecular structure of FVMQ

Table 26.4 Types of FKMS [10]

Class: fluorine content	Properties/applications
Copolymer of vinylidine fluoride (VF) and hexafluoropropylene (HFP): 65–65.5 %	Good fluid and best compression set
Terpolymer of VF, HFP and tetrafluoroethylene (TFE): 67 %	Better chemical resistance and inferior compression set
Tetrapolymer of VF, HFP, TFE and cure site monomer: 67–69 %	Improved chemical resistance and compression set compared to terpolymers

Fig. 26.12 Molecular structures of FKMs

$$- (CF_2-CH_2)_X - (CF-CF_2)_Y -$$
$$|$$
$$CF_3$$

VF-HFP COPOLYMERS

$$- (CF_2-CH_2)_X - (CF-CF_2)_Y - (CF_2-CF_2)_Z -$$
$$|$$
$$CF_3$$
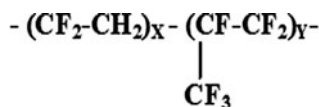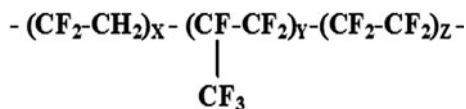
VF- HFP- TFE TERPOLYMERS

petroleum oils and hydrocarbon fuels, organic and silicate ester-based lubricants, and aromatic hydrocarbons. On the other hand, they have poor resistance to ethers, ketones, esters, amines, and hydraulic fluids based on phosphate esters. Superior tensile strengths make them suitable for dynamic sealing applications, with the lowest operating temperature between −15 and −18 °C, i.e. these elastomers are not suitable for low temperature applications. The excellent fluid resistance can be attributed to the fluorine content in the molecular structure. The fuel resistance of FKMs increases with the fluorine content at the expense of compression set.

Owing to their excellent fuel resistance and strength, FKMs are widely used in aircraft and spacecraft fuel systems as dynamic seals [29].

(xiii)   Perfluoroelastomers (FFKM)

An FFKM is chemically a terpolymer of tetrafluoroethylene (TFE) and per-fluromethylvinylether (PMVE) with a small amount of cure-site monomer. The molecular structure is depicted in Fig. 26.13. The absence of hydrogen atoms in cured FFKM polymers increases the heat and chemical resistance as compared to FKMs. The unique property of FFKMs is the long-term resistance to exposure at high temperatures up to 260 °C and short-term resistance up to 310 °C.

FFKMs are the most chemically resistant elastomers available—effectively a rubber form of PTFE (polytetrafluoroethylene). They are extremely inert and have excellent resistance to the majority of chemicals that attack other elastomers. They have outstanding resistance to ketones, hot fuming nitric acid, oil field sour gases and high temperature steam; and they give low out-gassing under vacuum. Also, they have good long-term high temperature compression set resistance. The major disadvantage is the poor low temperature flexibility. The high strength and high

Fig. 26.13 Molecular structure of FFKM

$$-(CF_2- CF_2)_n - (CF_2- CF)_m - (CF_2- CF_2)_x- \overset{*}{C}S-$$
$$|$$
$$O$$
$$|$$
$$CF_3$$
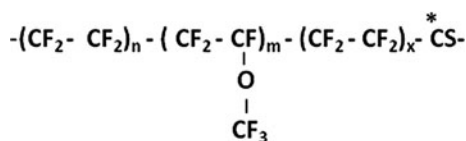
temperature resistance properties make FFKMs suitable for static and dynamic seals in aerospace applications [30].

26.1.6 Elastomer Aerospace Requirements

The exceptionally high elasticity, with elongation values from one hundred to several thousand percent, makes elastomers suitable for aircraft tyres, seals and gaskets. Tyres must have many capabilities [31], including supporting vehicle loads, maintaining dimensional stability, giving adequate tread life, and having low energy consumption. To meet these requirements they must combine enough rigidity and flexibility to cope with obstacles without sustaining damage, and give long flexural fatigue lives. Moreover, aircraft tyres must cope with use at high speeds and high loads relative to their size.

