Chapter

2

Plastics, Elastomers, and Composites

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2.1 Introduction

Prior to 1930, most household goods and industrial components were made of metals, wood, glass, paper, leather, or vulcanized rubber. Since then, plastics have made significant advances in the markets of all these materials as well as creating new markets of their own. The widespread use of plastics has been brought about because of their unique combination of properties such as strength, light weight, low cost, and ease of processing and fabrication. Plastics are not the panacea of industry's material problems, but they offer such a unique combination of properties that they have become one of the important classes of materials and have found widespread use in the electrical and electronics industries.

Plastics play a key role in these industries and function in a variety of ways. The most common application of polymers in electrical and electronic devices is for insulation, which prevents the loss of the signal currents and confines them to the desired paths. Insulation systems exist in a variety of forms (liquids, solids, and gases), and the type of material used determines the life span of the device. Plastic materials also perform structural roles, support the circuit physically, and provide environmental protection from such elements as moisture, heat, and radiation to sensitive electronic devices. Continuing improvements in the properties of plastics over the years have made them even more important to the electrical industry by extending their useful range.

It is the purpose of this chapter to present to the reader an overview of the nature of plastic materials. This overview will include topics related to plastic fundamentals, thermoplastics, thermosets, elastomers, and applications in electrical and electronic systems. The overview pertains only to plastics that are of significant importance in the electronics industry.

2.2 Fundamentals

2.2.1 Polymer definition

Polymers are macromolecules, that is, large molecules formed by the linking together of large numbers of small molecules called *monomers*. The process involved in the joining of these monomers is called *polymerization*. Plastics are a group of synthetic polymers made up of chains of atoms or molecules. The long molecular chains contain various combinations of oxygen, hydrogen, nitrogen, carbon, silicon, chlorine, fluorine, and sulfur. As more repeating units are added, molecular weight of the plastic increases and can reach into the millions but, typically, most polymers used for practical applications fall into the molecular weight range of 5000 to 200,000.

2.2.2 Types of polymers

There are several different ways to classify polymers. They can be differentiated by the way in which their monomers are joined together, that is, addition or condensation polymerization. In addition polymerization, the molecular chains are formed by the successive addition of one monomer to another. Typical addition polymers are polyolefins, polystyrenes, acrylics, vinyls, and fluoroplastics. Condensation polymers are prepared by the reaction of two different molecules, each having two reactive end groups. Molecular weight is built up by the linking together of these end groups and elimination of a small molecule (such as water). The small molecule must be removed from the reaction medium to attain a high molecular weight. Examples of condensation polymers include polyamides, polyesters, polyurethanes, and polyimides.

All polymers can be classified in this manner, but they can also be further subdivided to define their structural and compositional characteristics more accurately. They can be linear, branched, crystalline, amorphous, or liquid crystalline copolymers, elastomers, and alloys. All of these, except elastomers, can be divided into two major groups—thermoplastics and thermosets. Both types of plastics are fluid enough to be formed and molded at some stage in their conversion to the finished product. Thermoplastics solidify by cooling and can be remelted. Thermoset resins undergo cross-linking to form a three-dimensional network, and, unlike thermoplastics, they cannot be remelted and reshaped.

With few exceptions, to meet processing and performance requirements, polymers are mixed with other materials to yield a compounded polymer, which may be in the form of pellets, granules, powder, or liquid. A monomer may be polymerized with one or more different monomers in a process called *copolymerization*. These polymers are called *copolymers* or *terpolymers*, depending on whether two or three comonomers are used during the copolymerization. Another technique used to vary the properties of polymers is to blend one polymer with another mechanically to form an alloy. The properties of these alloys generally fall between those of the starting polymers.

Elastomers differ significantly from plastics. While they are also polymers, elastomers easily undergo very large reversible elongations at relatively low stresses. For this to happen, the polymer must be completely amorphous with a low glass transition temperature and low secondary forces so as to obtain high mobility of the polymer chains. Some degree of cross-linking is needed so that the deformation is rapidly reversible. Figure 2.1 illustrates the differences between rigid and flexible plastics, and elastomers by way of a stress-strain plot.

2.2.3 Structure and properties

In addition to the broad categories of thermoplastics and thermosets, polymeric materials can be classified in terms of their structure: linear, branched, cross-linked, amorphous, crystalline, and liquid crystalline. As mentioned, a polymer molecule consists of monomer molecules that have been linked to-

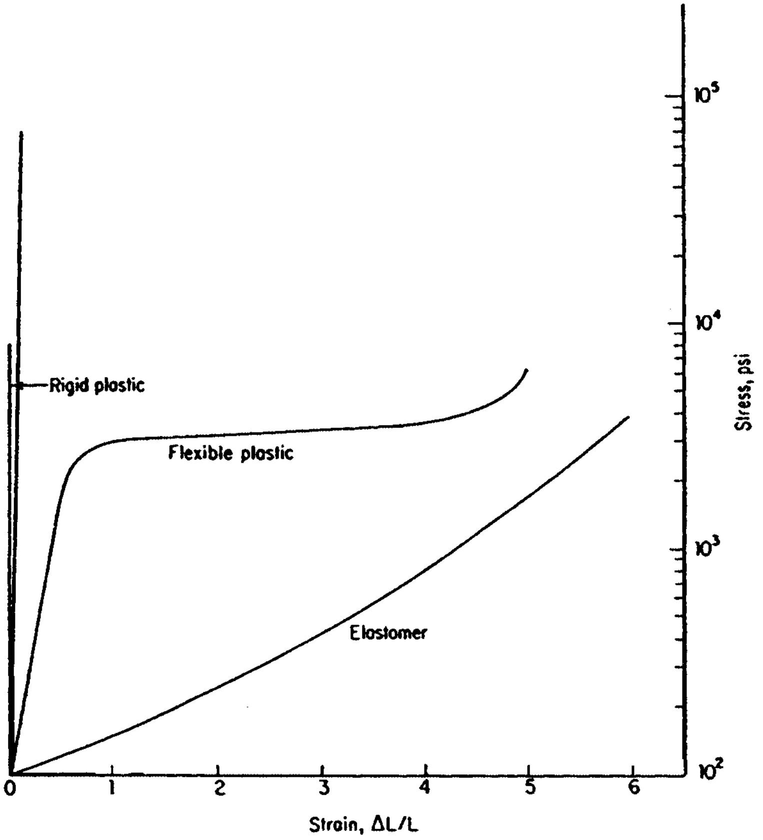

Figure 2.1 Stress-strain plots for typical flexible and rigid plastics and elastomers. *(From Odian,[1] reprinted with permission.)*

gether in one continuous length. Such a polymer is termed a *linear polymer.* Branched polymers are those in which there are side branches of linked monomer molecules protruding from various points along the main polymer chain. By carefully controlling the reaction conditions to prevent cyclization, it is possible to prepare hyperbranched polymer and *dendrimers*.[2] Hyperbranched polymers have an irregular structure and reactive sites throughout the structure. Dendrimers are more regular structures, having a core and layers of branched repeat units radiating from the core. By derivatizing, the outer layer materials having unique properties are accessible. Cross-linked polymers are those in which adjacent molecules are linked together, resulting in a complex interconnected network. Figure 2.2 is a schematic illustration of these structures.

In some thermoplastics, the chemical structure is such that the polymer chains will fold on themselves and pack together in an organized manner (Fig. 2.3). The resulting organized regions show the behavior characteristics of crystals. Plastics that have these regions are called *crystalline*. Plastics without these regions are called *amorphous*. All of the crystalline plastics have amorphous regions between and connecting the crystalline regions. For this reason, the crystalline plastics are often referred to as *semicrystalline* in the literature.

Liquid crystalline polymers are best thought of as being a separate and unique class of plastics. The molecules are stiff, rod-like structures that are organized in large parallel arrays or domains in both the melted and the solid states. These large, ordered domains provide liquid crystalline polymers with unique characteristics as compared to those of the crystalline and amorphous polymers.

Many of the mechanical and physical property differences between plastics can be attributed to their structures. As a generalization, the ordering of crystalline and liquid crystalline thermoplastics makes them stiffer, stronger, and less impact resistant than their amorphous counterparts. Moreover, crystal-

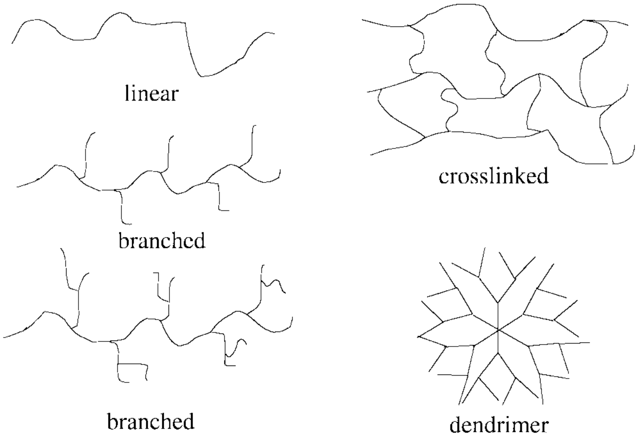

Figure 2.2 Structures of polymer molecules.

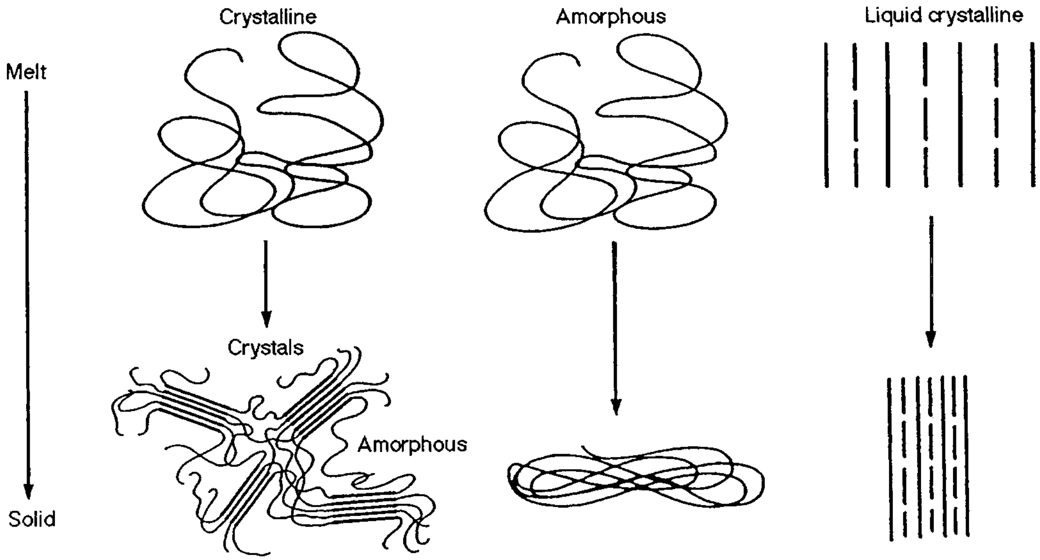

Figure 2.3 Two-dimensional representation of crystalline, amorphous, and liquid crystalline structures. *(From Hoechst Celanese,[3] reprinted with permission.)*

line and liquid crystalline materials have a higher resistance to creep, heat, and chemicals. Crystalline materials are typically more difficult to process, because they have higher melt temperatures and tend to shrink and warp more than amorphous polymers. Amorphous polymers soften gradually and continuously as heat is applied, and in the molding process they do not flow as easily as do melted crystalline polymers. Liquid crystalline polymers have the high melt temperature of crystalline plastic but soften gradually and continuously like amorphous polymers. They have the lowest viscosity, warpage, and shrinkage of the thermoplastics.

One of the most important characteristics of a polymer is its molecular weight, because the properties of a polymer are a consequence of its high molecular weight. Strength does not usually develop in polymers until a minimum molecular weight (5,000 to 10,000) is attained. Above this value, there is a rapid increase in mechanical properties, then a leveling off as the molecular weight increases further. In most instances, there is some molecular weight range for which a given polymer property will be optimal for a particular application. Polymers are not all homogeneous but are composed of molecules of different sizes. To characterize the size of a polymer completely, one should know both its molecular weight and its molecular weight distribution. Both of these properties affect processing and strength significantly.

2.2.4 Synthesis

There are four basic methods of producing a polymer. Many factors influence the choice of a particular method. In many instances, the nature of the reaction chemistry dictates the specific method to be used. In other instances, the characteristics of resultant polymer (low or semiviscous liquid, friable or rigid solid) may limit one's choice. The interested reader is referred to any basic organic polymer chemistry text for more detailed descriptions.

2.2.4.1 Bulk polymerization. From the point of view of equipment, complexity, and economics, the simplest method is mass or bulk polymerization. This procedure merely allows the monomer to react at a predetermined reaction temperature, with or without catalysts, to form the polymer. Theoretically, the monomer can be a gas, liquid, or solid, but in practice almost all mass polymerizations take place in a liquid phase. Gaseous-phase bulk polymerization takes place under pressure, often requiring specific catalysts for conversion.

The polymer may be either soluble or insoluble in the monomer. If the former, then the mass viscosity continually increases until the final degree of polymerization is obtained. In the latter, the polymer will precipitate from the remaining unreacted monomer and can be separated subsequently.

A serious drawback to bulk polymerization is control of the heat of reaction. The generated exothermic heat tends to stay within the mass and is not easily withdrawn. Stirring the mass helps, but as the viscosity continues to increase, stirring becomes more difficult, with a less efficient heat-dissipation mechanism. This lack of control causes difficulty in the control of the molecular weight and the molecular weight distribution (MWD) of the final polymer. The method does, however, lend itself for use in small casting or batch production.

In summary, mass or bulk polymerization uses simple equipment, is highly exothermic with difficult heat control, and yields a polymer with a broad MWD.

2.2.4.2 Solution polymerization. Heat removal can be simplified if the polymerization is carried out in a suitable solvent, because the solution of solvent, monomer, and polymer is less viscous than molten polymer. This technique is called *solution* polymerization. If a solvent can be found in which the monomer is soluble but the polymer is insoluble, the resultant polymer precipitation facilitates the separation steps.

In summary, one can control heat more readily in solution polymerization, although higher-molecular-weight polymers are difficult to produce. A solution of the polymer itself may be marketable, but the purification of solid polymer may involve complex procedures.

2.2.4.3 Emulsion polymerization. If the monomer can be polymerized in a water emulsion, then we can retain the low viscosity needed for good heat control without the hazards associated with the handling of solvents. Such a procedure is called *emulsion polymerization.*

Reaction rates and molecular weights are usually higher with this method than with mass or solution polymerization. The MWD is often quite narrow, water is cheaper and less hazardous than solvent, and recovery steps are not as complex. However, ingredients must be added to aid emulsification (emulsifying and stabilizing agents). This added contamination and the requirement of a drying step for the polymer constitute significant disadvantages to the process.

2.2.4.4 Suspension polymerization. Finally, there is suspension polymerization, in which the monomer and globules of the forming polymer are maintained in suspension by agitation without the use of an emulsifying agent. The polymer beads are formed by coalescence, and their size is regulated by suspension stabilizers and the amount and intensity of agitation. The final beads must be screened out of the liquid phase, washed, and dried before they can be used, although suspensions can be, and are, marketable. Control of exothermic heat is good, and high-molecular-weight polymers with relatively narrow MWDs are possible.

2.2.5 Terminology

To acquaint those unfamiliar with the language of polymers, Tables 2.1 and 2.2 present terms associated with polymers and their use in the electronics industry.

TABLE 2.1 Definition of Terms for Plastic Materials

Accelerator	A chemical used to speed up a reaction or cure. For example, cobalt naphthenate is used to accelerate the reaction of certain polyester resins. The term *accelerator* is sometimes used interchangeably with the term *promoter*. An accelerator is often used along with a catalyst, hardener, or curing agent.
Adhesive	Broadly, any substance used in promoting and maintaining a bond between two materials.
Aging	The change in properties of a material with time under specific conditions.
Arc resistance	The time required for an arc to establish a conductive path in a material.
B stage	An intermediate stage in the curing of a thermosetting resin. In this state, a resin can be heated and caused to flow, thereby allowing final curing in the desired shape. The term *A stage* is used to describe an earlier stage in the curing resin. Most molding materials are in the B stage when supplied for compression or transfer molding.
Blowing agent	Chemicals that can be added to plastics and that generate inert gases upon heating. This blowing or expansion causes the plastic to expand, thus forming a foam. Also known as *foaming agent*.
Bond strength	The amount of adhesion between bonded surfaces.
Capacitance	That property of a system of conductors and dielectrics that permits the storage of electricity when potential difference exists between the conductors. Its value is expressed as the ratio of the quantity of electricity to a potential difference. A capacitance value is always positive.
Cast	To embed a component or assembly in a liquid resin, using molds that separate from the part for reuse after the resin is cured. See *Embed, Pot*.

