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Polymers

James D. Idol
Richard L. Lehman

Edited by
Frank Kreith and Yogi Goswami
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Hydrogen embrittlement and hydrogen cracking can occur in the presence of stress and a hydrogen source. Embrittlement results when hydrogen diffuses into the metal and/or acts on the crack tip altering the fracture toughness. Hydrogen cracking may be regarded as a special case of stress corrosion cracking. Either environmental effect can lead to catastrophic failure. The source of hydrogen can be an acid solution, hydrogen evolved during corrosion, electrochemical treatment (plating, electropolishing), or hydrocarbons. Often isolation from the hydrogen source is difficult because hydrogen diffuses quickly through most materials and barrier coatings. Glass coating has met with some success.

Metal Surface Treatments

A number of treatments are employed to strengthen the surface of steels and make them more resistant to failure or wear. Some of the techniques may also be applied to selected nonferrous alloys. Flame, induction, and laser hardening provide intense heat to the outer surface of a medium- or high-carbon (hardenable) steel bringing it into the austenitic region, above Ac_3 (see subsection on fatigue). The bulk of the metal is not heated so that the surface can then be quenched rapidly forming hardening phases and a compressive surface stress. This provides strength and wear resistance. Another surface-hardening technique is carburizing. This can also be used on steels with lower carbon content. The metal is exposed to a controlled balance of carbon monoxide and carbon dioxide or is packed in graphite. At elevated temperature (usually above the Ac_3) carbon diffuses into the surface, converting it to a high-carbon steel. The steel is then either quenched directly from the carburizing temperature or reaustenitized and quenched. The result is similar to flame hardening, but higher hardness and surface compression can be accomplished compared with flame hardening. The center of the piece, with much lower carbon content, can provide fracture toughness, ductility, and safety. Nitriding exposes steel containing appropriate alloying elements (chromium, aluminum, vanadium, …) to monatomic nitrogen in the form of cracked ammonia, cyanide, or high-energy dissociated nitrogen gas. This is done below the eutectoid (lower transformation) temperature. Dispersed-phase nitrides are formed as nitrogen diffuses into the surface which harden the surface without a need for further heat treatment. The effects of both carburizing and nitriding can be introduced by carbonitriding above the transformation temperature and quenching or nitrocarburizing below the transformation to austenite.

Suggested Reading

ASM International, 1985, *Metals Handbook Desk Edition,* ASM International, Materials Park, OH.
ASM International, *Metals Handbook, 8th–10th ed.,* ASM International, Materials Park, OH.

12.2 Polymers

James D. Idol and Richard L. Lehman

Introduction

Polymers constitute a wide range of materials which are derived at least in part from organic, usually petroleum-based, raw materials; they consist of repeating molecular units and have special properties obtained by engineering the form of the molecular structures. The term *polymer* is derived from Greek roots and means "having many parts," a term which aptly describes the infinite number of compounds which can be synthesized from a relatively limited number of monomer units. The term *plastic* is often used in describing polymers, although this term is not in current usage since it is a general descriptive which refers to the forming rheology of many polymers but is too general to accurately describe this group of materials.

Polymers are used as engineering materials in the neat form, i.e., as the pure material, or in combination with a large diversity of additives, both organic and inorganic. These additives may be, among others,

TABLE 12.2.1 Physical Properties of Polymers

Properties of Plastics	ρ (kg m^{-3})	Tensile Strength (N mm^{-2})	Elongation (%)	E (GN m^{-2})	BHN	Machinability
Thermoplastics						
PVC rigid	1330	48	200	3.4	20	Excellent
Polystyrene	1300	48	3	3.4	25	Fair
PTFE	2100	13	100	0.3	—	Excellent
Polypropylene	1200	27	200–700	1.3	10	Excellent
Nylon	1160	60	90	2.4	10	Excellent
Cellulose nitrate	1350	48	40	1.4	10	Excellent
Cellulose acetate	1300	40	10–60	1.4	12	Excellent
Acrylic (methacrylate)	1190	74	6	3.0	34	Excellent
Polyethylene (high density)	1450	20–30	20–100	0.7	2	Excellent
Thermosetting plastics						
Epoxy resin (glass filled)	1600–2000	68–200	4	20	38	Good
Melamine formaldehyde (fabric filled)	1800–2000	60–90	—	7	38	Fair
Urea formaldehyde (cellulose filled)	1500	38–90	1	7–10	51	Fair
Phenol formaldehyde (mica filled)	1600–1900	38–50	0.5	17–35	36	Good
Acetals (glass filled)	1600	58–75	2–7	7	27	Good

Note: BHN = Brinell hardiness number, ρ = density, E = Young's modulus.

plasticizers which reduce the rigidity or brittleness of the material, fillers which increase strength and load deflection behavior under load, or stabilizers which protect the polymer against ultraviolet radiation.