Their outstanding dynamic properties make elastomers suitable as shock absorbers and passive dampers in the space industry, where they are mounted onboard launchers and satellites. Historically, the damping properties of elastomers were first used for launchers to prevent damage due to shock loads generated by stage separations. Subsequently, they were mounted inside spacecraft as passive damping equipment. The intention is always to limit shock level effects on equipment and micro-vibrations generated by onboard reaction wheels and gyroscopes.

The following elastomeric properties play major roles in aerospace applications:

(i) Mechanical characteristics

The main mechanical characteristic of elastomers is extreme flexibility. They can be strongly extended (more than 400 % elongation) without damage, and return to their original positions when the stress is removed. The extreme flexibility can be

Fig. 26.14 Schematic tensile stress–strain curves for an elastomer and aluminium [31]
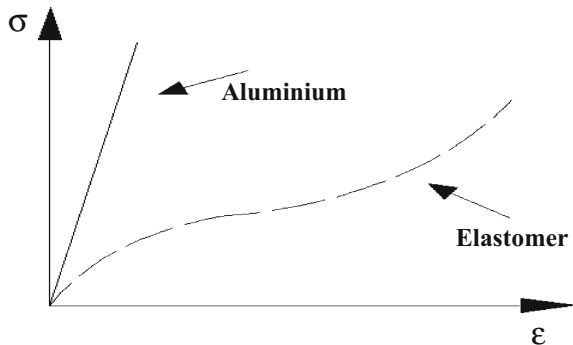
attributed to the long molecular chains made of monomer units rearranging themselves to dispense the applied stress. Moreover the network of cross-links formed between the molecular chain helps the elastomer to return to the original shape. Figure 26.14 compares the stress–strain behaviour of a metal and elastomer.

(ii)   Thermophysical aspects

Owing to the high mobility of the macromolecular chains, the glass transition temperature (Tg) of elastomers is lower than room temperature, and it also depends on the chemical structure of the elastomer. Elastomers above Tg will be soft, flexible and exhibit a delayed elastic response (viscoelasticity), while those below their Tg will be hard and brittle. When the temperature is higher than Tg, thermal agitation of macromolecular chains is very high inside the material, making the elastomer very elastic around Tg. This is the relaxation area where the damping of the elastomer is maximum.

(iii)   Viscoelasticity

Elastomers exhibit a viscoelastic behaviour intermediate between a perfectly elastic spring and a viscous fluid. This is why a first approximation to modelling a rubber damper is a spring connected to a dashpot, as shown schematically in Fig. 26.15.

This viscoelastic model is called the Voigt model. On loading, the spring tries to elongate instantaneously, but the piston in the dashpot moves rather slowly and delays the response of the spring. On releasing the load, the spring tries to pull the system back, but again the dashpot delays the motion. This is the phenomenon of delayed elasticity, which can be described by both the modulus and viscosity. The total stress (σ) is equal to the sum of the elastic and viscous stresses, as shown in Eq. (26.1). Here the modulus can be expressed as an in-phase component, the storage modulus (G'), which is the measure of the elastic behaviour. G'' is the measure of the viscous behaviour, and is known as the loss modulus. The ratio of the loss to the storage modulus, shown in Eq. (26.2), is called the damping (φ).