TABLE 2.1 Definition of Terms for Plastic Materials *(Continued)*

Catalyst	A chemical that causes or speeds up the cure of a resin but that does not become a chemical part of the final product. Catalysts are normally added in small quantities. The peroxides used with polyester resins are typical catalysts.
Coat	To cover with a finishing, protecting, or enclosing layer of any compound (such as varnish).
Coefficient of expansion	The fractional change in the dimension of a material for a unit change in temperature.
Cold flow (creep)	The continuing dimensional change that follows initial instantaneous deformation in a nonrigid material under static load.
Compound	Some combination of elements in a stable molecular arrangement.
Contact bonding	A type of adhesive (particularly non vulcanizing natural rubber adhesives) that bonds to itself on contact although solvent evaporation has left it dry to the touch.
Cross-linking	The forming of chemical links between reactive atoms in the molecular chain of a plastic. It is this cross-linking in thermosetting resins that makes them infusible.
Crystalline melting point	The temperature at which the crystalline structure in a material is broken down.
Cure	To change the physical properties of a material (usually from a liquid to a solid) by chemical reaction, by the action of heat and catalysts, alone or in combination, with or without pressure.
Curing agent	See *Hardener.*
Curing temperature	The temperature at which a material is subjected to curing.
Curing time	In the molding of thermosetting plastics, the time it takes for the material to be properly cured.
Dielectric constant (permittivity or specific inductive capacity)	The property of a dielectric that determines the electrostatic energy stored per unit volume for unit potential gradient.
Dielectric loss	The time rate at which electric energy is transformed into heat in a dielectric when it is subjected to a changing electric field.
Dielectric loss angle (dielectric phase difference)	The difference between 90° and the dielectric phase angle.
Dielectric loss factor (dielectric loss index)	The product of the dielectric constant and the tangent of the dielectric loss angle for a material.
Dielectric phase angle	The angular difference in phase between the sinusoidal alternating potential difference applied to a dielectric and the component of the resulting alternating current having the same period as the potential difference.
Dielectric power factor	The cosine of the dielectric phase angle (or sine of the dielectric loss angle).
Dielectric strength	The voltage that an insulating material can withstand before breakdown occurs, usually expressed as a voltage gradient (such as volts per mil).

TABLE 2.1 Definition of Terms for Plastic Materials *(Continued)*

Dissipation factor (loss tangent, tan δ, approximate power factor)	The tangent of the loss angle of the insulating material.
Elastomer	A material that, at room temperature, stretches under low stress to at least twice its length and snaps back to its original length on the release of stress. See *Rubber.*
Electric strength (dielectric strength or disruptive gradient)	The maximum potential gradient that a material can withstand without rupture. The value obtained for the electric strength will depend on the thickness of the material and the method and conditions of test.
Embed	To completely encase a component or assembly in some material—a plastic for current purposes. See *Cast, Pot.*
Encapsulate	To coat a component or assembly in a conformal or thixotropic coating by dipping, brushing, or spraying.
Exotherm	The characteristic curve of a resin during its cure, which shows heat of reaction (temperature) vs. time. Peak exotherm is the maximum temperature on this curve.
Exothermic	A chemical reaction in which heat is given off.
Filler	A material, usually inert, that is added to plastics to reduce cost or modify physical properties.
Film adhesive	A thin layer of dried adhesive. Also describes a class of adhesives provided in dry-film form with or without reinforcing fabric, which are cured by heat and pressure.
Flexibilizer	A material that is added to rigid plastics to make them resilient or flexible. Flexibilizers can be either inert or a reactive part of the chemical reaction. Also called a *plasticizer* in some cases.
Flexural modulus	The ratio, within the elastic limit, of stress to corresponding strain.
Flexural strength	The strength of a material in bending, expressed as the tensile stress of the outermost fibers of a bent test sample at the instant of failure.
Fluorocarbon	An organic compound having fluorine atoms in its chemical structure. This property usually lends stability to plastics. Teflon® is a fluorocarbon.
Gel	The soft, rubbery mass that is formed as a thermosetting resin goes from a fluid to an infusible solid. This is an intermediate state in a curing reaction, and a stage in which the resin is mechanically very weak. *Gel point* is defined as the point at which gelation begins.
Glass transition point	The temperature at which a material loses its glass-like properties and becomes a semiliquid.
Hardener	A chemical added to a thermosetting resin for the purpose of causing curing or hardening. Amines and acid anhydrides are hardeners for epoxy resins. Such hardeners are a part of the chemical reaction and a part of the chemical composition of the cured resin. The terms *hardener* and *curing agent* are used interchangeably. Note that these can differ from catalysts, promoters, and accelerators.
Heat-distortion point	The temperature at which a standard test bar (ASTM D-648) deflects 0.010 in under a stated load of either 66 or 264 lb/in^2.

TABLE 2.1 Definition of Terms for Plastic Materials *(Continued)*

Heat sealing	A method of joining plastic films by simultaneous application of heat and pressure to areas in contact. Heat may be supplied conductively or dielectrically.
Hot-melt adhesive	A thermoplastic adhesive compound, usually solid at room temperature, that is heated to a fluid state for application.
Hydrocarbon	An organic compound having hydrogen atoms in its chemical structure. Most organic compounds are hydrocarbons. Aliphatic hydrocarbons are straight-chained hydrocarbons, and aromatic hydrocarbons are ringed structures based on the benzene ring. Methyl alcohol and trichloroethylene are aliphatic; benzene, xylene, and toluene are aromatic.
Hydrolysis	The chemical decomposition of a substance involving the addition of water.
Hygroscopic	Tending to absorb moisture.
Impregnate	To force resin into every interstice of a part. Cloths are impregnated for laminating, and tightly wound coils are impregnated in liquid resin using air pressure or vacuum as the impregnating force.
Inhibitor	A chemical added to resin to slow down the curing reaction. Inhibitors are normally added to prolong the storage life of thermosetting resins.
Insulation resistance	The ratio of applied voltage to total current between two electrodes in contact with a specific insulator.
Modulus of elasticity	The ratio of stress to strain in a material that is elastically deformed.
Moisture resistance	The ability of a material to resist absorbing moisture, either from the air or when immersed in water.
Mold	To form a plastic part by compression transfer injection molding or some other pressure process.
NEMA standards	Property values adopted as standard by the National Electrical Manufacturers Association.
Organic	Composed of matter originating in plant or animal life, or composed of chemicals of hydrocarbon origin, either natural or synthetic. Used in referring to chemical structures based on the carbon atom.
Permittivity	Preferred unit of dielectric constant.
pH	A measure of the acid or alkaline condition of a solution. A pH of 7 is neutral (distilled water), pH values below 7 are increasingly acid as pH values go toward 0, and pH values above 7 are increasingly alkaline as pH values go toward the maximum value of 14.
Plastic	An organic resin or polymer.
Plasticizer	A material added to resins to make them softer and more flexible when cured.
Polymer	A high-molecular-weight compound (usually organic) made up of repeated small chemical units. Polymers can be thermosetting or thermoplastic.
Polymerize	To unite chemically two or more monomers or polymers of the same kind to form a molecule with higher molecular weight.
Pot	To embed a component or assembly in a liquid resin, using a shell, can, or case, which remains as an integral part of the product after the resin is cured. See *Embed, Cast*.

TABLE 2.1 Definition of Terms for Plastic Materials *(Continued)*

Pot life	The time during which a liquid resin remains workable as a liquid after catalysts, curing agents, promoters have been added; roughly equivalent to gel time. Sometimes also called *working life.*
Power factor	The cosine of the angle between the voltage applied and the resulting current.
Promoter	A chemical, itself a feeble catalyst, that greatly increases the activity of a given catalyst.
Resin	A high-molecular-weight organic material with no sharp melting point. For current purposes, the terms *resin, polymer,* and *plastic* can be used interchangeably.
Resistivity	The ability of a material to resist passage of electric current either through its bulk or on a surface. The unit of volume resistivity is the ohm-centimeter (Ω-cm), and the unit of surface resistivity is the ohm.
Rockwell hardness number	A number derived from the net increase in depth of impression as the load on a penetrator is increased from a fixed minimum load to a higher load and them returned to minimum load. Penetrators include steel balls of several specified diameters and a diamond cone.
Rubber	An elastomer capable of rapid elastic recovery.
Shore hardness	A procedure for determining the indentation hardness of a material by means of a durometer. Shore designation is given to tests made with a specified durometer.
Solvent	A liquid substance that dissolves other substances.
Storage life	The period of time during which a liquid resin or adhesive can be stored and remain suitable for use. Also called *shelf life.*
Strain	The deformation resulting from a stress, measured by the ratio of the change to the total value of the dimension in which the change occurred.
Stress	The force producing or tending to produce deformation in a body, measured by the force applied per unit area.
Surface resistivity	The resistance of a material between two opposite sides of a unit square of its surface. Surface resistivity may vary widely with the conditions of measurement.
Thermal conductivity	The ability of material to conduct heat; the physical constant for the quantity of heat that passes through a unit cube of a material in a unit of time when the difference in temperature of two faces is 1°C.
Thermoplastic	A classification of resin that can be readily softened and resoftened by repeated heating. Hardening is achieved by cooling.
Thermosetting	A classification of resin that cures by chemical reaction when heated and, when cured, cannot be resoftened by heating.
Thixotropic	Describing materials that are gel-like at rest but fluid when agitated.
Vicat softening temperature	A temperature at which a specified needle point will penetrate a material under specified test conditions.
Viscosity	A measure of the resistance of a fluid to flow (usually through a specific orifice).
Volume resistivity (specific insulation resistance)	The electrical resistance between opposite faces of a 1-cm cube of insulating material, commonly expressed in ohm-centimeters (Ω-cm). The recommended test is ASTM D-257-54T.

TABLE 2.1 Definition of Terms for Plastic Materials *(Continued)*

Vulcanization	A chemical reaction in which the physical properties of an elastomer are changed by causing it to react with sulfur or other cross-linking agents.
Water absorption	The ratio of the weight of water absorbed by a material to the weight of the dry material.
Wetting	The ability to adhere to a surface immediately on contact.
Working life	The period of time during which a liquid resin or adhesive, after mixing with a catalyst, solvent, or other compounding ingredients, remains usable. See *Pot life*.

TABLE 2.2 Significance of Important Electrical Insulation Properties

Property and definition	Significance of values
Dielectric strength	
All insulating materials fail at some level of applied voltage for a given set of operating conditions. The dielectric strength is the voltage that an insulating material can withstand before dielectric breakdown occurs. Dielectric strength is normally expressed in voltage gradient terms, such as volts per mil. In testing for dielectric strength, two methods of applying the voltage (gradual or by steps) are used. Type of voltage, temperature, and any preconditioning of the test part must be noted. Also, the thickness of the piece tested must be recorded because the voltage per mil at which breakdown occurs varies with the thickness of the test piece. Normally, breakdown occurs at a much higher volt-per-mil value in very thin test pieces (a few mils thick) than in thicker sections (1/8 in thick, for example).	The higher the value, the better the insulator. The dielectric strength of a material (per mil of thickness) usually increases considerably with a decrease in insulation thickness. Materials suppliers can provide curves of dielectric strength versus thickness for their insulating materials.
Resistance and resistivity	
Resistance of insulating material, like that of a conductor, is the resistance offered by the conducting path to passage of electric current. Resistance is expressed in ohms. Insulating materials are very poor conductors, offering high resistance. For insulating materials, the term volume resistivity is more commonly applied. Volume resistivity is the electrical resistance between opposite faces of a unit cube for a given material and at a given temperature. The relationship between resistance and resistivity is expressed by the equation $p = RA/l$, where p = volume resistivity in ohm-centimeters, A = area of the faces, and l = distance between faces of the piece on which measurement is made. This is not resistance per unit volume, which would be ohms per cubic centimeter, although this term is sometimes used erroneously. Other terms are sometimes used to describe a specific application or condition. One such term is surface resistivity, which is the resistance between two opposite edges of a surface film 1 cm square. Since the length and width of the path are the same, the centimeter terms cancel. Thus units of surface resistivity are actually ohms. However, to avoid confusion with usual resistance values, surface resistivity is normally given in ohms per square. Another broadly used term is insulation resistance, which again is a measurement of ohmic resistance for a given condition, rather than a standardized resistivity test. For both surface resistivity and insulation resistance, standardized comparative tests are normally used. Such tests can provide data such as effects of humidity on a given insulating material configuration.	The higher the value, the better; that is, a good insulating material. The resistance value for a given material depends on a number of factors. It varies inversely with temperature, and is affected by humidity, moisture content of the test part, level of the applied voltage, and time during which the voltage is applied. When tests are made on a piece that has been subjected to moist or humid conditions, it is important that measurements be made at controlled time intervals during or after the test condition has been applied, since dry-out and resistance increase occur rapidly. Comparing or interpreting data is difficult unless the test period is controlled and defined.

TABLE 2.2 Significance of Important Electrical Insulation Properties *(Continued)*

Property and definition	Significance of values
Dielectric constant	
The dielectric constant of an insulating material is the ratio of the capacitance of a capacitor containing that particular material to the capacitance of the same electrode system with air replacing the insulation as the dielectric medium. The dielectric constant is also sometimes defined as the property of an insulation which determines the electrostatic energy stored within the solid material. The dielectric constant of most commercial insulating materials varies from about 2 to 10, air having the value 1.	Low values are best for high-frequency or power applications, to minimize electric power losses. Higher values are best for capacitance applications. For most insulating materials, the dielectric constant increases with temperature, especially above a critical temperature region, which is unique for each material. Dielectric constant values are also affected (usually to a lesser degree) by frequency. This variation is also unique for each material.
Power factor and dissipation factor	
Power factor is the ratio of the power (watts) dissipated in an insulating material to the product of the effective voltage and current (volt-ampere) input and is a measure of the relative dielectric loss in the insulation when the system acts as a capacitor. The power factor is nondimensional and is a commonly used measure of insulation quality. It is of particular interest at high levels of frequency and power in such applications as microwave equipment, transformers, and other inductive devices. Low values are favorable, indicating a more efficient system, with lower losses. Dissipation factor is the tangent of the dielectric loss angle. Hence the term tan δ (tangent of the angle) is also sometimes used. For the low values ordinarily encountered in insulation, dissipation factor is practically the equivalent of power factor, and the terms are used interchangeably.	Low values are favorable, indicating a more efficient system, with lower losses.
Arc resistance	
Arc resistance is ak measure of an electrical breakdown condition along an insulating surface, caused by the formation of a conductive path on the surface. It is a common ASTM measurement, especially used with plastic materials because of the variations among plastics in the extent to which a surface breakdown occurs. Arc resistance is measured as the time, in seconds, required for breakdown along the surface of the material being measured. Surface breakdown (arcing or electrical tracking along the surface) is also affected by surface cleanliness and dryness.	The higher the value, the better, Higher values indicate greater resistance to breakdown along the surface due to arcing or tracking conditions.
Comparative tracking index	
This is an Underwriters Laboratories test which is run similar to arc resistance except that an electrolyte solution (ammonium chloride) is put on the surface. The CTI is the value of the voltage required to cause a conductive path to form between electrodes.	The test is useful because it measures the arc resistance on a contaminated surface, which is often the case with actual electrical and electronics equipment.

SOURCE: From Harper.[4] Reprinted with permission.

2.3 Thermoplastics

Thermoplastic materials are polymers that can be repeatedly softened when heated and hardened when cooled. Because the high temperatures required for melting may cause degradation, there is a limit to the number of reheat cycles for some thermoplastics. Thermoplastics are fabricated into parts by blow molding, extrusion, foaming, injection and rotational molding, stamping, and vacuum forming. Detailed descriptions of all thermoplastics can be found elsewhere.[5–7] Tables 2.3 to 2.6 contain basic property and application information on thermoplastics used in electrical and electronic applications. Supplier information is given in Kaplan,[5] and a brief description of these materials follows.