The following discussion will separate polymers into two groups, thermoplastic and thermosetting, based on the distinctly different thermal processing behavior of these two broad classes of polymers. Thermoplastic polymers soften when heated and can be reshaped, the new shape being retained on cooling. The process can be repeated many times by alternate heating and cooling with minimal degradation of the polymer structure. Thermosetting polymers (or thermosets) cannot be softened and reshaped by heating. They are plastic and moldable at some state of processing, but finally set to a rigid solid and cannot be resoftened. Thermosets are generally stronger and stiffer than thermoplastic.

Table 12.2.1 of this section gives an overview of the physical properties of the most commonly used industrial polymers. Table 12.2.2 provides an overview of properties such as chemical resistance, ease of machining, and compressive strength for thermoplastic and thermosetting plastics, while Table 12.2.3 is a selection guide for polymers by application. A detailed summary of polymer properties, including electrical properties, thermal properties, optical properties, and fabrication, is presented in Table 12.2.4.

Thermoplastic Polymers

Acetal and Polyacetal

These combine very high strength, good temperature and abrasion resistance, exceptional dimensional stability, and low coefficient of thermal expansion. They compete with nylon (but with many better properties) and with metal die castings (but are lighter). Chemical resistance is good except for strong acids. Typical applications are water-pump parts, pipe fittings, washing machines, car instrument housings, bearings, and gears.

Acrylics (Methylmethacrylate, PMMA)

These are noted for their optical clarity and are available as sheet, rod, tubings, etc., as Perspex (U.K.) and Plexiglas (U.S., Germany, etc.). They are hard and brittle and quite resistant to discoloring and, especially, weathering. Applications include outdoor display signs, optical lenses and prisms, transparent

TABLE 12.2.2 Relative Properties of Polymers

Material	Tensile Strength[a]	Compressive Strength[b]	Machining Properties	Chemical Resistance
Thermoplastics				
Nylon	E	G	E	G
PTFE	F	G	E	O
Polypropylene	F	F	E	E
Polystyrene	E	G	F	F
Rigid PVC	E	G	E	G
Flexible PVC	F	P	P	G
Thermosetting plastics				
Epoxy resin (glass-fiber filled)	O	E	G	E
Formaldehyde (asbestos filled)	G	G	F	G
Phenol formaldehye (Bakelite)	G	G	F	F
Polyester (glass-fiber filled)	E	G	G	F
Silicone (asbestos filled)	O	G	F	F

Note: O = outstanding, E = excellent, G = good, F = fair, P = poor.
[a] Tensile strength (typical): E = 55 Nmm^{-2}; P = 21 Nmm^{-2}.
[b] Compressive strength (typical): E = 210 Nmm^{-2}; P = Nmm^{-2}.

TABLE 12.2.3 Selection Guide for Polymers by Application

Application or Service	Properties Required	Suitable Plastics
Chemical and thermal equipment	Resistance to temperature extremes and to wide range of chemicals; minimum moisture absorption; fair to good strength	Fluorocarbons, chlorinated polyether, polyvinylidene fluoride, polypropylene, high-density polyethylene, and epoxy glass
Heavily stressed mechanical components	High-tensile plus high-impact strength; good fatigue resistance and stability at elevated temperatures; machinable or moldable to close tolerance	Nylons, TFE-filled acetals, polycarbonates, and fabric-filled phenolics
Electrostructural parts	Excellent electrical resistance in low to medium frequencies; high-strength and -impact properties; good fatigue and heat resistance; good dimensional stability at elevated temperatures	Allylics, alkyds, aminos, epoxies, phenolics, polycarbonates, polyesters, polyphenylene oxides, and silicones
Low-friction applications	Low coefficient of friction, even when nonlubricated; high resistance to abrasion, fair to good form stability and heat and corrosion resistance	Fluorocarbons (TFE and FEP), filled fluorocarbons (TFE), TFE fabrics, nylons, acetals, TFE-filled acetals, and high-density polyethylenes
Light-transmission components, glazing	Good light transmission in transparent or translucent colors; good to excellent formability and moldability; shatter resistance; fair to good tensile strength	Acrylics, polystyrenes, cellulose acetates, cellulose butyrates, ionomers, rigid vinyls, polycarbonates, and medium-impact styrenes
Housings, containers, ducts	Good to excellent impact strength and stiffness; good formability and moldability; moderate cost; good environmental resistance; fair to good tensile strength and dimensional stability	ABS, high-impact styrene, polypropylene, high-density polyethylene, cellulose acetate butyrate, modified acrylics, polyester–glass and epoxy–glass combinations