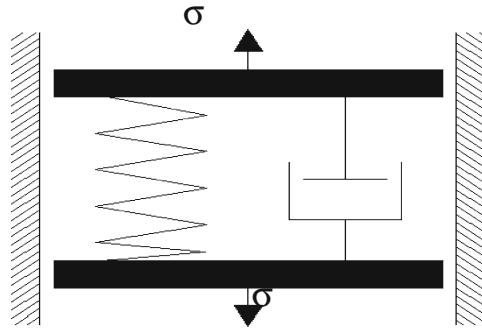$$\sigma = \gamma_0 [G'(\omega) \sin(\omega t) + G''(\omega) \cos(\omega t)] \tag{26.1}$$

and

$$\varphi = \tan^{-1}(G''/G') \tag{26.2}$$

- *Frequency influence*: From Eq. (26.1), G' and G'' depend on the frequency, ω:

  – when ω is low the molecular chains have time to return to their original positions. Here the viscous or liquid-like flow predominates. Hence the material appears flexible.

- when ω increases, the molecular chains lag behind the original positions and lead to unrecoverable deformation. Here the elasticity dominates and the material behaves in elastic fashion.
- finally, if ω continues to increase, the molecular chains cannot return to their original positions. The macromolecular chains are in permanent tension and the material appears rigid.

- *Temperature influence*: Temperature and frequency have opposite influences on elastomers:

  - at very low temperatures the elastic moduli are very high and the elastomer is rigid and brittle.
  - at high temperatures the elastic moduli are low and the elastomer is elastic.
  - at intermediate temperatures the elastomers are most viscous near the glass transition temperature Tg.

(iv) Fluid resistance [32]

Many aerospace products such as seals, gaskets and hoses encounter lubricating and hydraulic oils, greases, and fuels. Therefore it is important to select elastomers with resistance to these fluids.

Two relationships are of primary importance in the interaction of chemical compounds: solution and reaction. Many liquids are good solvents for particular elastomers but do not react with the material: these liquids cause reversible swelling and property changes in elastomers. Other liquids are not solvents but are highly reactive: these degrade elastomers by surface attack.

Liquids intermediate between these two extremes cause both swelling and irreversible changes in the properties. Swelling causes volume changes that alter the physical properties of elastomers. An immersion test under controlled conditions is the most reliable method for selecting an elastomer for use in the presence of specific fluids.

The fluid resistance of elastomers depends on the following factors:

- Elastomer grade
- Compounding ingredients
- Temperature and time of exposure
- Dimensions of the elastomer part
- Chemical composition of fluid medium.

26.1.7 Aerospace Applications of Elastomers

Elastomers are essential materials for the following aerospace systems:

(i) Airframe systems

- Structural system vibration damping elements
- Pressurization system sealing parts
- Control system power source, actuator, servo, and vibration damping parts
- Chemical, thermal, and abrasion-resistant coatings and parts
- Electrical system parts
- Heating and cooling system parts.

(ii) Instrument, weapon, indicator and guidance systems

- Power source and transmission parts
- Electrical insulation
- Shock absorption and vibration damping parts
- Chemical, thermal and abrasion resistant coatings and parts.

(iii) Landing gear systems

- Tyres
- Shock absorption and vibration damping parts
- Braking device parts
- Retraction mechanism parts.

(iv) Propulsion systems

- Fuel containment and transfer element parts
- Actuator and servo parts
- Shock absorption and vibration damping parts
- Electrical insulation
- Solid propellant ingredients.

26.2 Adhesives

26.2.1 Introduction

Adhesive bonding is widely accepted as a valuable method for obtaining structural assemblies with very good strength-to-weight ratios. The aerospace industry uses adhesive bonding extensively, for both metallic and composite structures, and also hybrid metal/composite structures and components.

Adhesives for elevated temperature applications must operate in severe environments. Hence one of the mandatory capabilities is to maintain the mechanical properties and structural integrity at the designed service temperatures. Adhesive systems that meet some of these requirements include epoxies (high strength and temperature resistance), silicones (excellent sealants for low stress applications, high degree of flexibility and very high temperature capabilities), phenolics, polyimides, bismaleimides and ceramic adhesives.

In recent years, adhesive bonding has either been replacing or supplementing conventional joining methods such as riveting, welding and mechanical fastening in a variety of applications [33]. This type of bonding is preferable for thin structures with defined loads, and is being extensively used to repair cracked sheet structures in aircraft, using composite patches [34]. However, thicker structures with heavy loads are more suited to mechanical fastening [35].