TABLE 2.3 General Characteristics of Thermoplastics

Material	Characteristic properties	Processing*	Electrical/electronic applications
Acrylics	Crystal clarity, good surface hardness, weatherability, chemical and environmental resistance, mechanical stability	1, 2, 3, 4, 5, 6	Colored electronic display filters, conformal coatings
Fluoroplastics	Heat resistance, superior chemical resistance, low dielectric losses, zero water absorption, low friction coefficient	9, 10, 11, 12, 13 Some fluoroplastics can be molded by more conventional methods (2, 7)	Wire and cable insulation, electrical components
Ketone plastics	Heat resistance, chemical resistance, high strength, resistance to burning, thermal and oxidative stability, excellent electrical properties, low smoke emission	1, 2, 8, 13	Wire insulation, cable connectors
Liquid crystal polymers	High-temperature resistance, chemical resistance, high mechanical strength, low thermal expansion	1	Chip carriers, sockets, connectors, relay cases
Nylon	Mechanical strength, tough, abrasion and wear resistance, low friction coefficient	1, 2, 3, 4, 6, 8	Connectors, wire jackets, wire ties, coil bobbins
Polyamide-imide	High-temperature resistance, superior mechanical properties at elevated temperature, dimensional stability, creep and chemical resistance, radiation resistance	1, 2, 7, 9	Connectors, circuit boards, radomes, films, wire coating
Polyarylate	Ultraviolet stability, dimensional stability, heat resistance, stable electrical properties, flame-retardant, flame-retardant, high arc resistance	1, 2, 3, 4	Connectors, coil bobbins, switch and fuse covers, relay housings
Polycarbonate	Clarity, toughness, heat resistance, flame-retardant	1, 2, 3, 4	Connectors, terminal boards, bobbins
Polyesters (PBT, PCT, PET)	Good electrical properties, chemical resistance, high-temperature resistance, low moisture absorption	1, 2	Connectors, sockets, chip carriers, switches, coil bobbins, relays

TABLE 2.3 General Characteristics of Thermoplastics *(Continued)*

Material	Characteristic properties	Processing*	Electrical/electronic applications
Polyetherimide	Good high-temperature strength, dimensional stability, chemical resistance, long-term heat resistance, low smoke generation	1, 2, 3, 7	Connectors, low-loss radomes, printed circuit boards, chip carriers, sockets, bobbins, switches
Polyolefins	Range of strength and toughness, chemical resistance, low friction coefficient, processability, excellent electrical properties	1, 2, 3, 4, 7, 8	Wire and cable insulation
Polyimides	Superior high-temperature properties, radiation resistance, flame resistance, good electrical properties	1, 6, 7	Insulation for electric motors, magnet wire, flat cable, integrated-circuit applications
Polyphenylene oxide	Low moisture absorption, good electrical properties, chemical resistance	1, 2, 3, 4	Connectors, fuse blocks
Polyphenylene sulfide	Flame resistance, high-temperature resistance, dimensional stability, chemical resistance, good electrical properties	1	Connectors
Polyphthalamide	Good combination of mechanical, chemical, and electrical properties	1	Connectors, switches
Styrenes	Range of mechanical, chemical, electrical properties depending on type of styrene polymer, low dielectric losses	1, 2, 3, 4, 8	Housings
Polysulfones	High-temperature resistance, excellent electrical properties, radiation resistance	1, 2	Circuit boards, connectors, TV components
Vinyls	Range of properties depending on type	1, 2, 3, 4	Wire insulation, tubing, sleeving

[*] 1 Injection molding
2 Extrusion
3 Thermoforming
4 Blow molding
5 Machining
6 Casting
7 Compression molding
8 Rotational molding
9 Powder metallurgy
10 Sintering
11 Dispersion coating
12 Compression molding
13 Electrostatic coating

SOURCE: From Harper[4] and Kaplan.[5] Reprinted with permission.

TABLE 2.4 Typical Physical Properties of Thermoplastics

Resin material	Coefficient of thermal expansion, 10^{-5} in/in/°C	Thermal conductivity 10^{-4} cal-cm/sec-cm^2°C	Water absorption 24 h, %	Flammability,* in/min	Specific gravity
ABS	6–13	4–9	0.2–0.5	1.0–2	1.01–1.07
Acrylic	–9	1.4	0.3	9–1.2	1.18–1.19

TABLE 2.4 Typical Physical Properties of Thermoplastics *(Continued)*

Resin material	Coefficient of thermal expansion, 10^{-5} in/in/°C	Thermal conductivity 10^{-4} cal-cm/sec-cm^2°C	Water absorption 24 h, %	Flammability,* in/min	Specific gravity
Chlorotrifluoroethylene	3.6	4–6	Nil	Nil	2.8–2.2
Fluorinated ethylene propylene	8.3–10.5	5.9	<0.05	Nonflammable	2.16
Polytetrafluoroethylene	2–12	6	<0.01	Nonflammable	2.14–2.28
Nylon 6	1.1–8.0	5.9	1.5	Self-extinguishing	1.07–1.15
Polycarbonate	6.7–7	4.6	0.15	Self-extinguishing	1.2
Polyethylene, low density	10–20	8	<0.01	Slow burning	0.910–0.925
Polyethylene, medium density	10–20	8	<0.01	Slow burning	0.926–0.940
Polyphthalamide	0.8–3.3	1.7–2.6	0.1–0.8	Self-extinguishing	1.13–1.70
Polyamide-imide	3.0	6.2	0.33	Self-extinguishing	1.42
Polyarylate	2.7–4.0	—	0.1–0.2	Self-extinguishing	1.19–1.22
Polybutylene terephthalate	6.0–9.5	4.2–6.9	0.08	—	1.30–1.38
Polyethylene terephthalate	6.5	3.4	0.1–0.2	—	1.29–1.40
Polyethylene, high density	5–11	11–12	<0.01	Slow burning	0.941–0.965
Polyethylene, high molecular weight	7–11	8	<0.01	Slow burning	0.93–0.94
Polyethylene, UHMW	13–20	—	<0.01	Slow burning	0.94
Polyimide	4.5–5.6	2.3–2.6	0.24	—	
Polypropylene	3.8–9	2.8–4	<0.01	Slow burning to non burning	0.90–1.4
Polystyrene	5–8	3	0.01–0.03	0.5–2.5	1.04–1.05
Polyurethane	10–20	7.4	0.60–0.80	Slow to self-extinguishing	1.11–1.26
Polyvinyl chloride (flexible)	7–25	3–5	0.15–0.75	Self-extinguishing	1.15–1.80
Polyvinyl chloride, rigid	5–10	3–5	0.07–0.40	Self-extinguishing	1.33–1.58
Polyvinyl dichloride, rigid	7–8	3–4	0.07–0.11	Self-extinguishing	1.50–1.54
Styrene acrylonitrile (SAN)	7	3	0.15–0.25	0.4–0.25	1.07–1.08
Polyphenylene oxide	3.8–7.0	3.8	0.06–0.1	Self-extinguishing	1.04
Polysulfone	5.6	6.2	0.3	Self-extinguishing	1.24–1.25

TABLE 2.4 Typical Physical Properties of Thermoplastics *(Continued)*

Resin material	Coefficient of thermal expansion, 10^{-5} in/in/°C	Thermal conductivity 10^{-4} cal-cm/sec-cm^2°C	Water absorption 24 h, %	Flammability,* in/min	Specific gravity
Polyarylsulfone	3.1–4.9	—	0.1	Self-extinguishing	1.37‘
Polyethersulfone	5.5	3.2–4.4	0.12–1.7	Self-extinguishing	1.37
Polyetheretherketone	4.0–4.7	—	0.1	Self-extinguishing	1.31
Polyetherketone	1.8	10.5	0.05	Self-extinguishing	1.30
Polycyclohexylene dimethyl terephthalate (PCT), 30% glass reinforced	2.0	6.9	0.05		
Polyetherimide	4.7–5.6	1.6	0.25	Self-extinguishing	1.27
Polyphenylene sulfide	2.7–4.9	2.0–6.9	0.05	Self-extinguishing	1.35

*Samples 0.125 in thick.
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2.3.1 Acrylics

Acrylic resins comprise a range of polymers and copolymers that are derived from acrylic acid-esters and their derivatives. These polymers are made by free-radical polymerization, and modifications are effected by the incorporation of other monomers during polymerization or by blending other resins such as vinyls, butadiene, polyester, or other acrylics so as to alter specific properties of the resin. Acrylics are characterized by their exceptional transparency (92 percent light transmission), with haze measurements ranging from 1 to 3 percent. They exhibit good weatherability and are resistant to solutions of inorganic acids, alkalies, and aliphatic hydrocarbons. Acrylics are attacked by chlorinated, aromatic, ester, and ketone solvents. The maximum service temperature is about 90°C, but it can go as high as 155°C with the new acrylic-imide copolymers. The excellent arc and track resistance of the acrylics has made them a good choice in some high-voltage applications such as circuit breakers. Acrylics are among the few plastics that exhibit an essentially linear decrease in dielectric constant and dissipation factor with increasing frequency. The acrylics are produced in many forms, including film, rod, sheet, tube, powder, solutions, and reactive syrups. Acrylics can also be formed into thermosetting resins, which are discussed in the section dealing with thermosetting resins. Resin suppliers include DuPont, Dow Chemical, Exxon, GE, ICI Acrylics, Asahi, and BASF.

2.3.2 Fluoropolymers

These materials are a class of hydrocarbon polymers that has some or all of its hydrogens replaced by fluorine or chlorine. They are polytetrafluoroethylene

TABLE 2.5 Typical Physical and Mechanical Properties of Thermoplastics

Resin material	Impact strength, notched (Izod), ft- lb/in, 1/8-in bar	Tensile strength 10^2 lb/in^2	Tensile modulus 10^2 lb/in^2	Elongation, %	Flexural strength 10^2 lb/in^2	Compressive strength 10^2 lb/in^2	Compressive modulus 10^2 lb/in^2	Heat distortion temperature, at 264 lb/in^2 °F	Heat resistance, continuous, °F
ABS	1.5–12	2.5–5.8	120–420	20–100	5–13.5	5–11	120–200	180–245	160–235
Acrylic	0.3–0.4	8.7–11.0	350–450	3–6	2–7	11–19	350–430	167–198	130–195
Chlorotrifluoroethylene	2.5–5.0	6	150–300	80–250	7.4–11	4.6–7.4	180	160–170	390
Fluorinated ethylene propylene	No break	2–3.2	50	250–350	—	2.2	70	124	400
Polytetrafluoroethylene	No break	2–5	50–80	200–400	—	1.7	70–90	132	500
Nylon 6		0.9–4	9.5–12.4	100–380	25–300	5.8–15.7	13–16	347	150–175
Polycarbonate	12–16	8–9.5	345	110–120	13.5	10–12.5	350	265–290	250
Polyethylene, low density	No break	1–2.4	14–38	100–965	—	—	—	—	140–175
Polyethylene, medium density	No break	1.7–2.8	50–80	100–965	—	—	—	—	150–180
Polyethylene, high density	0.4–4.0	2.8–5	75–200	10–1200	1–4	2.7–3.6	50–110	110–125	180–225
Polyethylene, high molecular weight	4.5	2.3–5.4	136	170–800	3.5	2.4	110	120	180–225
Polyimide	1.5	5–14.0	300	8–10	19–28.8	30–40	—	680	500–600
Polyethylene	0.5–1.5	4.5–6.0	150–650	100–600	6.0	5–8	—	140–205	250
Polystyrene	0.40	5.2–7.5	400–500	1.5–2.5	10–15	11.5–16	300–560	160–215	150–190
Polyurethane	No break	4.5–8	1–3.7	60–120	0.1	>20	85	—	190
Polyvinyl chloride, flexible	Varied	1–4	—	200–450	—	—	—	—	150–175
Polyvinyl chloride, rigid	0.4–22	7.5	200–600	40–80	10–15	10–11	300–400	140–175	160–165

TABLE 2.5 **Typical Physical and Mechanical Properties of Thermoplastics *(Continued)***

Resin material	Impact strength, notched (Izod), ft- lb/in, 1/8-in bar	Tensile strength 10^2 lb/in^2	Tensile modulus 10^2 lb/in^2	Elongation, %	Flexural strength 10^2 lb/in^2	Compressive strength 10^2 lb/in^2	Compressive modulus 10^2 lb/in^2	Heat distortion temperature, at 264 lb/in^2 °F	Heat resistance, continuous, °F
Polyvinyl dichloride, rigid	1.0–6.0	7.5–9.0	360–450	160–240	14.2–17	13–22	—	212–235	195–235
Styrene acrylonitrile (SAN)	0.4–0.6	10	475–560	2–3	11–19	15–17.5	650	200–218	170–210
Polyphenylene oxide	3–6	6.8–7.8	380	50	8.3–12.8	15	380	375	250
Polysulfone	0.6–1.0	10.2	360	50–100	15.4	15.4	370	345	300
Polyphthalamide	1.0	>1.5	—	—	23.3	—	—	248	300
Polamide-imide	2.7	22	650	7	27.4–34.9	32	—	532	430
Polybutylene terephthalate	0.7–1.0	8.2	280–430	50–300	12–16.7	8.6–14.5	—	122–185	270
Polyethylene terephthalate	0.25–0.7	7–10	400–600	30–300	14–18	11–15	—	70–100	—
Polyethylene, UHMW	No break	5.6–7.0	—	420–525	—	—	—	110–120	—
Polyarylsulfone	1.2	9.0	310–380	40–60	12.4–16.1	—	374	400	—
Polyethersulfone	1.4	9.8–13.8	350	6–80	17–18.7	11.8–15.6	—	395	350
Polyetherketone	1.6	13.5	520	50	24.5	20	—	323	—
Polyetheretherketone	2.0	10–15	—	30–150	16	18	—	—	—
Polyetherimide	1.1	14	430	60	22	20	420	390	330–350
Polyphenylene sulfide	<0.5	7–12	480	1–3	14–20	16	—	250	350–400
Polycyclohexylene di-methyl terephthalate (PCT), 30% glass reinforced	1.7	18–19	—	1.9	24–28	—	—	500	300

SOURCE: From Harper[4] and Kaplan.[5] Reprinted with permission.

TABLE 2.6 Typical Electrical Properties of Thermoplastics

Resin material	Volume resistivity Ω-cm	Dielectric constant at 60 Hz	Dielectric strength, ST, 1/8-in thickness, V/mil	Dissipation or power factor at 60 Hz	Arc resistance, s
ABS	10^{15}–10^{17}	2.6–3.5	300–450	0.003–0.007	45–90
Acrylic	$>10^{14}$	3.3–3.9	400	0.04–0.05	No tracking
Chlorotrifluoroethylene	10^{18}	2.65	450	0.015	>360
Fluorinated ethylene propylene	$>10^{18}$	2.1	500	0.0002	>165
Polytetrafluoroethylene	$>10^{18}$	2.1	400	<0.0001	No tracking
Nylon 6	10^{14}–10^{15}	6.1	300–400	0.4–0.6	140
Polycarbonate	6.1×10^{15}	2.97	410	0.0001–0.0005	10–120
Polyethylene, low density	10^{15}–10^{18}	2.98	450–1,000	0.006	Melts
Polyethylene, medium density	10^{15}–10^{18}	2.3	450–1,000	0.0001–0.0005	Melts
Polyethylene, high density	6×10^{15}–10^{18}	2.3	450–1,000	0.002–0.0003	Melts
Polyethylene, high molecular weight	$>10^{16}$	2.3–2.6	500–710	0.0003	Melts
Polyimide	10^{16}–10^{17}	3.5	400	0.002–0.003	230
Polypropylene	10^{15}–10^{17}	2.1–2.7	450–650	0.005–0.0007	36–136
Polystyrene	10^{17}–10^{21}	2.5–2.65	500–700	0.0001–0.0005	60–100
Polyurethane	2×10^{11}	6–8	850–1,100	0.276	—
Polyvinyl chloride, flexible	10^{11}–10^{15}	5–9	300–1,000	0.08–0.15	60–80
Polyvinyl chloride, rigid	10^{12}–10^{16}	3.4	425–1,040	0.01–0.02	—
Polyvinyl dichloride, rigid	10^{15}	3.08	1,200–1,550	0.018–0.0208	—
Styrene acrylonitrile (SAN)	10^{15}	2.8–3	400–500	0.006–0.008	100–500
Polyphenylene oxide	10^{17}	2.58	400–500	0.00035	75
Polysulfone	5×10^{16}	2.82	425	0.008–0.0056	122
Polyarylate	2×10^{14}	3.08	610	0.002	125
Polybutylene terephthalate (PBT)	1.4×10^{15}	3.3	420	0.002	190
Polybutylene terephthalate (PBT)	2×10^{15}	3.2	470–530	0.0018	68–136

TABLE 2.6 Typical Electrical Properties of Thermoplastics

Resin material	Volume resistivity Ω-cm	Dielectric constant at 60 Hz	Dielectric strength, ST, 1/8-in thickness, V/mil	Dissipation or power factor at 60 Hz	Arc resistance, s
Polyethylene terephthalate (PET)	1×10^{15}	3.8	650	0.0059	123
Polyphenylene sulfide, 40% glass	10^{16}	3.5–3.8	340–450	0.0012	34
Polyetherimide	$6.7–10^{17}$	3.15	750–831	0.0013	126
Polyetherketone	10^{17}	3.5	—	0.002	—

SOURCE: From Harper[4] and Kaplan.[5] Reprinted with permission.

(PTFE), fluorinated ethylene-propylene (FEP), perfluoroalkoxy (PFA), ethylene-tetrafluoroethylene (ETFE), polyvinylidene fluoride (PVDF), polychlorotrifluoroethylene (PCTFE), ethylene-chlorotrifluoroethylene (ECTFE), and polyvinyl fluoride (PVF). The fluoropolymers and copolymers are synthesized by free-radical polymerization techniques. The polymers are characterized by their unique combination of chemical, electrical, mechanical, and thermal properties. They do not support flame propagation, are unaffected by most chemicals, and have excellent arc resistance, low dielectric losses, and essentially zero water absorption. Their limitation is that these polymers are relatively soft, difficult to process, expensive, and subject to creep. Service temperatures for these materials range from 110 to 260°C, depending on the type of polymer. Some specific properties of these materials are given in Table 2.7. Fluoropolymers are used in electronic circuits as coatings, films, tubing, fibers, and tapes. Suppliers include Elf Atochem, DuPont, Dyneon, Creanova, Solvay, and Ausimont.