coverings, drafting instruments, reflectors, control knobs, baths, and washbasins. They are available in a wide range of transparent and opaque colors.

Acrylonitrile-Butadiene-Styrene (ABS)

This combination of three monomers gives a family of materials which are strong, stiff, and abrasion resistant with notable impact-resistance properties and ease of processing. The many applications include

TABLE 12.2.4 Properties of Polymers

Chemical class	Cellulose acetate	Cellulose acetate	Cellulose acetate butyrate	Cellulose acetate butyrate	Nylon	Polycarbonates	Polyethylene	Polyethylene
	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic
	Soft	Hard	Soft	Hard	6/6	Unfilled	Low Density	Medium Density
ELECTRICAL PROPERTIES								
D.C. resistivity, ohm-cm	10^{10}-10^{13}	10^{10}-10^{13}	10^{10}-10^{12}	10^{10}-10^{12}		2×10^{16}	$>10^{15}$	$>10^{15}$
Dielectric constant, 60 cps	3.5-7.5	3.5-7.5	3.5-6.4	3.5-6.4	4.0-4.6	3.17	2.3-2.35	2.3
Dielectric constant, 10^6 cps	3.2-7.0	3.2-7.0	3.2-6.2	3.2-6.2	3.4-3.6	2.96	2.3-2.35	2.3
Dissipation factor, 60 cps	0.01-0.06	0.01-0.06	0.01-0.04	0.01-0.04	0.014-0.04	0.0009	<0.0005	<0.0005
Dissipation factor, 10^6 cps	0.01-0.10	0.01-0.10	0.01-0.04	0.01-0.04	0.04	0.01	<0.0005	<0.0005
MECHANICAL PROPERTIES								
Modulus of elasticity, 10^3 psi	86-250	190-400	74-126	150-200		290-325	14-38	35-90
Tensile strength, psi	1,900-4,700	4,600-8,500	1,900-3,800	5,6800	9,000-12,000	8,000-9,500	1,000-1,400	1,200-3,500
Ultimate elongation, %	32-50	6-40	60-74	38-54	60-300	20-100	400-700	50-600
Yield stress, psi	2,200-4,200	4,100-7,600	1,200-2,600	3,600-6,100		8,000-10,000	1,100-1,700	1,500-2,600
Yield strain, %							20-40	10-20
Rockwell hardness	R 49-R 103	R 101-R 123	R 59-R 95	R 108-R 117	R 108-R 120	M 70-M 180		
Notched Izod impact strength, ft lb/in.	2.0-5.2	0.4-2.7	2.5-5.4	0.7-2.4	1.0-2.0	8-16	No break	0.5->16
Specific gravity	1.27-1.34	1.27-1.34	1.15-1.22	1.19-1.25	1.13-1.15	1.2	0.91-0.925	0.926-0.941
THERMAL PROPERTIES								
Burning rate	Medium	Medium	Medium	Medium	Self-extinguishing	Self-extinguishing	Very slow	Slow
Heat distortion, 264 psi. C	44-57	60-113	49-58	70-99		135-145		
Specific heat, cal/g	0.3-0.42	0.3-0.42	0.3-0.4	0.3-0.4	0.4	0.3	0.55	0.55
Linear thermal expansion coefficient, 10^{-5}, C	8-16	8-16	11-17	11-17	8.0	6.6	10-20	14-16
Maximum continuous service temperature, C					80-150	138-143	60-77	71-93
CHEMICAL RESISTANCE								
Mineral acids, weak	Fair to good	Fair to good	Good	Good	Very good	Excellent	Good	Excellent
Mineral acids, strong	Poor	Poor	Fair to good	Fair to good	Poor	Fair	Good	Excellent
Oxidizing acids, concentrated	Very poor	Very poor			Poor		Good to poor	Good to poor
Alkalies, weak	Poor	Poor	Good	Good	No effect	Poor	Good	Excellent
Alkalies, strong	Very poor	Very poor	Poor	Poor	No effect	Poor	Good	Excellent
Alcohols	Poor	Poor	Poor	Poor	Good	Poor	Excellent to poor	Excellent to poor
Ketones	Poor	Poor	Poor	Poor	Good	Poor	Excellent to poor	Excellent to poor
Esters	Poor	Poor	Poor	Poor	Good	Poor	Excellent to poor	Excellent to poor
Hydrocarbons, aliphatic	Fair to good	Fair to good	Fair to good	Fair to good	Very good	Poor	Fair	Fair
Hydrocarbons, aromatic	Poor to fair	Poor to fair	Poor	Poor	Fair to good	Poor	Fair	Good
Oils: vegetable, animal, mineral	Fair to good	Fair to good	Good	Good	Good	Poor	Good	Excellent
MISCELLANEOUS PROPERTIES								
Clarity	Excellent	Excellent	Good to excellent	Good to excellent	Clear	Clear	Translucent	Translucent
Color	Pale to colorless	Pale to colorless	Pale to colorless	Pale to colorless	Pale amber to colorless	Colorless	Colorless	Colorless
Refractive index, n_D	1.46-1.50	1.46-1.50	1.46-1.49	1.46-1.49	1.53	1.60	1.50-1.54	1.52-1.54
FABRICATION								
Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MC—blow molding, MC—compression molding, MI—injection molding, S—spreading	Cs, E, F, MB, MC, MI, S	Cs, E, F, MB, MC, MI, S	Cs, E, F, MB, MC, MI, S	Cs, E, F, MB, MC, MI, S	E, F, MB, MC, MI	Cs, E, F, MB, MC, MI	Cl, E, F, MB, MC, MI	Cl, E, F, MB, MC, MI