26.2.2 Advantages of Adhesive Bonding

There are many potentially advantageous industrial applications [36, 37] of adhesives relevant to aerospace structures, for which the major concerns are structural efficiency (light weight), safety and reliability. In recent years the use of adhesive bonded aerostructures has increased tremendously due to the following advantages:

- Improvement of load carrying capability
- Excellent fatigue properties
- Attractive fracture mechanics properties
- Corrosion resistance
- Weight reduction.

However, there are also various disadvantages like the requirement of stringent process control and difficulties with various testing methods.

26.2.3 Mechanisms of Adhesive Bonding

26.2.3.1 Adhesion

The mechanisms [38, 39] and factors mainly responsible for developing strong and durable bonded joints are

- Molecular attraction, mechanical interlocking or electrostatic attraction of surfaces held together.
- Wetting of surfaces
- Contact angles
- Adherend surface quality
- Adhesive type and properties.

26.2.3.2 Adherend surface

The surface roughness of the adherend surface plays a major role. The rougher the surface, the more surface area is available for bonding. Good adhesion can be achieved with good wetting of the adherend surfaces and uniform spreading of the adhesives. In this respect the surface cleanliness is paramount for successful bonding.

26.2.4 Surface Treatment of Substrates

Surface preparation is a key factor for the satisfactory service life. There is a wide range of surface treatments available [40– 44]. All the substrates have to be chemically treated to remove impurities and promote good adhesion. Best practice is collected in ISO Standards 4588 (metals) and 13895 (plastics). The techniques can be classified into five groups, according to treatment type:

(i) **Cleaning/Degreasing**: Grease, oil, wax and other organic contaminants can be removed by wiping, dipping or spraying with organic solvents or alkaline aqueous solutions. Dust can be removed by a clean brush or blast of air.

(ii) **Surface Roughening**: An abrasion treatment increases the surface roughness and energy. Abrasive materials enhance the roughness and improve the chemical activity of the adhesives.

(iii) **Chemical Treatments**: The type of chemical treatment depends on the variety of substrate. A chemically active surface can be achieved by immersion of the substrate in the chemical solution.

(iv) **Physical Treatments**: The surface of the substrate is exposed to ionized or active gases, e.g. corona discharges, plasmas, flames and ozone. This method has wide scope for fine tuning the substrate surface properties.

Table 26.5 Surface pre-treatment methods [40, 41]

Mechanical	Chemical	Energetic
Alumina grit blast	Solvent cleaning	Plasma
Cryo-blast (Dry ice blast)	Detergent wash	Corona discharge
Soda-blast	Acid etch	Flame
Ply peeling	Anodizing	Excimer laser
Silicon carbide abrasion	Primer	

(v) **Primers**: Primers provide protection and durability to the chemically or mechanically treated surface. These coatings prevent the surface from corrosion and are applied by dipping, brushing or spraying.

Each of the above categories can be further divided into a given technique or method of surface preparation, see Table 26.5.

Selection of a pre-treatment will be based on the type of substrate, durability, health and safety, and production costs. Pre-treatment facilities can include equipment, chemicals and consumables. Key surface features are wettability, roughness, soundness, stability, lack of contamination, uniformity and adhesive compatibility.

26.2.5 Adhesive Type and Properties

The selection of adhesives [45–47] for aerostructures is vital in achieving satisfactory performance. The following points list the factors involved in the selection of adhesives.

- Basic type of adhesive system
- Cure parameters of bonded structure
- Temperature range of exposure
- Durability
- Mechanical properties
- Environmental resistance
- Performance evaluation.