2.3.3 Ketone resins

These materials are partially crystalline polymers and are characterized by the presence of the phenyl ring and both ether (–O–) and ketone (R_2–C=O) groups in the polymer chain. There are several types of ketone polymers that are synthesized by condensation polymerization. The major ketone polymers are polyetherketone (PEK), polyetheretherketone (PEEK), and polyetherketonetherketoneketone (PEKEKK). These polymers are characterized by their excellent elevated-temperature properties, with continuous service temperatures approaching 260°C. The polymers are tough and have high impact strength as well as good dielectric strength, volume, and surface resistivity. Only concentrated, anhydrous, or strong oxidizing acids have an effect on these polymers. Common organic solvents do not attack these polymers, and they are highly resistant to hot-water hydrolysis. Their main use is for wire and cable insulation and connectors. Suppliers include Solvay, Shell, and Victrex.

TABLE 2.7 Properties of Fluoropolymers

	PTFE	FEP	PFA	ETFE	PVDF	PCTFE	ECTFE	PVF
Percent fluorine	76.0	76.0	76.0	59.4	59.4	48.9	39.4	41.3
Melting point, °C	327	265	310	270	160	218	245	200
Upper use temperature, °C	260	200	260	180	150	204	170	110
Density, g/cm^3	2.13	2.15	2.12	1.7	1.78	2.13	1.68	1.38
Oxygen index, %	>95	95	95	28–32	44	—	48–64	—
Arc resistance, seconds	>240	>300	≥300	72	60	2.4	18	—
Dielectric constant	2.1	2.1	2.1	2.6	9–10	2.5	2.5	9
Dissipation factor	0.0002	0.0002	0.0002	0.0008	0.02–0.02	0.02	0.003	0.002
Tensile strength, lb/in^2	5000	3100	4300	7000	6200	6000	—	—
Specific gravity	2.2	2.17	2.17	1.7	1.78	2.2	1.68	—
Water absorption, % 24 h	0	0	0.03	0.03	0.06	0	—	—
Electrical strength, V/mil	480	600	500	400	280	600	—	—

SOURCE: From Harper.[8] Reprinted with permission.

2.3.4 Liquid crystal polymers

These polymers belong to a material class that exhibits a highly ordered structure in both melt and solid states. Because of the high degree of molecular ordering, liquid crystal polymers (LCPs) exhibit a high degree of anisotropy. If the liquid crystalline phase forms on melting the polymer, it is known as a *thermotropic* liquid crystal, and if it forms in solution as the result of solvent addition, it is known as *lyotropic*. Condensation polymerization has been used to prepare these polymers. A number of polymers exhibit liquid crystalline behavior, but the three commercially important polymers are Xydar (Solvay Advanced Polymers, LLC), Vectra (Ticona Corp.), and the Zenite series (E.I. DuPont de Nemours & Co). There is no one chemical structure that characterizes LCPs; however, all LCPs have these common characteristics: the molecular shape has a large aspect ratio (length or diameter to width or thickness), the molecule has a large polarizability along the rigid chain axis as compared to the transverse direction, and the molecule must have good molecular parallelism of the rigid units comprising its structure.[8] To meet these requirements, an LCP should possess a rigid molecular structure, as do all three of these materials.

The major properties that characterize LCPs are low melt viscosity; exceptional tensile, compressive, and modulus values; and outstanding chemical, radiation, and thermal stability. A general comparison of flexural moduli and mold shrinkage for LCPs and other polymers is given in Figs. 2.4 and 2.5, and

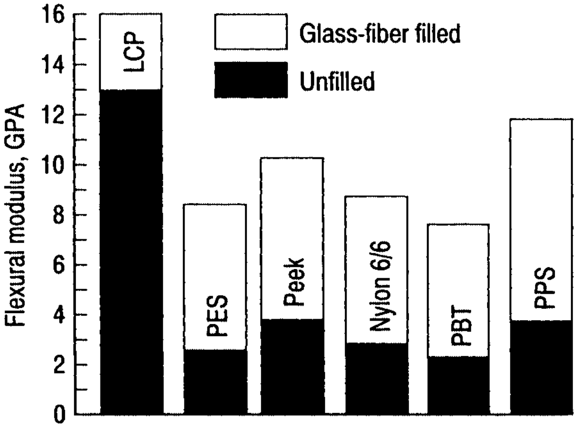

Figure 2.4 Comparison of flexural moduli of selected thermoplastics. *(From Klein,[10] reprinted with permission.)*

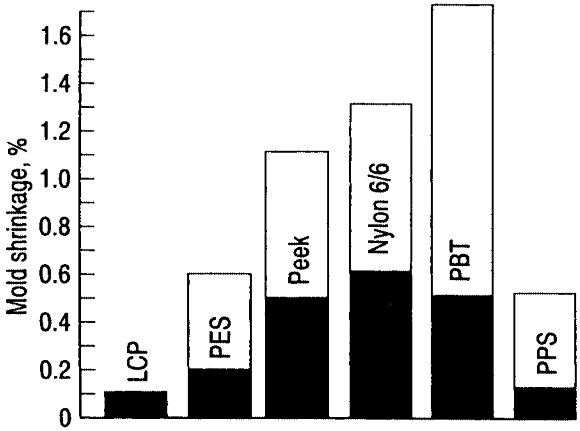

Figure 2.5 Comparison of mold shrinkage of selected thermoplastics. *(From Klein,[10] reprinted with permission.)*

Table 2.8 presents a comparison of specific properties of filled LCPs. The main uses for these polymers in the electronics industry are for the molding of high-precision complex parts, chip carriers, sockets, connectors, pin-grid arrays, bobbins, and relay cases.

2.3.5 Nylons

These materials, also known as polyamides, are characterized by having the amide group (–CONH–) as an integral part of the polymer structure. While this chemical unit is present in all nylons, the multiplicity of monomers that can be used to prepare nylons has led to a wide variety of materials with different properties. Presently, there are 12 types of nylons available;[11] 10 are aliphatic, and 2 are aromatic. Nylons are synthesized by both condensation

TABLE 2.8 Typical Properties of LCP Molding Compounds

Grade	[*]Vectra A130	*Vectra B230	*Vectra A430	[†]Xydar G930	†Xydar MG350	[‡]Zenite 3130	‡Zenite 6140
Fillers	30% glass fiber	30% carbon fiber	50% glass/mineral, 5% graphite flake	30% glass fiber	50% mineral/ glass	30% glass fiber	40% glass fiber
Tensile strength, 10^3 lb/in^2	27.7	29.1	23.3	19.6	13.1	20.3	19.2
@ temperature	1.9 @ 400°F	—	1.5 @ 400°F	2.8 @ 500°F	2.3 @ 500°F	—	—
Elongation, %	2.1	6.2	0.7	1.6	0.9	1.8	1.4
Flex modulus, 10^6 lb/in^2	2.2	3.7	1.0	2.26	2.33	1.7	2.2
@ temperature	0.85 @ 428°F	0.41 @ 428°F	—	0.46 @ 500°F	0.29 @ 500°F	—	—
Impact strength, notched, ft-lb/in	2.8	1.4	1.9	1.8	0.9	—	1.6
Coeff. thermal expansion, ppm/°F							
Flow direction	0.6	1.1	0.6	2.7	4	—	—
Transverse	26	2.1	45	43	33	—	—
Dielectric strength, V/mil	790¶	—	—	1,000§	970	—	—
Heat deflection temperature @ 264 lb/in^2, °F	446	440	437	520	532	441	522
Dielectric constant @ 1 MHz	3.7	3.2	2.7	3.9	3.9	—	—
Dissipation factor @ 1 MHz	0.018	—	0.016	—	0.029	—	—
Resistivity, Ω-cm	10^{15}	10	10^{15}	—	—	—	—

[*] Ticona
[†] Solvay Advanced Polymers
[‡] DuPont
¶At 1.50-mm thickness
§At 1.6-mm thickness
SOURCE: Supplier web sites

polymerization (types 6/6, 6/9, 6/10, 6/12) and addition polymerization (types 6, 11, 12). Most nylons are partially crystalline polymers. The nylons can be modified by the addition of additives or copolymerized with other monomers to produce a wide range of materials with different properties. In addition, some blending of nylon polymers can be done with acrylonitrile-butadiene-styrene and polyphenylene ether polymers. Transparent nylon is available, and, unlike the other grades of nylon polymers, it is amorphous. The nylons are strong, tough thermoplastics having good tensile, flexural, friction, and impact properties. Nylons can operate satisfactorily over the temperature range of 0 to 149°C. All nylons are hygroscopic, although the degree of water absorption decreases with increasing hydrocarbon chain length. This moisture absorption affects some physical properties. For example, it has a plasticizing effect on the polymer and increases flexural and impact strength while decreasing tensile strength. The electrical properties of nylons are quite sensitive to moisture and deteriorate with increasing water content. Nevertheless, these properties are quite adequate to allow the use of nylons in most 60-Hz power applications. Nylons have good chemical resistance to hydrocarbons and aromatic and aliphatic solvents and are attacked by strong acids, bases, and phenols. Elevated temperature and ultraviolet radiation exposure will degrade nylon depending on the duration and level of the exposure. The nylons can be processed by almost all of the common thermoplastic fabrication techniques. The reader is directed to the references for additional information and specific properties.[4,6,10] Applications for nylons include card guides, connectors, terminal blocks, antenna mounts, coil bobbins, and receptacle plugs. Resin suppliers include Honeywell, Quadrant, DuPont, Elf Atochem, and Bayer.

2.3.5.1 High-temperature nylon. . In addition to the aforementioned nylons, there is another class of polyamides that is based on the presence of an aromatic ring in the chemical structure. Two materials compose this class: Nomex [(poly)1,3-phenylene isophthalamide] and Kevlar [(poly)1,4-phenylene terephthalamide] (both registered trademarks of E.I. dupont de Nemours & Co.).

Kevlar is spun into fiber and is mostly used in composite applications, while Nomex is processed into fiber, paper, sheet, and pressboard and is used extensively in the electrical industry as insulation for transformer coils and motor stators. Nomex is recognized by Underwriters Laboratories as a 220°C material. Table 2.9 gives some electrical properties of Nomex.

2.3.6 Polyamide-imides

These polymers are amorphous materials produced by the condensation polymerization of trimellitic anhydride and aromatic diamines. The characteristic chemical groups in the polymer chain are the amide linkage (–CONH–) and the imide linkage (–CONCO–). These polymers can be solution cast into film or converted into powders for further processing into various forms. The poly-

TABLE 2.9 Electrical Properties of Nomex[*]

Nomex	Thickness, mil	Dielectric, strength, V/mil, ASTM D-149	Dielectric constant, at 60 Hz, ASTM D-150	Dissipation factor at 60 Hz, ASTM D-150	Volume resistivity, Ω-cm, ASTM D-257
410	3	540	1.6	0.005	10^{16}
411	5	230	1.2	0.003	—
414	3.4	530	1.7	0.005	10^{16}
418	3	730	2.9	0.006	10^{16}
419	7	325	2.0	—	—
992	125	380	1.7	0.020	10^{17}
993	120	540	2.6	0.015	10^{17}
994	250		3.5	0.010	10^{16}

[*] Unless otherwise noted, the Nomex properties are typical values measured by air under "standard" conditions (in equilibrium at 23°C, 50% relative humidity) and should not be used as specification limits. The dissipation factors of types 418, 419, 992, and 993 and all of the volume resistivities are measured under dry conditions. Nomex is a registered trademark of E.I. duPont de Nemours & Co. for its aramid products.

SOURCE: From duPont Co.[12] Reprinted with permission.

mers possess outstanding high-temperature (260°C) and radiation stability (109 rads) as well as excellent mechanical properties, low dielectric losses, and good wear resistance. The polymers are useful over a wide temperature range (–195 to +260°C) and are inherently fire-resistant (oxygen index of 43 and UL-94 rating of V-0). Their chemical resistance is excellent, but they are attacked by hot caustics and acid as well as steam. Applications for molded parts include electronic connectors and jet engine component generator parts. The solution form of the polymer is used for wire enamels and a variety of electronics applications. Suppliers include Quadrant and Solvay.

2.3.7 Polyimides

These materials are derived from the solution condensation polymerization of aromatic dianhydrides and diamines and are characterized by the presence of only the imide linkage (–CONCO–). The polyimides are characterized by high glass transition temperatures, excellent radiation resistance, toughness, good electrical properties, and good flame resistance. The properties of polyimides can be modified by adjusting both the type and the ratio of the monomers. Fillers have also been added to polyimides to alter their properties. These modifications have produced a variety of polyimide materials. The polyimides can be processed in solution or powder form and can be converted into films, molding powders, tapes, and varnishes. Polyimides can be compression and injection molded, but considerable expertise is required because of the high glass transition temperatures and melt viscosities of these polymers. Kapton® is perhaps the most widely known of the polyimide family, but other types include Vespel® and Pyralin® (DuPont), and Pyre ML® (Industrial Summit Technologies). Although there are differences in the properties of the various polyimides, the properties of the polyimide family are illustrated with those of Kapton film. Tables 2.10 and 2.11 show these properties. Further details are available in Ghosh and Mittal.[14]

TABLE 2.10 Physical and Electrical Properties of Kapton 100 HN Film

Physical properties	Typical values at 23°C (73°F)	Typical values at 200°C (392°F)	Test method
Ultimate tensile strength, MPa (psi)	231 (33,500)	139 (20,000)	ASTM D-882-91, Method A*
Yield point at 3%, MPa (psi)	69 (10,000)	41 (6,000)	ASTM D-882-91
Stress to produce 5% elongation, MPa (psi)	90 (13,000)	61 (9,000)	ASTM D-882-91
Ultimate elongation, %	72	83	ASTM D-882-91
Tensile modulus, GPa (psi)	2.5 (370,000)	2.0 (290,000)	ASTM D-882-91
Impact strength, N-cm (ft–lb)	78 (0.58)		DuPont pneumatic impact test
Folding endurance (MIT) cycles	285,000		ASTM D-2176-89
Tear strength—propagating (Elmendorf), N (lbf)	0.07 (0.02)		ASTM D-1922-89
Tear strength—initial (Graves), N (lbf)	7.2 (1.6)		ASTM D-1004-90
Density, g/cc	1.42		ASTM D-1505-90
Coefficient of friction–kinetic (film-to-film)	0.48		ASTM D-1894-90
Coefficient of friction–static (film-to-film)	0.63		ASTM D-1894-90
Refractive index (sodium D line)	1.70		ASTM D-542-90
Poisson's ratio	0.34		Avg. 3 samples Elongated at 5%, 7%, 10%
Low temperature flex life	Pass		IPC TM650, Method 2.6.18
Dielectric strength at 60 Hz, V/mil	7,700		ASTM D-149-91
Dielectric constant at 1 kHz	3.4		ASTM D-150-92
Dissipation factor	0.0018		ASTM D-150-92
Volume resistivity, Ω-cm	1.5×10^{17}		ASTM D-257-91

*Specimen size: 25 × 150 mm; jaw separation: 100 mm; jaw speed 50 mm/min; "ultimate" refers to the tensile strength and elongation measured at break.

SOURCE: DuPont,[12] reprinted with permission.

TABLE 2.11 Thermal Properties of Kapton 100HN Film

Thermal properties	Typical values	Test condition	Test method
Melting point	None	None	ASTM E-794-85 (l989)
Coefficient of thermal expansion	20 ppm/°C (11 ppm/°F)	–14 to +38°C	ASTM D-696-91
Thermal conductivity (W/m-K)	0.12	296 K	ASTM F-433-77 (l987)
(cal/cm-s-°C)	2.87×10^{-4}	23°C	
Specific heat (J/g-K)	1.09		Differential Scanning
(cal/g-°C)	0.261		Calorimetry
Flammability	94 V-O		UL-94 (2-8-85)
Shrinkage (%)	0.17	30 min @ 150°C	IPC TM 650, Method 2.2.4A
	1.25	120 min @ 400°C	ASTM D-5214-91
Heat sealability	Not heat sealable		
Limiting oxygen index, %	37		ASTM D-2863-87
Solder float	Pass		IPC-TM-650, Method 2.4.13A
Smoke generation	DM<1	NIST smoke chamber	NFPA-258
Glass transition temperature	A second-order transition occurs in Kapton between 360°C (680°F) and 410°C (770°F) and is assumed to be the glass transition temperature. Different measurement techniques produce different results within the above temperature range.		

SOURCE: DuPont[12] Reprinted with permission.