TABLE 12.2.4 (continued) Properties of Polymers

Polyethylene	Polymethyl-methacrylate	Polypropylene	Polypropylene	Polystyrene	Polystyrene-acrylonitrile	Polytetrafluoro-ethylene	Polytrifluorochloro-ethylene	Polyvinylchloride and vinylchloride acetate	Polyvinylchloride and vinylchloride acetate	Epoxy
Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic	Thermosetting
High Density	Unmodified	Unmodified	Copolymer	Unmodified	Unmodified	Unmodified	Unmodified	Unmodified, rigid	Plasticized, non-rigid	Unfilled
$>10^{15}$	$>10^{14}$	$>10^{15}$	$>10^{17}$	$>10^{16}$	10^{13}-10^{17}	10^{18}	10^{18}	10^{12}-10^{16}	10^{11}-10^{14}	10^{12}-10^{14}
2.3-2.35	3.5-4.5	2.2-2.6	2.3	2.5-2.65	2.6-3.4	2.	2.2-2.8	3.2-4.0	5.0-9.0	3.5-5.0
2.3-2.35	3.0-3.5	2.2-2.6	2.3	2.5-2.65	2.5-3.1	2.	2.3-2.5	3.0-4.0	3.0-4.0	3.4-4.4
<0.0005	0.04-0.06	<0.0005	0.0001-0.0005	0.0001-0.0003	0.006-0.008	0.0002	0.001	0.01-0.02	0.03-0.05	0.001-0.005
<0.0005	0.02-0.03	0.0005-0.002	0.0001-0.002	0.0001-0.0004	0.008-0.01	0.0002	0.005	0.006-0.02	0.06-0.1	0.03-0.05
85-160	350-500	1.4-1.7		400-600	$>10^{16}$	33-65	150	200-600		>300
3,100-5,500	7,000-11,000	4,300-5,500	2,900-4,500	5,000-10,000	9,000-12,000	2,000-4,500	4,500-6,000	5,000-9,000	1,500-3,000	4,000-13,000
15-100	2.0-10	>220	200-700	1.0-2.5	1.0-2.5	200-400	250	2.0-40	200-400	2.0-6.0
2,400-5,000		4,900				1,600-2,000	4,200			
5-10		15				50-75	10	1.0-5.0		
R 30-R 50	M 80-M 105	93	R 50-R 96	M 65-M 85	M 75-M 90	D 50-D 65	J 75-J 95	R 110-R 120		M 75-M 110
1.5-20	0.3-0.6	1.0	1.1-12	0.25-0.60	0.3-0.6	2.5-4.0	2.5-4.0	0.4-2.0		0.2-1.0
0.941-0.965	1.18-1.20	0.90	0.90	1.04-1.08	1.05-1.1	2.1-2.3	2.1-2.3	1.36-1.4	1.15-1.35	1.115
Slow	Slow	Medium	Medium	Medium to slow	Slow	Self-extinguishing	Self-extinguishing	Self-extinguishing	Slow to self-extinguishing	Slow
	66-99				91-104	60		60-80		Up to 120
0.55	0.35	0.5	0.5	0.32-0.35	0.32-0.35	0.25	0.22	0.2-0.28	0.36-0.5	0.25-0.4
11-13	5.0-9.0	5.8-10	8-10	6.0-8.0	3.6-3.8	10	7.0	5.0-18	7.0-25	4.5-9.0