The key types of structural adhesives [48] may be summarized as follows:

- **Epoxies**—Epoxy adhesives consist of an epoxy resin plus a hardener. They are available in one-part, two-part and film form. There are many resins and different hardeners, providing a great variety in formulation and performance. Polyamines are generally used as the hardeners for epoxy adhesives. However, dicyanamide is used for high temperature curing. Epoxy adhesives form extremely strong durable bonds with most of the substrates. The adhesive joints show good resistance to fatigue, creep, heat, moisture and solvents. **Toughened epoxies** contain an epoxy resin toughened with an elastomer. In general, Nitrile

rubber is used for elastomer-modified epoxy resin systems. Elastomers improve the bond durability, fracture and impact resistance. They are extensively used in larger wing and honeycomb assemblies for aircraft structures.

- **Polyurethanes**—Polyurethane adhesives basically consist of polyisocyanates, polyols and chain extenders. They are produced by the reaction of polyiso-cyanates and polyols. This type of resin is usually two-part and fast curing. They have high impact resistance and durability. They are useful for bonding to glass-reinforced plastics. Fibre-reinforced plastic surfaces to be bonded are often treated with solvent based primers.
- **Cyanoacrylates**—These are very important adhesives because of rapid curing. They are produced by anionic polymerisation of cyanoacrylic acid ester. These adhesives are not suitable for high temperature applications. **Toughened acrylics** are elastomer-modified acrylics, which are fast curing and offer high impact resistance.
- **Modified phenolics**—The epoxy and nitrile modified phenolics find use in military and space applications for metal to metal joints. They have excellent short-time resistance to high temperatures. Epoxy phenolics have good resistance to high humidity environments.
- **Hot melts**—Hot melt adhesive systems include ethylene-vinyl acetate copolymers, polyolefins, polyamides, polyesters and thermoplastic elastomers. They remain solid up to a certain temperature. At this temperature they start melting and are applied to the surface. Cooling results in rapid setting. They are usually designed for light loads, and only polyamides and polyesters can withstand limited loads at elevated temperatures without creep. They are typically used in door panels, tail-light assemblies, electronic controls and window seals.
- **High temperature adhesives**—These are used for high service temperatures. Epoxy and phenolic resins weaken due to rapid thermal degradation at high temperatures. Thus for specialist applications where brittle ceramic adhesives are not appropriate, recourse must be made to more exotic, synthetic polymers. Polyimide and bismaleimide adhesives are the most established types in this class. They are available as liquids or films, but are relatively expensive and difficult to handle. However, they are superior to most other adhesive types with regard to long-term strength retention at elevated temperatures.
- **Rubber adhesives**—These are based on various elastomer solutions or latexes, and solidify through loss of solvent or water medium. They are not suitable for sustained load.

26.2.6 Adhesive Joint Design [47, 48]

The important motives to use adhesive joints are to avoid welding or mechanical fastening, which can introduce local damage. In aerospace applications the substrate may be a metallic or composite structure. Hence it is very important to have an

optimum joint design resistant to failure. The following points are key factors in designing bonded joints:

- Joint geometry
- Adhesive selection
- Mechanical properties of adhesive and substrate
- Stress in the joint
- Surface preparations of substrate
- Processing and curing conditions.

The bonded joints may be subjected either to the following types of load or combinations of loads [47].

- Tensile
- Compression
- Shear
- Cleavage
- Peel.

Adhesive joints show great resistance in shear, compression and tension, but become vulnerable under peel and cleavage loading. Hence the two main criteria of design are (i) uniform distribution of stresses over the bonded joints and (ii) the stress should be tensile, compression or shear: peel and cleavage loading should be avoided because they concentrate the applied forces into a single line of high stress. Thus for maximum strength the cleavage and peel stresses should be as much as possible designed out of the joints.

Generally in aeronautical structures two or more following basic type of bonded joints [48, 49] may be used in combination.

- Simple Lap Joint
- Tapered Lap Joint
- Scarf Joint
- Stepped Lap Joint
- Double Strap Joint
- Tapered Double Strap Joint.