2.3.8 Polyetherimide

Although this material belongs to the polyimide family of resins and has properties similar to those of the all-aromatic polyimides, it has lower thermal stability. (It is UL-rated for 170°C continuous use, compared to 220°C for Kapton polyimide.) It is an amorphous polyimide having aromatic imide and ether repeating units in its molecular chain. It processes much better on conventional thermoplastic equipment compared to the completely aromatic polyimides and is easily molded into complex shapes. It has a UL-94 V-0 flame resistance rating and an oxygen index of 47. Chemical resistance is good against hydrocarbons, and it resists mild acid and base for short exposure times. It has excellent ultraviolet and gamma radiation resistance (94 percent retention of tensile strength after exposure to 400 Mrads of cobalt irradiation). The polymer retains 85 percent of its tensile strength after 104 h in boiling water. Electrical properties show very good stability under various conditions of temperature, humidity, and frequency. Its low dissipation factor makes it transparent to microwaves. Applications include low-loss radomes, printed-wiring boards, IC chip carriers, bobbins, and infrared switches. Selected properties of Ultem®, a representative polyetherimide from GE Plastics, are listed in Table 2.12.

TABLE 2.12 Properties of Ultem® Polyetherimide

Property	Ultem 1000 unfilled	Ultem 2300 30% glass	Method
Tensile strength (psi @ 0.2 in/min)	16,000	24,500	ASTM D-638
Tensile modulus (psi @ 0.2 in/min)	520,000	1,350,000	ASTM D-638
Flexural modulus (psi)	510,000	1,300,000	ASTM D-790
Izod impact, notched (ft-lb/in @ 73°F)	1.0	1.6	ASTM D-256
Coefficient of thermal expansion			ASTM E-831
Flow (ppm/°F @ 0–300°F)	31	11	
Cross-flow (ppm/°F @ 0–300°F)	30	—	
Thermal conductivity (W/m-C)	0.22	—	ASTM C-177
Volume resistivity (Ω-cm)	1×10^{17}	3×10^{16}	ASTM D-257
Dielectric strength (V/mil in air; 0.062 in)	831	630	ASTM D-149
Dielectric constant (1 kHz)	3.15	3.70	ASTM D-150
Dissipation factor (1 kHz)	0.0015	0.0015	ASTM D-150

SOURCE: GE Plastics web site, www.geplastics.com

2.3.9 Polyarylate and polyesters

The thermoplastic polyesters include polyarylate (PA), polybutylene terephthalate (PBT), polyethylene terephthalate (PT), and polycyclohexylene dimethylene terephthalate (PCT). These linear polyesters range from amorphous to crystalline materials and have the characteristic ester functional group (–COOR–) present along the polymer chain. Except for the polyarylates, the other polyesters are made by a transesterification of the appropriate alcohol and ester monomers. Polyarylate is prepared from the reaction of bisphenol A and a mixture of isophthalic and terephthalic acids. Because of the variety of alcohols, acids, and esters that are available for reaction, polyesters with a broad range of properties can be synthesized. Suppliers include Eastman, Honeywell, Bayer, DuPont, Dow Chemical, GE, Ticona, and Creanova.

Polyarylate (PA) resins are aromatic, linear, amorphous polyesters with excellent toughness, ultraviolet resistance, flex strength, dimensional stability, flame retardance, and electrical properties. Electrical properties are fairly constant over a broad temperature range. These polymers are susceptible to stress cracking when exposed to ketone, aromatic hydrocarbon, ester, and chlorinated solvents. If polyarylates are alloyed with other polymers, the stress crack resistance is improved. Polyarylates are processed by most conventional melt processes such as injection extrusion, flow molding, and thermoforming. Electrical applications include connectors, relay housings, coil bobbins, and switch and fuse covers.

Polybutylene terephthalate (PBT) is a linear, semicrystalline, aliphatic polyester, although it does have some aromatic character. It has excellent chemical and temperature resistance and good electrical properties that are unaffected by humidity. PBT is unaffected by water, weak acids and bases, and common organic solvents at room temperature. It cannot be solvent bonded because of its solvent resistance. PBT resins are processed mostly by injection molding.

Polyethylene terephthalate (PET) is also a linear, semicrystalline, aliphatic polyester that is produced as a standard-grade and an engineering-grade material. The latter grade has superior properties (strength, stiffness, dimensional stability, chemical and heat resistance, and electrical properties) and is therefore preferred for electrical applications. The material is processed by injection molding and is used for lamp sockets, coil forms (audio/video transformers), connectors, and terminal blocks.

Polycyclohexylene dimethylene terephthalate (PCT) is a linear high-temperature semicrystalline material. Its high heat resistance distinguishes it from PET and PBT. PCT has a melting point of 290°C, as compared to 224°C for PBT and 250°C for PET. This high-temperature resistance makes PCT useful for surface-mount electronic components. The material has an excellent balance of physical, chemical, electrical, mechanical, and thermal properties. Injection molding is the preferred processing method. Applications include sockets, chip carriers, pin grid arrays, coil bobbins, and surface-mount components.

2.3.10 Polycarbonates

Polycarbonate is a linear, amorphous material synthesized by interfacial polymerization. The characteristic properties of this polymer are excellent transparency, toughness, and high-temperature properties (up to 140°C). The polymer is essentially self-extinguishing. The electrical properties are good with a stable dielectric constant over a wide temperature and frequency range. The ultraviolet and chemical resistance of polycarbonate is limited. The polymers are attacked by alkali, amines, ketones, esters, and aromatic hydrocarbons. Stressed polycarbonate parts are sensitive to many solvents and will crack on exposure. Polycarbonate is processed by most conventional thermoplastic processing methods. Applications include connectors, circuit breaker boxes, and bobbins. Suppliers include Bayer, Dow Chemical, and GE.

2.3.11 Polyolefins

This class of materials includes the polymers and copolymers of polyethylene and polypropylenes. The grades include a range of densities (0.83 g/cm^3 for polymethylpentene to 0.96 g/cm^3 for the high-density polymers) and a range of molecular weights, including ultrahigh molecular weight. These polymers are characterized by the –(–CH_2– or –CHR)– repeat unit, where R represents hydrogen or an alkyl radical. There are a multitude of materials available, but they all have a low dielectric constant, low dissipation factor, low water absorption, low coefficient of friction, and excellent chemical resistance (resistant to acids, alkalis, and most solvents). Special grades of polyolefins, such as the higher-molecular-weight material, exhibit increased toughness, abrasion resistance, and freedom from environmental stress cracking. Wire and cable insulation are the main uses for these materials in the electrical industry. Suppliers include Eastman, Quadrant, Honeywell, Elf Atochem, DuPont, Dow Chemical, Nova Chemical, and Equistar. Further information is available in Vasile.[15]

2.3.12 Polyphenylene oxide

Polyphenylene oxide (PPO) is a linear amorphous polymer made by a procedure called *oxidative coupling*. The glass transition temperature of pure PPO is 210°C. This polymer is not used in its neat form but rather is blended with polystyrene to produce the commercial materials Noryl® and Prevex® (both General Electric Co.). This modification reduces the glass transition temperature of the blend. The PPO alloys have good resistance to acids and alkalis but are attached by some aromatic and chlorinated solvents. A number of grades are available, all of which can be easily processed on conventional thermoplastic molding equipment. Applications include computers, connectors, fuse blocks, relays, and bus bar insulation.

2.3.13 Polyphenylene sulfide

Polyphenylene sulfide (PPS) is a semicrystalline material that is inherently flame retardant. Two forms of PPS are available, a linear and a branched polymer. The former has better strength and melt viscosity properties. PPS is inert to all solvents except hot nitric acid. It is processed like most thermoplastics and can be injection and compression molded. Cross-linkable grades are available with exceptional heat resistance. The PPS polymers are rated UL-94 V-0. The polymers have stable electrical properties over broad temperature, frequency, and humidity ranges. Both volume and insulation resistance are excellent in wet and dry environments, and the arc resistance is good. The primary uses of PPS resins are in electric connectors, coil forms, bobbins, yokes, and terminal boards. Suppliers include Chevron Phillips, GE, Ticona, and Toyobo.

2.3.14 Styrenics

The styrene polymers include acrylonitrile-butadiene-styrene (ABS), acrylic-styreneacrylonitrile (ASA), polystyrene (PS), styrene-acrylonitrile (SAN), styrene-butadiene (SB), and styrene-maleic anhydride (SMA). The properties of these polymers are dependent on the ratio of the monomeric components, which leads to a broad range of material properties. These polymers are generally not used in electrical applications except as electronic housings. Polystyrene has very low dielectric losses ($\varepsilon' = 2.45$, $\tan \delta = 0.001$), and its chief use in electronics is in striplines. The styrenics are amenable to all forms of thermoplastic processing. Suppliers include Chevron-Phillips, Elf Atochem, Bayer, Dow Chemical, GE, and Creanova.

2.3.15 Polysulfones

Polysulfones are amorphous polymers of high-temperature resistance. These materials contain the arylsulfone group as part of their chemical structure. There are three important sulfone polymers, all of which have excellent electrical properties: polysulfone, polyarylsulfone, and polyethersulfone. These materials are resistant to acid and alkaline hydrolysis but can exhibit stress crazing when exposed to certain chemicals (esters, ketones, and some hydrocarbons). All the polymers have excellent creep and radiation resistance. Processing is carried out on standard thermoplastic equipment. Applications include printed-wiring board substrates, television components, coil bobbins, connectors, and switch housings. Suppliers include Solvay and BASF.

2.3.16 Vinyls

The vinyl polymers include polyvinylchloride (PVC), polyvinylidene chloride (PVDC), and chlorinated polyvinylchloride (CPVC). The vinyl resins contain the structural unit $–(–CH_2–CHCl–)–$ in the polymer chain, although the PVDC and CPVC contain extra chlorine atoms. All the resins show good chemical and flame resistance, with PVC being the weakest member of the family with regard to these properties. PVC is the most versatile of the plastics because of its wide blending capability. CPVC has excellent chemical resistance, rigidity, strength, and weatherability. PVDC has low permeability to gases and liquids, good barrier properties, and also good chemical resistance. All the vinyl resins are processed on conventional thermoplastic equipment. Electrical applications include wire insulation, cable jackets, sleeving, and tubing. Suppliers include BASF, Creanova, Dow Chemical, Eastman Chemical, Elf Atochem, Geon, and Solvay.

2.3.17 Thermoplastic alloys and blends

The ability of polymers to be mixed together to form a new polymer mixture with greatly expanded properties has given rise to this new group of materials. Alloys are synergistic polymer combinations with real property advantages derived from a high level of thermodynamic compatibility between the components. Alloys exhibit strong intermolecular forces and form single-phase systems with one glass transition temperature.[5] Noryl, an alloy of polystyrene and PPO, is a typical example. Blends do not have the exacting thermodynamic capabilities that alloys have, and they exhibit discrete phases and multiple glass transition temperatures. In general, the properties of a blend reflect the weighted average of the properties of the components of the blend.

Alloys and blends are processed on all conventional thermoplastic equipment. A list of common alloys and blends is given in Table 2.13 along with supplier names and important properties. More detailed information on alloys and blends can be obtained in Utracki.[16]

TABLE 2.13 Common Alloys and Blends

Alloy or blend	Trade name	Supplier	Key properties
PPO/PS	Noryl Luranyl Vestoran Xyron	GE Plastics BASF Creanova Asahi Chemicals	Heat resistance, toughness, good moisture resistance, low cost, injection molding, blow molding, calendaring, extrusion
Nylon/ABS	Stapron Triax Ultramid	DSM Bayer ASF	Heat and chemical resistance, wear and abrasion resistance, low-temperature impact strength, injection molding, extrusion, thermoforming
Nylon/elastomers	Capron Durethan Fiberfil Minlon Technyl Ultramid Vydyne Zytel	Honeywell Bayer DMS DuPont Rhodia BASF Dow Chemical	Improved toughness, fatigue resistance, chemical and heat resistance, extrusion, injection molding, compression molding, transfer molding, blow molding
PPO/Nylon	Noryl GTX Xyron	GE Plastics Asahi Chemicals	High-temperature resistance, chemical resistance, low moisture absorption, dimensional stability, high temperature creep resistance, extrusion, thermoforming, injection molding
ABS/PC	Bayblend Cycoloy Iupilon Lexan	Bayer GE Plastics Mitsubishi Engineering Plastics	Heat resistance, processability, low-temperature impact, high stiffness and strength, injection molding, extrusion, thermoforming
PPO/PBT	Gemax	GE Plastics	High-temperature resistance, solvent resistance, dimensional stability, processability
Polyester/elastomer	Celanex Rynite Makroblend Ultradur	Ticona DuPont Bayer BASF	Stiffness, toughness, high-temperature and solvent resistance, injection molding, extrusion, compression molding
PC/PBT, PET	Makroblend Xenoy	Bayer GE Plastics	High impact strength and modulus of wide temperature range, chemical resistance, injection molding, extrusion
ASA/PC	Geloy	GE Plastics	Impact resistance, thermal stability, weather resistance, extrusion, injection molding
PET/PBT	Celanex Valox	Ticona GE Plastics	Heat resistance, fast molding, low cost

TABLE 2.13 Common Alloys and Blends *(Continued)*

Alloy or blend	Trade name	Supplier	Key properties
Acetate/elastomer	Celcon Delrin Thermocomp Ultraform	Ticona DuPont LNP Engineering Plastics BASF	Stiffness, toughness, fatigue, wear, extrusion, injection molding, compression molding, transfer molding
SMA/ABS	Cadon Luran Magnum Terluran	Bayer BASF Dow Chemical	Heat resistance, impact, low cost, plating, extrusion, thermoforming, injection molding
Polysulfone/ABS	Mindel	Solvay Advanced Polymers	Processability, lost cost, heat resistance, plating, extrusion, injection molding
PEEK/PES	Victrex	Victrex	High heat distortion temperature, processability, low cost, impact resistance, injection molding, extrusion, compression molding
PC/TPU	Texin	Bayer	Stiffness, wear, low-temperature impact, extrusion, injection molding
Nylon/PE	Selar	DuPont	Heat/chemical resistance, barrier properties, wear resistance, extrusion, injection molding, compression molding

2.4 Thermosets

Unlike thermoplastics, thermoset materials are polymers that form three-dimensional cross-linked networks of polymer chains that cannot be softened or reheated for additional use. In general, these materials can provide higher temperature capability than the thermoplastic materials. Thermoset materials, before being cured, are fabricated by casting, compression molding, filament winding, laminating, pultrusion, or injection and transfer molding. Most thermoset materials, before they are cross-linked, are considerably more fluid than thermoplastics during processing. A thermoset material must contain a functionality greater than 2 to facilitate cross-linking; that is, the polymer chain must have enough reactive sites to form a three-dimensional network. Difunctional materials form linear or branched uncross-linked polymers but can be cross-linked through the addition of either a catalyst or a curing agent. These ingredients promote the formation of active sites for further reaction. The curing or cross-linking reaction is an exothermic reaction, and consideration must be given to control the temperature rise to prevent a runaway reaction. Thermoset materials usually shrink when they are cross-linked, but the shrinkage can be controlled with additives such as fillers and reinforcing fibers or fabrics. The conversion of these materials to the thermoset state can be accomplished at room or elevated temperature, the latter giving a faster and more complete cure of the resin. The reader is referred to other texts for more detailed descriptions of all thermosetting plastics.[5–7,17] Properties of thermosets for electronics applications are given in Table 2.14.

TABLE 2.14 Properties of Thermosetting Plastics

		Epoxy		Phenolics			Alkyds								
	DAP (GDI-30)	Glass-filled	Mineral-filled	General-purpose	Glass-filled	Mineral-filled	MAG	MAI-60	Polyester GPO-3	Polyimide	Polyurethane	Mineral-filled silicone	Bismale imides	Cyanate esters	Benzo-cyclo-butene
Dielectric constant, D-150															
60Hz	4.2	5.0	4.0	12.0	50.0	6.0	6.3	5.6	4.5	3.5	6	3.6	—	—	—
10^6 Hz	3.5	4.6	5.0	6.0	6.0	10.0	4.7	4.6	—	3.4	3	3.7	3.5	2.66–3.10	2.65–2.70
Dissipation factor, D-150															
60Hz	0.004	0.01	0.01	0.3	0.3	0.07	0.04	0.10	0.05	0.0025	0.1	0.005	—	—	—
10Hz	0.01	0.01	0.01	0.7	0.8	0.10	0.02	0.02	—	0.01	0.04	0.003	0.007	0.01–0.005	–0.002
Dielectric strength, D-149; V/mil															
	400	360	400	400	350	400	400	375	300	6500	500	425	480–508		
Volume resistivity, D-257; Ω-cm															
	10^{13}	3.8×10^{15}	9×10^{15}	10^{13}	10^{13}	10^{14}	10^{14}	10^{13}	—	10^{18}	10^{14}	10^{15}	—	10^{16}	9×10^{19}
Arc resistance, D-495; seconds															
	140	140	180	50	70	180	>180	180	>180	230	120	240	—	Excellent	—
Specific gravity, D-792															
	1.7	1.8	2.1	1.45	1.95	1.83	2.24	2.07	1.95	1.4	1.1	2.05	1.30	1.10–1.43	
Water absorption, D-570; % 24 h															
	<0.2	0.2	0.04	0.7	0.5	0.5	0.08	0.07	0.5	2.9	0.2	0.15	4.0–4.4*	0.6–2.5*	—
Heat deflection temperature, D-648; at 264 lb/in², °F															
	500	400	250	340	400	500	350	>400	—	680	190	>500	520	480	—
Tensile strength (Izod), D-256; ft-lb/in															
	10,000	30,000	15,000	10,000	7000	11,000	3000	6000	9000	17,000	1000	6500	12,000	13,000	—
Impact strength (Izod), D-256; ft-lb/in															
	5.0	10	0.4	0.3	3.5	15.0	0.3	9.5	8.0	1.5	25	0.5	0.3–0.5	0.7–0.9	—
Coefficient of thermal expansion, D-696; 10^{-5}/°F															
	2.6	1.7	2.2	2.5	—	0.88	3	2	2	2.8	25	2.8	40 ppm/°C	50 ppm/°C	42–70 ppm/°C
Thermal conductivity, C-177; Btu-in(h-ft²-°F)															
	—	6	—	0.3	0.34	0.2	7.2	3.6	4	6.8	0.1	3.1	—	—	—

*500-h water boil.