92-200	60-93		190-240	66-82	77-88	260	200	70-74	80-105	80
Excellent	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Fair to good	Excellent
Excellent	Fair to poor	Excellent	Excellent	Excellent	Good to excellent	Excellent	Excellent	Good to excellent	Fair to good	Fair to good
Good to poor	Attacked	Good to poor	Poor	Poor	Poor	Excellent	Excellent	Fair to good	Poor to fair	Excellent
Excellent	Good	Excellent to good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Fair to good	Excellent
Excellent	Poor	Excellent to good	Good	Excellent	Good to excellent	Excellent	Excellent	Good	Fair to good	Excellent
Excellent to poor		Excellent to good	Good below 80 C	Excellent	Good to excellent	Excellent	Excellent	Excellent	Fair	Poor
Excellent to poor	Dissolves	Excellent to good	Good below 80 C	Dissolves	Dissolves	Excellent	Excellent	Poor	Poor	
Excellent to poor	Dissolves	Excellent to good	Good below 80 C	Poor	Dissolves	Excellent	Excellent	Poor	Poor	Excellent
Fair	Good	Good to fair	Good below 80 C	Poor	Good	Excellent	Excellent	Excellent	Poor	Excellent
Fair	Softens	Good to fair	Good below 80 C	Dissolves	Fair to good	Excellent	Excellent	Poor	Poor	Excellent
Good	Good	Good		Fair to poor	Good to excellent	Excellent	Excellent	Excellent	Poor	
Translucent		Transparent	Transparent	Transparent	Transparent	Translucent	Transparent	Transparent	Transparent	Transparent
Colorless	Colorless	Colorless to sl. yellow	Colorless to sl. yellow	Colorless	Colorless to amber	Colorless to gray	Colorless to pale	Colorless to amber	Colorless to amber	Colorless
1.54	1.48-1.50	1.49		1.59-1.60	1.56-1.57	1.30-1.40	1.43	1.54	1.50-1.55	1.58
Cl, E, F, MB, MC, MI	Cs, E, F, Lq, MB, MC, MI		Cl, E, F, MB, MC, MI	E, F, MB, MC, MI	Cl, E, F, MB, MC, MI	E, F, MC, MI	Cs, E, F, I, MC, MI, S	Cl, Cs, E, F, I, MB, MC, MI, S	Cl, Cs, E, MB, MC, MI, S	Cs, I, S

TABLE 12.2.4 (continued) Properties of Polymers

Properties of Polymers [continued]