The significance of tapering the ends of joints is a more uniform distribution of stresses and therefore reductions of stress concentrations.

26.2.7 Aerospace Applications of Adhesives

Adhesives are widely used for bonding applications [50–52] in the aerospace industry. Current applications are summarized here:

Aircraft:

- Aluminium alloy or composite skins, frames and stiffeners bonded to form major structural parts (fuselage, wings and empennage). Bonding is usually combined with some mechanical fastening (rivets and bolts).
- Aluminium alloy skins bonded to aluminium honeycomb for flight control surfaces.
- Composite structures such as honeycomb-based floor panels, engine and transmission decks, cabin work decks and tunnel covers.
- Nano-toughened epoxy paste adhesives with outstanding mechanical properties are currently used for aircraft structural metal and composite bonding.
- Radomes: Glass-fibre-reinforced plastic skins bonded to glass-fibre-reinforced plastic honeycomb. Cyanate ester formulations offer outstanding electrical properties, and are good candidates for both composite matrices and film adhesives for radome applications.
- Rotor blades: aluminium, titanium, or carbon fibrereinforced plastic skins bonded to metal ribs.

Spacecraft:

- Apollo command module: leak-tight aluminium alloy sheet and honeycomb core sandwich structures bonded with epoxy-phenolic adhesive.
- Apollo heat shield: this was an epoxy novolac resin with special additives in a fibreglass honeycomb matrix. Adhesives were used to bond the glass-reinforced honeycomb core to stainless steel to form a sandwich substructure.
- Apollo Service Module: aluminium alloy skins and composite honeycomb core sandwich bonded with epoxy-phenolic tape adhesive.
- Lunar Module: Seals for mechanical fasteners, and seams with epoxy-based adhesive for sandwich structure.
- Epoxy-glass skins co-bonded to aluminium honeycomb core for solar panels.
- Solar cells bonded onto polyimide film laminated with a thin glass-epoxy layer.
- Second surface mirrors: Thin fragile glass or quartz plates, metallised on the back faces, and bonded on the spacecraft.
- Reflective radiation surfaces: bonded on spacecraft exteriors.
- Multi-layer circuit boards, antenna reflectors, tabular truss configurations, mounting panels, re-entry heat shields.
- Space Shuttle: bonding of tiles for temperature protection. The adhesive used to bond the ceramic tiles was an RTV (room temperature vulcanising) silicone rubber [53, 54]. During re-entry to the atmosphere the adhesive strength was sufficient to hold the tiles in place at the extreme temperatures.

Tactical Missiles:

- Adhesive bonding technology is used for wings, bonding of insulators and bonding of liners to solid rocket propellant motors, and bonding nozzles to propellant engines.

26.3 Indian Scenario

Various *ab initio* projects in the Indian aerospace field of elastomer compounds and adhesives have resulted in much indigenous manufacture and use. At present an enormous number of elastomer compounds are indigenised as per the aeronautical elastomer specifications, and are being used in Indian aerospace organizations.

In a similar way, many adhesives such as rubber-based polychloroprene, nitrile, epoxy resin, and lanolin are indigenously available. Epoxy resin with the commercial designation Araldite is widely used as an adhesive in the Indian aeronautical field. Epoxy resins are used in electrical and electronic components, and also for bonding glass, carbon and aramid fibre in reinforced plastics, and for bonding metals to non-metals.

26.4 Conclusions

The types of elastomers used in the aerospace industry include Natural, Nitrile, Neoprene, Butyl, Silicone, Fluorocarbon, and Ethylene Propylene rubbers; and Hypalon and Fluorosilicones. Their exceptionally high elasticity and elongation characteristics make them especially suitable for aircraft tyres, vibration dampers and seals.

Adhesives are extensively used in the aerospace industry for bonding metal-to-metal, metal-to-composite and composite-to-composite parts. There are many types of structural adhesives. However, high-performance epoxies, nitrile phenolics and bismaleimides are the most prevalent.

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