SOURCE: From Harper.[8] Reprinted with permission.

2.4.1 Allyl resins

The allyl resins are thermosetting polyester materials that retain their desirable physical and electrical properties on prolonged exposure to severe environmental conditions such as high temperature and humidity. These resins have good chemical resistance and can withstand between 10^4 and 10^{12} rads of gamma radiation.[17] These polymers have the allyl radical $CH_2–CH=CH_2$ as part of their chemical structure. The principal allyl resins are based on diallyl phthalate (DAP) and isophthalate (DAIP) monomers and prepolymers. There are other resins that are used alone or in combination with DAP and DAIP. They are diethylene glycol bis(allyl carbonate), allyl methacrylate, diallyl fumarate and maleate, as well as triallyl cyanurate. The allyl resins are converted to thermoset materials by heat and by the addition of free-radical sources such as benzoyl peroxide and t-butyl perbenzoate to the resin formulation. Curing of these resins is slow below 150°C. These resins are used as cross-linking agents in other polyester systems and as molding compounds, preimpregnated glass cloth, sealants, insulating coatings, and decorative laminates. Most critical electronics applications requiring high reliability under adverse conditions use allyl resins, such as connectors in communications, computers, and aerospace systems; insulator switches; chip carriers; and circuit boards. The allyl resins have a low loss factor, high volume and surface resistivity, and high arc resistance. Those properties are retained under high-humidity conditions. The allyl resins can be compression, transfer, and injection molded, and they can also be used in prepregging operations. In general, DAP compounds are designed for continuous operation at about 176°C, whereas DAIP can operate at about 232°C. Suppliers include Cosmic Plastics and Rogers.

2.4.2 Bismaleimides

Within the polyimide family of resins, there is a class of thermosetting polymers that have a preimidized structure and form a three-dimensional network via addition polymerization without the evolution of volatile material. These materials are classified as bismaleimides (BMIs), and the monomers and prepolymers are prepared by the reaction of maleic anhydride and diamines. The material is very reactive and can be homopolymerized or copolymerized to produce a wide variety of thermosetting resins. The polymers are characterized as having the processing ease of epoxy resins but superior elevated-temperature performance properties. Epoxies operate in the 150°C temperature range, and the BMIs operate in the range of 200 to 232°C. Compression, transfer, and injection molding; filament winding; and prepregging are the normal processing methods for bismaleimides. Bismaleimides are sold as powders or as solutions in polar solvents. These materials are primarily used in printed-wiring board substrates.

2.4.3 Epoxy resins

Epoxy resins are characterized by the presence of the epoxy (oxirane) ring. Most commercial epoxy resins are derived from bisphenol A and epichlorohydrin, but there are many other types based on the epoxidation of multifunctional molecules that give rise to epoxy resins with a broad range of properties. Epoxy resins can be liquids or solids. Curing of these resins is accomplished by reaction through the epoxide and hydroxyl functional groups. Curing agent type and amount, and temperature determine the condition of cure and the final properties of the resin. Typical curing agents include the aliphatic amines and amides for ambient-temperature cure, and the anhydrides, organic acids, aromatic amines, and various phenolic condensation products for elevated-temperature cure. Most common epoxy resins are solventless (100 percent solids). However, higher-molecular-weight and multifunctional epoxies are solid and are usually processed in solution form. The curing reaction is exothermic, which may be necessary to control in large-batch operations. The cured resins have an excellent combination of physical, chemical, mechanical, and electrical properties and are used extensively in many electrical and nonelectrical applications. Epoxies can be compression and transfer molded and filament wound. They are used in casting, prepregging, and laminating operations. Epoxies can be formulated to produce conformal coatings, adhesives, and varnishes and are used in the electrical industry as bobbins, connectors, and chip carriers, and as the matrix resin in printed-wiring-board substrates. Suppliers include Dow Chemical, Vantico, and Resolution Performance Products.

2.4.4 Phenolic resins

Phenolic resins are the reaction product of phenol and formaldehyde. Two kinds of phenolics are produced: the resols (alkaline condensation products) and the novolacs (acid condensation products). The basic difference between a resol and a novolac is the presence of one or more free methylol groups on the resol. The resins are heat cured to form a dense cross-linked network, which gives the phenolic resins their high heat resistance and dimensional stability. Phenolic resins have poor arc resistance. They are available in solution form or as powders and can be converted to molding compounds, varnishes, and laminates. They are processed by injection, compression, and transfer molding. Phenolics are used as chip carriers, connectors, and bobbins, and as matrix resins for printed-wiring board substrates. Suppliers include Durez, Plenco, and Rogers.

2.4.5 Polyesters

Polyester resins are versatile materials and are available as low-viscosity liquids up to thick pastes. Included within the polyester family are alkyd resins, unsaturated resins, vinyl esters, and the allyl resins discussed in Sec. 2.4.1. The characteristic functional group present in these resins is the ester group (–COOR–), but the composition of these polyester resins can be varied tremendously to produce resins having widely different properties. Table 2.15 lists the various components available for preparing polyester resins. Cross-linking of these materials is accomplished by the addition of polyfunctional acids or alcohols, unsaturated monomers, and a peroxide catalyst. Curing is done from

TABLE 2.15 Unsaturated Polyester Components

Components	Ingredients	Characteristics
Unsaturated anhydrides and dibasic acids	Maleic anhydride	Lowest cost, moderately high heat-deflection temperature (HDT)
	Fumaric acid	Highest reactivity (cross-linking), higher HDT, more rigidity
Saturated anhydrides and dibasic acid	Phthalic (orthophthalic) and anhydride	Lowest cost, moderately high HDT, provides stiffness, high flexible and tensile strength
	Isophthalic acid	Higher tensile and flexible strength, better chemical and water resistance
	Adipic acid, azelaic acid sebacic acid	Flexibility (toughness, resilience, impact strength); adipic acid is lowest in cost of flexibilizing acids
	Chlorendic anhydride	Flame retardance
	Nadic methyl anhydride	Very high HDT
	Tetrachlorophthalic	Flame retardance
Glycols	Propylene glycol	Lowest cost, good water resistance and flexibility, compatibility with styrene
	Dipropylene glycol	Flexibility and toughness
	Ethylene glycol	High heat resistance, tensile strength, low cost
	Diethylene glycol	Greater toughness, impact strength, and flexibility
	Bisphenol-A adduct	Corrosion resistance, high HDT, high flexible and tensile strength
	Hydrogenated bisphenol-A adduct	Corrosion resistance, high HDT, high flexible and tensile strength
Monomers	Styrene	Lowest cost, high reactivity, fairly good HDT, high flexible strength
	Diallyl phthalate	High heat resistance, long shelf life, low volatility
	Methyl methacrylate	Light stability, good weatherability, fairly high HDT
	Vinyl toluene	Low volatility, more flexibility, high reactivity
	Triallyl cyanurate	Very high HDT, high reactivity, high flexible and tensile strength
	Methyl acrylate	Light stability, good weatherability, moderate strength

SOURCE: From Schwartz and Goodman.[7] Reprinted with permission.

room temperature to about 160°C. Fillers, pigments, and fibers can be mixed with the resins. Characteristic properties include ease of processing, low cost, good electrical properties, and high arc resistance. Applications include bobbins, terminal boards, connectors, and housings. Polyester resins can be compression or transfer molded, laminated, pultruded, and filament wound. Suppliers include Bayer, Creanova, DSM, DuPont, Eastman Chemical, GE Plastics, Honeywell, and Ticona.

2.4.6 Polyurethanes

These polymers are derived from the reaction of polyfunctional isocyanates and polyhydroxy (polyether and polyester polyols) compounds that yield linear or branched polymers. The basic chemical unit of polyurethanes is the urethane (–RNHCOOR–). These resins are produced as castable liquids (prepolymers) and are cross-linked by adjusting the stoichiometry and functionality of the isocyanate or polyol. Catalysts are added to enhance the rate of reaction. A variety of other ingredients (active hydrogen compounds) can be added to produce polyurethanes with different properties, ranging from elastomeric to rigid polymers. The polyether urethanes are more hydrolytically stable than the polyester urethanes, but the latter give better strength and abrasion resistance. Polyurethanes have poor solvent resistance. They are sensitive to chlorinated and aromatic solvents as well as to acids and bases. Urethanes are used as conformal coatings to encapsulate sensitive electronic components. They are processed by reaction injection molding (RIM), compression molding, and casting. Suppliers include Bayer, BASF, and Dow Chemical.

2.4.7 Silicones

Silicones are polymers that consist of alternating silicon and oxygen atoms along the backbone of the polymer chain. The backbone is modified by attaching organic side groups to the silicon atom; in so doing, this imparts the unique properties found in these polymers. The silicones can be produced in the form of liquids, greases, elastomers, and hard resins. The organic group attached to the silicon atom can be aliphatic, aromatic, or vinyl, which affects the properties of the final silicone polymer. The silicone fluids are low-molecular-weight polymers in which the organic group on the silicone is methyl or phenyl, or a mixture of both. The silicone resins are branched polymers that cure to a solid while the elastomers are linear oils or higher-molecular-weight silicones that are reinforced with a filler and then vulcanized (cross-linked). The elastomers come in three forms: heat-cured rubber, two-component liquid injection molding compounds, and room-temperature vulcanizing (RTV) products. The conversion of silicones to cross-linked elastomers can be accomplished by free-radical condensation, addition, and ultraviolet radiation curing techniques. The silicones are characterized by their useful properties over a broad temperature range (–65 to 248°C). They exhibit excellent weatherability; arc and track resistance; and impact, abrasion, and chemical resistance. Silicones can also be copolymerized with other polymers to produce materials with a variety of interesting properties, such as silicone-polyimide, silicone-EPDM, and silicone-polycarbonate. Electronics applications include wire enamels, laminates, sleeving and heat-shrinkable tubing, potting for electronic components, conformal coatings, and varnishes. Properties of various silicone polymers are listed in Tables 2.16 through 2.19. Suppliers include Dow-Corning and GE Silicones.

TABLE 2.16 Approximate Physical Properties at 25°C of Methylpolysiloxane Fluids (Rhodorsil Oil 47V)

Viscosity, cSt	VTC[*]	Specific gravity	Flash point, °C	Freezing point, °C	Surface tension, dynes/cm	Vapor[†] pressure, mm Hg	VCE,[‡] cm^3/cm^3-°C	Dielectric constant[¶]	Dielectric strength, kV/mm
5	0.55	0.910	136	–65	19.7	—	1.05×10^{-3}	2.59	—
10	0.57	0.930	162	–65	20.1	—	1.08×10^{-3}	2.63	13
20	0.59	0.950	230	–60	20.6	1×10^{-2}	1.07×10^{-3}	2.68	—
50	0.59	0.959	280	–55	20.7	1×10^{-2}	1.05×10^{-3}	2.8	15
100	0.60	0.965	>300	–55	20.9	1×10^{-2}	0.05×10^{-3}	2.8	16
300	0.62	0.970	>300	–50	21.1	1×10^{-2}	0.95×10^{-3}	2.8	16
500	0.62	0.970	>300	–50	21.1	1×10^{-2}	0.95×10^{-3}	2.8	16
1000	0.62	0.970	>300	–50	21.1	1×10^{-2}	0.95×10^{-3}	2.8	16
5000 to 2,500,000	0.62	0.973	>300	45	21.1	1×10^{-2}	0.95×10^{-3}	2.8	18

[*] Viscosity/temperature coefficient = 1 – (viscosity at 99°C/viscosity at 38°C).
[†] At 200°C.
[‡] Volume coefficient of expansion between 25 and 100°C.
[¶] Between 0.5 and 100 kHz.

SOURCE: From Goodman.[17] Reprinted with permission.

TABLE 2.17 Typical Properties of Condensation Cure Methylphenyl RTV Silicone Rubber Products Cured at Room Temperature

Viscosity, cSt	Specific gravity	Hardness, Shore A	Tensile strength, lb/in^2	Useful temperature range, °F	Dielectric strength, V/mil	Dielectric constant at 1 kHz	Dissipation factor at 1 kHz
16,000	1.21	42	380	–175 to +400	520	3.6	0.005
30,000	1.35	55	690	–175 to +500	540	3.9	0.02
700,000	1.35	48	440	–175 to +500	470	3.9	0.02

SOURCE: From Goodman.[17] Reprinted with permission from *General Electric Silicones.*

TABLE 2.18 Typical Properties of Addition Cure Clear RTV Silicone Rubber Products

Viscosity, cSt	Specific gravity	Hardness, Shore A	Tensile strength, lb/in^2	Useful temperature range, °F	Dielectric strength, V/mil	Dielectric constant at 1 kHz	Dissipation factor at 1 kHz
4,000	1.02	44	920	–75 to +400	520	2.7	0.0006
5,200	1.04	45	920	–175 to +400	530	2.69	0.0004

SOURCE: From Goodman.[17] Reprinted with permission from *General Electric Silicones.*

TABLE 2.19 Estimated Useful Life of Silicone Rubber at Elevated Temperatures

Service temperature, °F	Useful life*
250	10–20 years
300	5–10 years
400	2–5 years
500	3 months
600	2 weeks

*Retention of 50 percent elongation.

SOURCE: From Goodman.[17] Reprinted with permission from *General Electric Silicones*.

2.4.8 Cross-linked thermoplastics

Overall property enhancement is the underlying principle for the commercial development of cross-linked thermoplastics. This enhancement manifests itself in improved resistance to thermal degradation of physical properties, stress cracking, creep, and other environmental effects. Thermoplastics are cross-linked by radiation and chemical techniques. The techniques, which include X-rays, gamma rays, high-energy electrons, and organic peroxides, under controlled conditions, can be used to produce beneficial changes in the properties of irradiated polymers. Typical polymers capable of being cross-linked include the polyolefins, fluoroplastics, vinyls, neoprene, and silicone. Electrical applications include shrink-fit tubing, underground cable insulation, and microwave insulation. Table 2.20 lists cross-linked thermoplastic products and their applications.

2.4.9 Cyanate ester resins

Cyanate ester resins are bisphenol derivatives containing the cyanate –O–C≡N functional group. These monomers and polymers cyclotrimerize on heating to form a cross-linked network of oxygen-linked triazine rings via addition polymerization. The cyanate ester resins range from liquids to solids and are characterized by superior dielectric properties, adhesion, low mois-

TABLE 2.20 Heat–Shrinkable Insulation and Encapsulation Tubings

	Product	Description	Typical Applications
Flexible polyolefins	RNF-100 type 1	General-purpose, flame-retarded, flexible polyolefin	Insulation of wire bundles; cable and wire identification; terminal and component insulation, protection, and identification
	RNF-100 type 2	General-purpose, flexible, transparent polyolefin	Transparent coverings for components such as resistors, capacitors, and cables where markings must be protected and remain legible
	RT-876	Highly flame-retarded, very flexible polyolefin with low shrink temperature	Coverings for cables and components where excellent flexibility and outstanding flame retardance are needed
	RT-102	Highly flexible, flame-retarded, polyolefin with very low shrink temperature	Flexible material for general-purpose protection and insulation; especially effective for low-temperature use
	RVW-1	Highly flame-retarded, flexible polyolefin	Lightweight harness insulation, terminal insulation, wire strain relief and general-purpose component packaging and insulation where a UL recognized product with a VW-1 (FR-1) rating is needed
Semirigid polyolefins	CRN type 1	General-purpose, flame-retarded, semirigid polyolefin	Insulation and strain relief of soldered or crimped terminations; protection of delicate components; cable and component identification
	RT-3	Semirigid, flame-retarded, opaque polyolefin	Particularly suited for automated application systems to insulate and strain relieve crimped or soldered terminals; furnished in cut pieces
Dual-wall polyolefins	SCL	Meltable inner walls, selectively cross-linked semirigid polyolefin	Encapsulation of components, splices, terminations, requiring moisture resistance, mechanical protection and shrink ratios as high as 6:1.
	TAT	Flexible, dual-wall adhesive tubing	Insulates and seals electrical splices, bimetallic joints, and components from moisture and corrosion

	ATUM	Semiflexible, high expansion, heavy dual-wall, adhesive tubing	Environmental protection for a wide variety of electrical components, including wire splices and harness breakouts
Fluoro-plastics	Kynar[*]	High-temperature, flame-resistant, clear, semirigid fluoroplastic	Transparent insulation, mechanical protection of wires, solder joints, terminals, connections, and component covering
	Conovolex	Convoluted, flexible, irradiated polyvinylidene fluoride	Mechanical protection of cable harnesses; excellent flexibility and chemical resistance; good high-temperature performance
	RT-218	Semirigid, white, high-temperature, low-outgassing fluoroplastic tubing	Insulation of splices and terminations in aircraft and mass transit markets; cable and wire identification
Vinyl	PVC	Flexible, flame-resistance, polyvinyl chloride	Insulation and covering of cables, components, terminals, handles
Elastomers	NT (neoprene)	Heavy-duty, flexible, abrasion-resistant, flame-retarded elastomer	Insulation and abrasion protection of wire bundles and cable harnesses
	SFR (silicone)	Highly flexible, flame-retarded, heat or cold shock-resistant	Cable and harness protection requiring maximum flexibility and resistance to extreme temperatures; ablative protection for cables in rocket blast
	Viton[†] (fluoro-elastomer)	Flexible, flame-retarded, heat and chemical resistant fluoroelastomer	Insulation and protection of cables exposed to high temperature and/or solvents such as jet fuel
Caps	PD	Semirigid polyolefin, meltable inner wall	Encapsulation of stub splices, especially fractional-horsepower motor windings

[*] Registered trademark of Atofina Chemicals, Inc.