Melamine-formaldehyde	Melamine-formaldehyde	Phenol-formaldehyde	Phenol-formaldehyde	Phenol-formaldehyde	Polyester (styrene-alkyd)	Silicones	Urea Formaldehyde	Acrylonitrile-butadiene-styrene (ABS)	Acetal	Alkyd resins
Thermosetting	Thermosetting	Thermosetting	Thermosetting	Thermosetting	Thermosetting	Thermosetting	Thermoplastic	Thermoplastic	Thermoplastic	Thermosetting
-Cellulose filled	Mineral filled (electrical	Cord filled	Cellulose filled	Unfilled cast phenolic, mechanical and chemical grade	Glassfiber mat reinforced	Mineral filled	-Cellulose filled	High-heat resistant	Homopolymer	Synthetic-fiber filled
10^{12}-10^{14}	10^{13}-10^{14}	10^{11}-10^{12}	10^{11}-10^{13}	$1.0\text{-}7.0 \times 10^{12}$	10^{11}	$>10^{12}$	0.5-5.0	2.4-5.0		3.8-5.0
7.9-9.4	10.2	7.0-10.0	5.0-9.0	6.5-7.5	4.0-5.5	3.5-3.6	7.7-9.5	2.4-3.8	3.7	3.6-4.7
7.2-8.4	6.1	5.0-6.0	4.0-7.0	4.0-5.5	4.0-5.5	3.4-3.6	6.7-8.0	0.003-0.008		0.012-0.026
0.03-0.08	0.10	0.1-0.3	0.04-0.3	0.10-0.15	0.01-0.04	0.004	0.036-0.043	0.007-0.015	0.004	0.01-0.016
0.03-0.043	0.051	0.04-0.09	0.03-0.07	0.04-0.05	0.01-0.06	0.005-0.007	0.025-0.035			
1,300	1,950	900-1,300	800-1,200	4.0-5.0	500-1,500		1,300-1,400	7,000-8,000	10,000-12,000	4,500-6,500
7,000-13,000	5,500-6,500	6,000-9,000	6,500-8,500	6,000-9,000	30,000-50,000	3,000-4,000	5,500-13,000	1.0-20	15-75	
0.6-0.9		0.5-1.0	0.6-1.0	1.5-2.0	0.5-1.5		0.6	4,000-9,000		10,000-13,000
M 110-M 124	E 90		M 110-M 120	M 93-M 120	M 80-M 120	M 85-M 95	E 94-E 97	R 110-R 115	M 94, R 120	E 76
0.24-0.35	0.3-0.4	4.0-8.0	0.24-0.34	0.25-0.4	7.0-30	0.25-0.35	0.24-0.40	2.0-4.0	1.4-2.3	0.50-4.5
1.47-1.52	1.78	1.36-1.43	1.32-1.55	1.307-1.318	1.5-2.1	1.8-2.8	1.47-1.52	1.06-1.08	1.43	1.24-2.6
Self-extinguishing	Self-extinguishing	Self-extinguishing	Self-extinguishing	Self-extinguishing	Self-extinguishing	Self-extinguishing	Self-extinguishing	Slow	Slow	Self-extinguishing
204	130	121-127	143-171	74-80	93-288	>260	130	115-118		
0.4			0.35-0.40		0.2-0.4	0.2-0.3	0.6	0.3-0.4	0.35	
2.0-5.7	2.1-4.3		3.0-4.5	6.0-8.0	1.8-3.0	2.0-4.0	2.2-3.6	6.0-6.5	8.1	4.0-5.5
99.0	149	121	149-177		121-204	288	77	88-110	84	149-220
Good	Fair	Variable	Variable	Fair to good	Good	Fair to good	Poor	Good	Fair	Good
Poor	Poor	Poor	Poor	Poor to good	Poor	Poor to good	Poor	Good	Poor	Fair
Poor	Poor	Poor	Poor	Poor	Poor		Poor	Poor	Poor	
Good	Fair	Variable	Variable	Poor to good	Good	Fair	Fair	Good	Poor	Good
Poor	Poor	Poor	Poor	Poor	Poor	Poor	Poor	Good	Poor	Fair
Good	Good	Good	Good to excellent	Good to excellent	Good	Poor	Good	Good	Good	Fair to good
Good	Good	Poor to fair	Fair	Fair	Poor	Poor	Good	Poor	Good	Fair to good
Good	Good	Fair to good	Fair to good	Fair to good	Good		Good	Poor	Good	Fair to good
Good	Good	Fair to good	Excellent	Good to excellent	Good	Fair to good	Good	Fair	Good	Fair to good
Good	Good	Fair to good	Excellent	Good	Poor to fair	Poor	Good	Fair	Good	Fair to good
Good	Good	Good	Excellent	Excellent	Good	Good	Good	Good	Good	
Translucent	Opaque	Opaque	Opaque	Clear	Translucent	Opaque	Translucent	Translucent to opaque	Translucent to opaque	Opaque
Colorless	Dark			Colorless to amber	Colorless	Pale to dark	Colorless	Colorless	Colorless	Colorless
							1.54-1.56		1.48	
MC	MC	MC	MC	Cs, F	I	MC	MC	CI, E, MB, MI	MI, E	Cs MC, MI