[†] Registered trademark of E.I. duPont de Nemours & Co.

SOURCE: From Goodman.[17] Reprinted with permission from RayChem Corp.

ture absorption, flame resistance, high-temperature capability, and excellent dimensional stability. Glass transition temperatures range from 250 to 290°C. Several grades are available and can be formulated to produce laminating varnishes for impregnating inorganic and organic reinforcements. The formulations can be homopolymers, blends with other cyanate esters or with bismaleimides, and epoxy resins. Some properties of the neat resins are shown in Figs. 2.6 through 2.9[18] and of E-glass laminates in Tables 2.21 and 2.22.[18] Cyanate ester resins can be processed by melt polymerization, prepregging, and lamination operations. Applications in the electrical industry include printed-wiring-board substrates and radome structures. Cyanate ester resins can be toughened with thermoplastics such as polyethersulfone, polyetherimide, polyarylates, polyimides, and methylethylketonesoluble copolyesters and elastomers. Suppliers include Vantico.

TABLE 2.21 Comparison of AroCy B-40S Laminate Properties with 60 Percent Epoxy Modification and FR-4 Reference[*]

Laminate property	100% cyanate[‡]	60% epoxy[†] 40% cyanate[‡]	100% Epoxy[†]
Press cure, h/°C	1/177	1/177	1/177
Post cure, h/°C	3/225	—	—
T_g (T_{MAS}), °C	225	183	130
CTE (Z), ppm/°C	44	55	60
Steam/solder, min	120	120	45
Flammability, UL-94	Burns	V–0	V–0
Peel strength, lb/in			
25°C	12.3	11.4	12.0
200°C	9.4	8.5	4.2
$D_{k,}$ 1 MHz	4.05	4.2	4.8
$D_{k,}$ 1 MHz	0.003	0.008	0.020

[*] Laminates are 8-ply, style 7628 E-glass reinforced; 55 ± 2% resin by volume.
[†] Brominated hard epoxy, WPE 500, 27% Br.
[‡] AroCy B-40S.

SOURCE: From Shimp.[18] Reprinted with permission.

2.4.10 Benzocyclobutenes

Benzocyclobutenes (BCBs) are thermally polymerized (addition polymerization) to produce a cross-linked resin without the evolution of volatiles. BCB is

TABLE 2.22 Comparison of E-glass Laminate Properties for Several Resin Systems at Equal Resin Volume Content[*]

Resin	D_k, 1 MHz, vol. %		$D_f (10^{-3})$	DMA T_g, °C	TGA Onset, °C	Flammability rating, UL-94	Peel strength, lb/in		Pressure cooker, min.
	70	55					258C	2008C	
Cyanate ester									
ArOCy F-40S	3.5	3.9	2	290	400	V–0	11	9	120
ArOCy M-40S	3.6	4.0	2	290	415	VI	12	10	120
XU 71787	3.6	4.0	3	255	426	†	8	6	120
ArOCy B-40S	3.7	4.1	3	290	405	†	12	10	120
Polyimide									
BMI-MDA	4.1	4.5	9	312	400	VI	9	6	120
Epoxy FR-4	4.5	4.9	20	145	300	V–0	12	4	45

[*] Except for D_k measurements on 70 vol % resin laminates, tests were performed on 55 vol %, 0.060-in, 8-ply laminates prepared with 7628 E-glass and postcured 4 h at 225–235°C.

[†] Burn times exceed self-extinguishing classifications.

SOURCE: From Shimp.[18] Reprinted with permission.

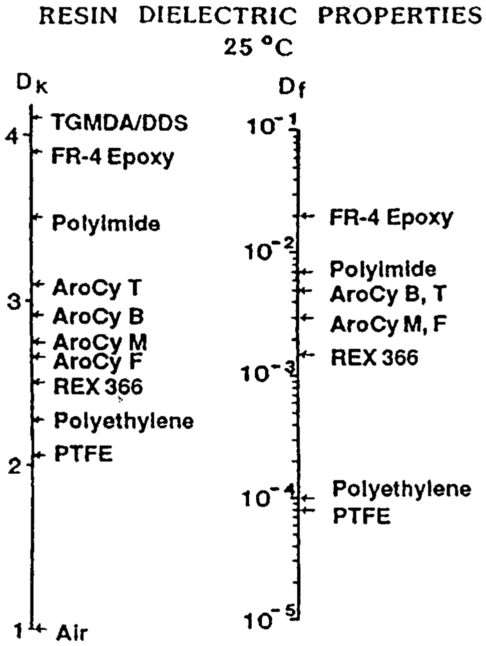

Figure 2.6 Comparison of dielectric constant and dissipation factor values measured at 25°C and 1 MHz for representative thermoset and thermoplastic polymers. *(From Shimp,[18] reprinted with permission.)*

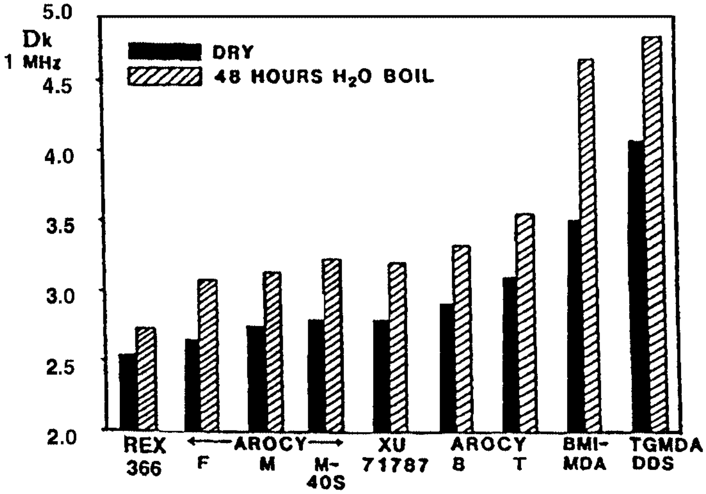

Figure 2.7 Effect of moisture conditioning on dielectric constant of several thermoset resins. *(From Shimp,[18] reprinted with permission.)*

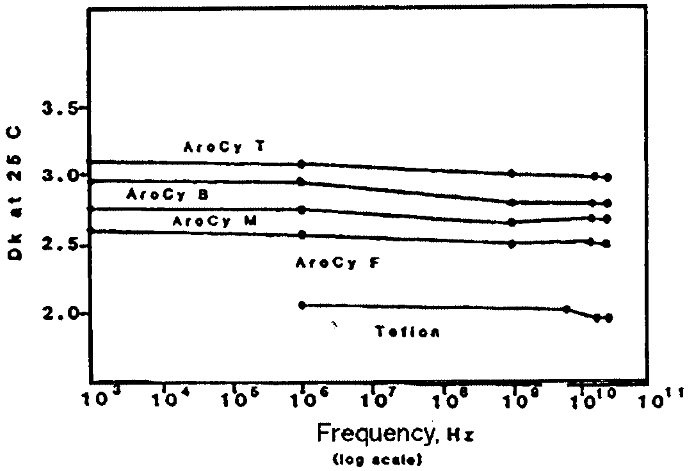

Figure 2.8 Flat dielectric constant response of cyanate ester homopolymers to increasing test frequency. *(From Shimp,[18] reprinted with permission.)*

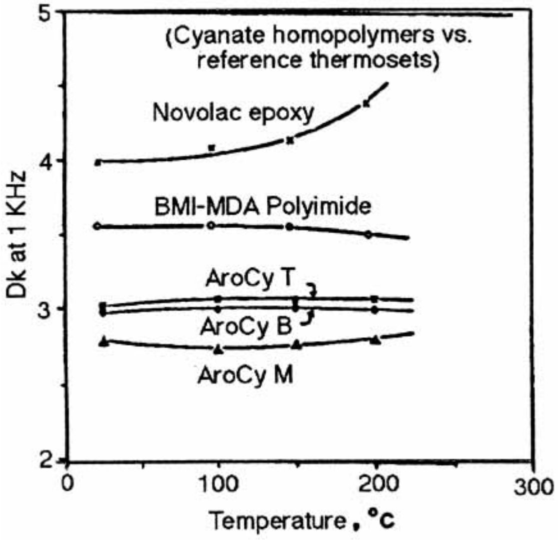

Figure 2.9 Flat dielectric constant response of cyanate ester homopolymers over 25 to 200°C temperature range. Epoxy novolac is reference resin. *(From Shimp,[18] reprinted with permission.)*

supplied as a prepolymer partially polymerized in hydrocarbon solvents such as toluene or mesitylene (20 to 70 percent solids). BCB resins have low dielectric constant, low water absorption, good thermal stability, high adhesion, and good planarization and chemical resistance. Properties of several BCB resins are listed in Table 2.23.[19] Suppliers include Dow Chemical.

TABLE 2.23 Typical Properties of BCB–Based Resins

Property	
Glass transition temperature (°C)	>350
Tensile modulus (GPa)	2.9
Tensile strength (MPa)	87
Coefficient of thermal expansion, 25 to 175°C, (ppm/°C)	40–60
Dielectric constant	2.5 (1 GHz)
Dissipation factor	0.0008 (1 MHz); 0.002 (10 GHz)

SOURCE: So et al.[19]

2.5 Elastomers

Elastomers are considered apart from other polymeric materials because of their special properties.[8,20] The distinguishing characteristics of elastomers are their ability of sustain large deformations (5 to 10 times the unstretched dimensions) and their capacity to spontaneously recover nearly all of that deformation without rupturing. The unique structural feature of all rubber-like substances is the presence of long polymer chains interwoven and joined together through cross-linkages. Generally, elastomers are not as widely used as plastics for electronics applications, and only a brief review of elastomer types, properties, and their applications will be presented here. A compilation of electrical property information on thermoplastics, thermosets, and elastomers is given in Ku.[21] For a detailed listing of the properties, the reader is referred to Kaplan[5] and Ohm.[22]

2.5.1 Properties

Elastomers are almost always used in the compounded state. The neat material is blended with a variety of additives to cure and enhance the properties of the elastomer.

2.5.1.1 Aging. Elastomers are affected by the environment more than other polymers. Thermal aging of the elastomer increases stiffness and hardness and decreases elongation. Radiation has a similar effect. Elastomers are sensitive to oxidation and in particular to the effects of ozone. Ultraviolet radiation acts similarly to ionizing radiation, so some elastomers do not weather well. Environmental effects are especially noted on highly stressed parts, and some elastomers are particularly affected by hydrolysis.

2.5.1.2 Creep. Creep with regard to elastomers refers to a change in strain when stress is held constant. Special terms are used for elastomers. Compression set (ASTM D-395)[23] is creep that occurs when the elastomer has been held at either constant strain or constant stress in compression. Constant strain is most common and is recorded as a percentage of permanent creep divided by original strain. Strain of 25 percent is common. Permanent set is deformation remaining after a stress is released.

2.5.1.3 Hardness. The hardness of elastomers is a measure of the resistance to deformation measured by pressing an instrument into the elastomer surface. Special instruments have been developed, the most common being the Shore durometer. Figure 2.10 shows the hardness of elastomers and plastics.

2.5.1.4 Hysteresis. Hysteresis is energy loss per loading cycle. This mechanical loss of energy is converted into heat in elastomers and is caused by internal friction of the molecular chains moving against each other. The effect causes a heat buildup in the elastomer, increasing its temperature, changing its properties, and aging it. A similar electrical effect can occur at high frequencies when the dissipation factor of the elastomer is high.

2.5.1.5 Low-temperature properties. As temperatures are decreased, elastomers tend to become stiffer and harder. Each material exhibits a stiffening range and a brittle point at the glass transition temperature. These effects are usually time-dependent.

2.5.1.6 Tear resistance. This is a measure of the stress needed to continue rupturing a sheet elastomer after an initiating cut or notch. Elastomers vary widely in their ability to withstand tearing.

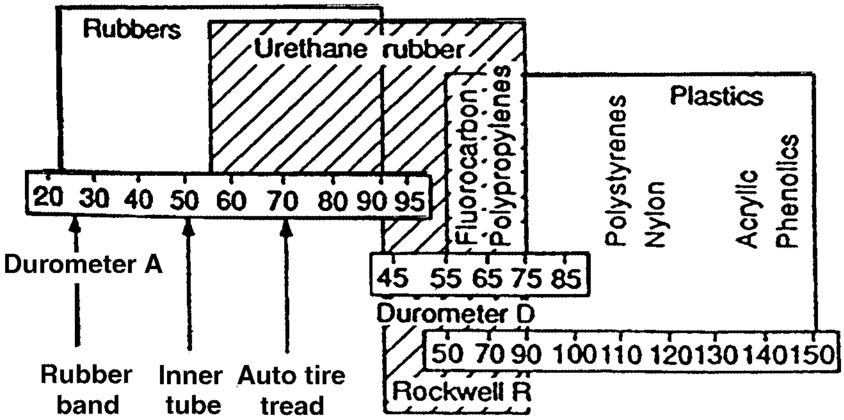

Figure 2.10 Hardness of rubber and plastics. *(From Harper.[8])*

2.5.1.7 Tensile strength, elongation, and modulus. In tension, metals behave in accordance with Hooke's law, and in strain, they react linearly to the yield point. Polymers and plastics (unreinforced) deviate somewhat from linearity (logarithmically). Special tensile tests are used for elastomers per ASTM D-412.[24] Elastomers are not generally designed for tensile service, but many other physical properties of the elastomers correlate with tensile strength.

2.5.2 Types of elastomers

A large number of chemically different elastomers exist. ASTM D-1418[25] describes many of these. Tables 2.24 and 2.25 list elastomers and their properties.

Natural rubber (NR) is still used in many applications. It is not one uniform product but varies with the nature of the plant producing the sap, the weather, the locale, the care in producing the elastomer, and many other factors. A variant of NR, *guttapercha,* was used in most of the early electrical products, especially cable. It has excellent electrical properties (as shown in Table 2.25), low creep, and high tear strength. On aging it reverts to the gum.

Isoprene rubber (IR) is similar in chemistry to NR but it is produced synthetically. Polyisoprene constitutes 97 percent of its composition. It is more consistent and much easier to process than NR.

Acrylic elastomer (ABR) has a heat resistance that is almost as good as that of fluorinated compounds and silicones. It also ages well but is sensitive to water. Its chief use is in contact with oils.

Butadiene elastomer (BR) is used to copolymerize with SBR and NR in tire stocks.

Epichlorohydrin elastomer (CO, ECO) are flame-retardant because of the presence of chlorine. Their electrical properties are modest, but they age well and resist most chemicals. Dissipation factors are high.

Carboxylic elastomer (COX) has good low-temperature performance, excellent weather resistance, and extremely good wear resistance. Electrical properties are average.

Neoprene (CR) (chloroprene) was the first synthetic elastomer and is widely used in industry. It is nonflammable and resists ozone, weather, chemicals, and radiation. However, it is highly polar and has a high dissipation factor and dielectric constant.

Chlorosulfonated polyethylene (CSM) is similar to CR, with some improvement in electrical properties and better heat resistance. It is available in colors and often used in high-voltage applications.

Ethylene-propylene terpolymer (EPDM) is synthesized from ethylene, propylene, and a third monomer, a diene. The diene permits conventional sulfur vulcanization. The elastomer is exceptionally resistant to radiation and heat. The glass transition temperature is –60°C, and electrical properties are good.