TABLE 12.2.4 (continued) Properties of Polymers

Properties of Polymers [continued]

Chemical class	Polyketone							
	aliphatic thermoplastic							
	neat resin							
ELECTRICAL PROPERTIES								
D.C. resistivity, ohm-cm	103							
Dielectric constant, 60 cps	5-6							
Dielectric constant, 10^6 cps								
Dissipation factor, 60 cps								
Dissipation factor, 10^6 cps	0.04							
MECHANICAL PROPERTIES								
Modulus of elasticity, 10^3 psi	250							
Tensile strength, psi	>9000							
Ultimate elongation, %	300							
Yield stress, psi	9000							
Yield strain, %	2.2							
Rockwell hardness								
Notched Izod impact strength, ft lb/in.	4							
Specific gravity	1.24							
THERMAL PROPERTIES								
Burning rate								
Heat distortion, 264 psi. C	105-110							
Specific heat, cal/g								
Linear thermal expansion coefficient, 10^{-5}, C	9-11							
Maximum continuous service temperature, C								
CHEMICAL RESISTANCE								
Mineral acids, weak	Good							
Mineral acids, strong	Fair							
Oxidizing acids, concentrated	Fair							
Alkalies, weak	Good							
Alkalies, strong	Good							
Alcohols	Excellent							
Ketones	Excellent							
Esters	Excellent							
Hydrocarbons, aliphatic	Excellent							
Hydrocarbons, aromatic	Excellent							
Oils: vegetable, animal, mineral								
MISCELLANEOUS PROPERTIES								
Clarity	translucent							
Color	white crystals							
Refractive index, n_D								
FABRICATION								
Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MC—blow molding, MC—compression molding, MI—injection molding, S—spreading	E, MI							

pipes, refrigerator liners, car-instrument surrounds, radiator grills, telephones, boat shells, and radio and television parts. Available in medium, high, and very high impact grades.

Cellulosics

"Cellulose nitrate" is inflammable and has poor performance in heat and sunlight. Its uses are therefore limited. Cellulose acetate has good strength, stiffness, and hardness and can be made self-extinguishing. Glass-filled grades are made. Cellulose acetate-butyrate (CAB) has superior impact strength, dimensional stability, and service temperature range and can be weather stabilized. Cellulose proprionate (CP) is similar to CAB, but has better dimensional stability and can have higher strength and stiffness. Ethyl cellulose has better low-temperature strength and lower density than the others. Processing of cellulose plastics is by injection molding and vacuum forming. Applications include all types of moldings, electrical insulation, and toys.

Ethylene-Vinyl Acetate (EVA)

This material gives tough flexible moldings and extrusions suitable for a wide temperature range. The material may be stiffened by the use of fillers and is also specially formulated for adhesives. Applications include all types of moldings, disposable liners, shower curtains, gloves, inflatables, gaskets, and medical tubing. The material is competitive with polyvinyl chloride (PVC), polyethene, and synthetic rubbers, and is also used for adhesives and wax blends.

Fluorocarbons

This class of polymers, characterized by fluorine substitution, has outstanding chemical, thermal, and electrical properties and is characterized by the following four main classes of structures.

Polytetrafluoroethylene (PTFE), known commercially as Teflon or Fluon, is the best-known material and resists all known chemicals, weather, and heat, has an extremely low coefficient of friction, and is "non-stick." These materials are inert with good electrical properties. They are nontoxic, nonflammable, and have a working temperature range of –270 to 260°C. They may be glass filled for increased strength and rigidity. They do not melt and they must be formed by sintering of powders. Applications include chemical, mechanical, and electrical components, bearings (plain or filled with glass and/or bronze), tubing, and vessels for "aggressive" chemicals.

Fluoroethylenepropylene (FEP), unlike PTFE, can be processed on conventional molding machines and extruded, but thermal and chemical resistance properties are not quite as good.

Ethylenetetrafluoroethylene (ETFE) possess properties similar to but not as good as those of PTFE. However, the material exhibits a thermoplastic character similar to that of polyethylene which gives it a very desirable molding behavior.