Ethylene-propylene copolymer (EPM), which was often used as a wire insulation, is being replaced by EPDM, because its processing qualities are somewhat inferior to those of EPDM.

TABLE 2.24 Chemical Description of Elastomers

ASTM D-1418	Chemical type	Properties
NR	Natural rubber polyisoprene	Excellent physical properties
IR	Polyisoprene synthetic	Same as NR, but more consistency and better water resistance
ABR	Arylate butadiene	Mechanical elastomer; excellent heat and ozone resistance
BR	Polybutadiene	Copolymerizes with NR and SBR; abrasion resistance
CO	Epichlorohydrin	Chemical resistance
COX	Butadiene-acrylonitrite	Used with NBR to improve low-temperature performance
CR	Chloroprene, neoprene	Withstands weathering, flame-retardant, chemical resistance
CSM	Chlorosulfonated polyethylene	Colors available, weathering and chemical resistance, poor electrical properties
EPDM	Ethylenepropylene terpolymer	Similar to EPM, good electrical properties, resists water and steam
EPM	Ethylene-propylene copolymer	Similar to EPDM, good heat resistance, wire insulation
FPM	Fluorinated copolymers	Outstanding heat and chemical resistance
IIR	Isobutyleneisoprene, butyl	Outstanding weather resistance, low physical properties, track resistance
NBR	Butadiene-acrylonitrite, nitrile, Buna N	General-purpose elastomer, poor electrical properties
PVC/NBR	Polyvinyl chloride and NBR	Colors available, weather, chemical, and ozone resistance
SBR	Styrene: butadiene, GRS, Buna S	General-purpose elastomer, good physical properties, poor oil and weather resistance
SI (FSI, PS1, VS1, PVS1)	Silicone copolymers	Outstanding at high and low temperatures, arc-and track-resistance, resist weather and ozone, excellent electrical properties, poor physical properties
T	Polysulfide	Excellent weather resistance and solvent resistance
U	Polyurethane	High physical and electrical properties

SOURCE: From Harper.[8] Reprinted with permission.

Fluorinated elastomers (FPM) include several types—fluorocarbons, fluorosilicones, and fluoroalkoxy phosphazenes. The elastomers can be used to 315°C, do not burn, are unaffected by most chemicals, and have excellent electrical properties. In thermal stability and aging, only the silicones are better. Physical property qualities are high, but so is the cost.

TABLE 2.25 Electrical Properties of Elastomers

ASTM elastomer	Dielectric strength, V/mil	Dissipation factor tan δ	Dielectric constant	Volume resistivity, Ω-cm
COX	500	0.05	10	10^{15}
CR	700	0.03	8	10^{11}
CSM	700	0.07	8	10^{14}
EPDM	800	0.007	3.5	10^{16}
FPM	700	0.04	18	10^{13}
IIR	600	0.003	2.4	10^{17}
MR	800	0.0025	3	10^{16}
SBR	800	0.003	3.5	10^{15}
SI	700	0.001	3.6	10^{15}
T	700	0.005	9.5	10^{12}
U	500	0.03	5	10^{12}

SOURCE: From Harper.[8] Reprinted with permission.

Butyl rubber (IIR) is highly impermeable to water vapor. Its nonpolar nature gives it good electrical properties. Compounded with aluminum oxide trihydrate, it has exceptional arc and track resistance. Butyl has good aging characteristics and good flexibility at low temperatures.

Nitrile rubber (NBR) is resistant to most chemicals, but its polarity gives it poor electrical properties, so its major use is in mechanical applications.

Polyvinyl chloride copolymers (PVC/NBR) are similar to NBR. They can be colored and are used in wire and cable jackets.

GRS (SBR) stands for "government rubber, styrene," a nomenclature derived during World War II when natural rubber was not available in the West. It is used in mechanical applications.

Silicone elastomers (SI), which are composed of silicon and oxygen atom backbones, have the highest temperature ability (315°C), a wide temperature range (–100 to 600°F), and excellent electrical properties. They do not burn and are arc resistant. Physical properties are modest.

Polysulfides (T) weather best of all and are highly chemical resistant. Dissipation factors are excellent (as low as 0.001); physical properties are modest.

Polyurethanes (U) are either ester- or ether-based. Ester-based elastomers are poor in water resistance. They are excellent in electrical applications, with outstanding physical properties. Abrasion resistance is particularly high. They become stiff at low temperatures. They can be compounded like regular elastomers, used as cast elastomers, or injection molded like thermoplastics.

2.5.3 Thermoplastic elastomers (TPEs)

These materials have the functional requirements of elastomers (extensibility and rapid retraction) and the processability of thermoplastics. The principal advantages of the TPEs as compared to vulcanized rubber are (1) reduction in compounding requirements, (2) easier and more efficient processing cycles, (3) scrap recycling, and (4) availability of thermoplastic processing methods. There are six generic classes of TPES: styrenic block copolymers, polyolefin blends (TPO), elastomeric alloys, thermoplastic polyurethanes (TPU), thermoplastic copolyesters, and thermoplastic polyamides. TPEs are processed almost exclusively by extrusion and injection molding but can be blow molded, thermoformed, and heat welded. None of these methods is available to thermoset-type elastomers. Additional information can be obtained from Kaplan[5] and Bhowmick and Stephens.[20]

2.6 Applications

This section describes how polymers are processed and used in a variety of forms in electrical and electronic applications. The fundamental differences among the classes of polymers, namely, thermoplastics, thermosets, and elastomers, dictate the processing method to be used. Furthermore, within each class, the differences in the thermal and melt properties of the polymers also dictate what processing methods are best suited for a given material. This section is designed to acquaint the reader with some basic information about polymer processing. The reader is directed to the references for a more detailed description of each of the processing methods.[4–6] It is recommended that the plastics suppliers be used as a resource for guidance in both design and processing of polymers. The process sequence for all polymers involves heating the polymer to soften it, forcing the softened polymer into a mold or through a die to shape it, and then cooling or curing the molten polymer into its final shape. While polymers are not necessarily all solids (some are liquids), heating facilitates their processing.

2.6.1 Laminates

Most printed wiring boards (PWBs) are fabricated from reinforced thermosetting resins, although thermoplastics may be used in special applications. Laminates are prepared by impregnating a woven reinforcement material with a liquid resin, which is usually dissolved in a solvent. The impregnated fabric is heated to drive off the solvent and advance the cure of the resin slightly to the “B stage” so that the material is stiff at room temperature and easily handled. At this point, the composite material is referred to as a “prepreg.” A PWB is fabricated by stacking several layers of prepreg and laminating with heat and pressure to reflow the resin and bring about full cure. Before laminating, a prepreg may be bonded with copper on one or both sides so as to create a conductive layer or conductive traces in the finished PWB. Considerable effort is given to ensure good compatibility between the resin and reinforcement material to avoid delamination, microcracks, voids, and other defects in the finish composite. Resin and reinforcement materials must be chosen carefully for each application. PWB materials are chosen for a given application based on requirements for thermal expansion, dielectric constant and loss, and thermal stability. Table 2.26 gives some key properties of various classes of PWB materials.

For selected applications, PWBs based on high-performance thermoplastics may be chosen. In particular, PWBs based on fluoropolymers and liquid crystal polymers are attractive for high-frequency applications because of their low dielectric constant and low loss, which are important in microwave applications. In many cases, these materials can be processed in the same manner as the thermosetting laminates, because they incorporate a fluoropolymer fabric reinforcement in a low-loss thermosetting material. In other cases, they are essentially filled thermoplastics, so they are processed like a thermoplastic by, for example, injection molding.

A processing method related to laminating is filament winding, used for preparing cylindrical or rounded shapes. Continuous filaments are wrapped around a mandrel then impregnated with a resin and cured. Removing them from the mandrel leaves the cured piece. Tubes and cylindrical vessels are fabricated using this technique.

2.6.2 Molding and extrusion

These processing methods are discussed together because, in many cases, the techniques are combined. In extrusion, powdered or pelletized material is fed into a machine that contains a screw in a heated barrel, which may melt, mix, and devolatilize the mixture while pushing it through a die. Extrusion may also be used to compound a formulation and pelletize it for subsequent molding or extrusion into its final shape. Details on molding and extrusion are available in other texts.[27,28]

Hollow parts can be fabricated by blow molding, rotational molding, or slush molding. In *blow molding,* an extruded thermoplastic tube is placed in a mold while still hot from the extruder and expanded into the mold with gas pressure. The mold is opened and the part ejected. *Slush molding* starts with a thermosetting molding powder, which is poured into a heated mold. Before the material is completely polymerized, the mold is opened and uncured material remove from the center of the piece. The part is then removed and taken to full cure in an oven. In *rotational molding*, the inside of the mold is coated by rotating it, and unreacted or excess material is removed after a sufficient thickness builds up on the inside surface of the mold.

Solid parts can be fabricated by compression molding, injection molding, and transfer molding. Many microelectronic packages are made by one of these molding processes. In *compression molding,* a thermoplastic or B-staged thermosetting powder is subjected to heat and pressure in a mold. The material flows, and heat cures the part, or the mold is cooled sufficiently that the part can be removed from the mold. A related process is *injection molding*, in which the raw material (either thermoplastic or thermoset powder) is heated to a softening point then forced into a mold, solidified rapidly, and then ejected

TABLE 2.26 Properties of Selected PWB Laminate Materials

Laminate	T_g (°C)	CTE below T_g (ppm/°C)		Water uptake	Dielectric constant (@ 1MHz)	Dissipation factor (@ 1MHz)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Thermal conductivity (W/m°C)
		x, y	z	MIL-P-13949F	z	z	x, y	x, y	z
E-glass/epoxy	120	12–16	60–80	10	4.7	0.021	276	17.4	0.35
E-glass/polyimide	220–300	11–14	60–80	25	4.5	0.018	345	19.6	0.35
E-glass/PTFE	75	24	261	—	2.3	0.006	68–103	1.0	0.26
Quartz/polyimide	260	6–12	34	25	3.6	0.010	—	27.6	0.13
Quartz/Quartrex	185	—	62	—	3.5	—	—	18.6	—
Kevlar-49/Quatrex	185	3–8	105	10	3.7	0.030	—	22–28	0.16
Kevlar-49/polyimide	180–200	3–8	83	25	3.6	0.008	—	20–27	0.12

SOURCE: Pecht, et al.[26]

from the mold. In the related process of *reaction injection molding*, liquid components of a thermosetting formulation are pumped through a mixing head into the mold and cured in the mold. *Transfer molding* is a similar process in which a thermosetting material is softened in a transfer chamber then forced into a mold, cured, and ejected. While in the transfer chamber or the mold, the chamber may be evacuated to reduce void content of the molded part.

2.6.3 Casting and potting

Low-volume production can be accomplished by casting liquid thermosets into a mold and curing. Many electrical assemblies include a potting step in which a thermoset material is cast around a component, connector pins, or printed wiring boards. Depending on the application, the potting resin may be intended to protect the components from environmental exposure, dirt, moisture, mechanical shock, or vibration. Casting resins include epoxies, polyesters, polyurethanes, silicones, bismaleimides, and cyanate esters. For electrical applications, these materials are typically formulated without solvents to prevent void formation during cure at elevated temperature. Low-viscosity components also help prevent void formation by minimizing trapped air during the casting or potting process. In choosing a casting or potting resin, there are several characteristics to consider in addition to the desired electrical or mechanical properties in the cured material. In particular, stress on the embedded components can be minimized by having a low shrinkage during cure and by having a coefficient of thermal expansion that matches that of the embedded components, and adhesion to the components should be good to minimized cracking and void formation. A general comparison of encapsulating resins is offered in Table 2.27

TABLE 2.27 A Comparison of Encapsulating Resins

Resin	Dielectric properties	Overall adhesion	Shrinkage	Maximum-use temp.,°C	Coefficient of thermal expansion	Chemical resistance
Epoxy	Excellent	Excellent	Low	150	Moderate	Good
Bismaleimide	Excellent	Good	Moderate	180	Low	Good
Cyanate ester	Excellent	Excellent	Low	175	Low	Excellent
Polyester	Good	Fair	High	175	Moderate	Poor
Silicone	Excellent	Low	Low	200	High	Good
Silicon-carbon (SYCAR)	Excellent	Good	Low	160	Moderate	Excellent

2.6.4 Adhesives

Adhesives used in electrical and electronic applications often have special requirements related to electrical or thermomechanical properties. In some applications, dielectric constant and loss tangent may be important. Often, the adhesive is called on to accommodate the mismatch in thermal expansion between bonded pieces, such as semiconductor and a plastic or ceramic package or between a ceramic package and an organic PWB.

2.6.5 Organic coatings

Coatings are applied to a variety of substrates primarily to protect that substrate from deterioration due to the action of outside agents. They give the substrate an extra level of protection against chemical, radiation, thermal, and oxidative attack. A detailed list of all types of organic coatings can be found in Stevens.[11] Although most organic polymers can be used as coatings in one form or another, only polymers that can be converted into formulations for conformal applications are discussed in this section. Conformal coatings are generally liquid resin formulations used in the protection of assembled printed-wiring boards from a variety of environmental effects. These resins conform to the topography of the board and the components thereon and are cured to form a relatively thin (1 to 10 mil) protective coating. The main function of the coating is to provide a moisture barrier for circuit traces and components, but secondary benefits are provided as protection against dust, other contaminants, chemicals, and abrasion, and some degree of shock and vibration. No coating will totally resist the effects of environmental stresses, and so these coatings do have a finite time of protection and are designed to operate under the requirements of the system in which they are used. Humidity and process contaminants can lead to serious degradation of electrical components, causing lower insulation resistance between conductors, premature high-voltage breakdown, corrosion of conductors, and even short circuits. As a result, the chosen coating material must have an excellent combination of physical, chemical, and electrical properties in addition to ease of application.

2.6.5.1 Conformal coating types. A variety of conformal coating materials are available to meet specific application needs. MIL-I-46058 defines five classes of polymers for conformal coatings. They are acrylics, epoxies, polyurethanes, silicones, and paraxylylene polymers. While not defined in the MIL specifications, other polymer types that could be considered include the polyimides, diallyl phthalate resins, and the benzocyclobutenes. The properties of these materials are shown in Table 2.28. These coatings can be solvent based, water based, or solventless systems. They can be applied as liquids, solids (powder), or film (vapor deposition), and the coatings can be cured either thermally or with radiation. They can be applied by brushing, spraying, dipping, or flow coating. A relative coating selection chart is given in Table 2.29.

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TABLE 2.28 Typical Characteristics of Various Coating Materials

Properties	Acrylic	Urethane	Epoxy	Silicone	Polyimide	DAP
Volume resistivity (50% RH, 23°C), Ω-cm	10^{15}	11×10^{14}	$10^{12} \times 10^{17}$	2×10^{16}	10^{16}	1.8×10^{16}
Dielectric constant						
60 Hz	3–4	5.4–7.6	3.5–5.0	2.7–3.1	3.4	3.6
1 kHz	2.5–3.5	5.5–7.6	3.5–4.5		3.4	3.6
1 MHz	2.5–3.5	4.2–5.1	3.3–4.0	2.6–2.7	3.4	3.4
Dissipation (power) factor						
60 Hz	0.02–0.04	0.015–0.048	0.002–0.010	0.007–0.001	—	0.010
1 kHz	0.02–0.04	0.04–0.060	0.002–0.02	—	0.002	0.009
1 MHz	2.5–3.5	0.05–0.07	0.030–0.050	0.001–0.002	0.005	0.011
Thermal conductivity, 10^{-4} cal/(s-cm^3-°C)	3–6	1.7–7.4	4–5	3.5–7.5	—	4–5
Thermal expansion, 10^{-3}/°C	5–9	10–20	4.5–6.5	6–9	4.0–5.0	—
Resistance to heat, continuous, °F	250	250	250	400	500	350
Effect of weak acids	None	Slight to dissolve	None	Little or none	Resistant	None
Effect of weak alkalis	None	Slight to dissolve	None	Little or none	Slow attack	None
Effect of organic solvents	Attacked by ketones, aromatics, and chlorinated hydrocarbons	Resists most	Generally resistant	Attacked by some	Very resistant	Resistant

SOURCE: From Coombs.[29] Reprinted with permission.

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TABLE 2.29 Coating Selection Chart[*]

	Acrylic	Urethane	Epoxy	Silicone	Polyimide	DAP
Application	A	B	C	C	C	C
Removal (chemically)	A	B	—	C	—	—
Removal (burn through)	A	B	C	—	—	—
Abrasion resistance	C	B	A	B	A	B
Mechanical strength	C	B	A	B	B	B
Temperature resistance	D	D	D	B	A	C
Humidity resistance	A	A	B	A	A	A
Humidity resistance (extended period)	B	A	C	B	A	A
Pot life	A	B	D	D	C	C
Optimum cure	A	B	B	C	C	C
Room-temperature curing	A	B	B	C	—	
Elevated-temperature curing	A	B	B	C	C	C

[*] Property ratings (A–D) are in descending order, A being optimum.

SOURCE: From Coombs.[29] Reprinted with permission.

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