Perfluoroalkoxy (PFA) is the fourth group of fluorinated polymers. These materials have the same excellent properties as PTFE, but the compound is melt processible and, therefore, suitable for linings for pumps, valves, pipes, and pipe fittings.

Ionomers

These thermoplastics are based on ethylene and have high melt strength, which makes them suitable for deep forming, blowing, and other similar forming processes. They are used for packaging, bottles, moldings for small components, tool handles, and trim. They have a high acceptance of fillers.

Polymethylpentene

Polymethylpentene (TPX) is a high-clarity resin with excellent chemical and electrical properties and the lowest density of all thermoplastics. It has the best resistance of all transparent plastics to distortion at high temperature — it compares well with acrylic for optical use, but has only 70% of its density. It is used for light covers, medical and chemical ware, high-frequency electrical insulation, cables, microwave oven parts, and radar components. It can withstand soft soldering temperatures.

Polyethylene Terephthalate

Polyethylene terephthalate (PETP) and modified versions thereof have high strength, rigidity, chemical and abrasion resistance, impact resistance in oriented form, and a low coefficient of friction. It is attacked by acetic acid and concentrated nitric and sulfuric acids. It is used for bearings, tire reinforcement, bottles, automotive parts, gears, and cams.

Polyamides (Nylons)

The polyamides are a family of thermoplastics, e.g., Nylon 6, Nylon 66, and Nylon 610, which are among the toughest engineering plastics with high vibration-damping capacity, abrasion resistance, inherent lubricity, and high load capacity for high-speed bearings. They have a low coefficient of friction and good flexibility. Pigment-stabilized types are not affected by ultraviolet radiation and chemical resistance is good. Unfilled nylon is prone to swelling due to moisture absorption. Nylon bearings may be filled with powdered molybdenum disulfide or graphite. Applications include bearings, electrical insulators, gears, wheels, screw fasteners, cams, latches, fuel lines, and rotary seals.

Polyethylene

Low-density polyethylene (orinally called *polythene*) is used for films, coatings, pipes, domestic moldings, cable sheathing, and electrical insulation. High-density polyethylene is used for larger moldings and is available in the form of sheet, tube, etc. Polyethylene is limited as an engineering material because of its low strength and hardness. It is attacked by many oxidizing chemical agents and some hydrocarbon solvents.

Polyketone, Aliphatic

Aliphatic polyketones are relatively strong, tough, ductile polymeric resins derived from equal proportions of ethylene and carbon monoxide with an additional few percent of higher olefin for property and processibility adjustment. Their physical, thermal, and mechanical properties are similar to polyamides and polyacetals. Mechanical properties are characterized by preservation of high levels of stiffness, toughness, and strength over a broad temperature range. Resistance to hydrolysis, swelling, and permeation provides broad chemical resistance. Relatively new in commercial supply, they find application in gears, machine components, and similar engineering applications. Tribological performance is very good, and in particular they have a low coefficient of friction and a low wear factor against steel. The electrical properties of the neat polyketone are typical of those of polar, semicrystalline thermoplastics.

Polyethersulfone

Polyethersulfone is a high-temperature engineering plastic — useful up to 180°C in general and some grades have continuous operating ratings as high as 200°C. It is resistant to most chemicals and may be extruded or injection molded to close tolerances. The properties are similar to those of nylons. Applications are as a replacement for glass for medical needs and food handling, circuit boards, general electrical components, and car parts requiring good mechanical properties and dimensional stability.

Polystyrene

This polymer is not very useful as an engineering material because of brittleness in unmodified forms, but it is well known for its use in toys, electrical insulation, refrigerator linings, packaging, and numerous commercial articles. It is available in unmodified form as a clear transparent resin and also in clear and opaque colors. High-impact forms are achieved by compounding with butadiene or other rubbery resins and heat-resistant forms are achieved by the use of fillers. Polystyrene can be stabilized against ultraviolet radiation and also can be made in expanded form for thermal insulation and filler products. It is attacked by many chemicals, notably aromatic hydrocarbon solvents, and by ultraviolet light.

Polysulfone

Polysulfone has properties similar to nylon, but these properties are retained up to 180°C compared with 120°C for nylon, which greatly expands the range of applications. Its optical clarity is good and its moisture absorption lower than that of nylon. Applications are as a replacement for glass for medical needs and chemistry equipment, circuit boards, and many electrical components.

Polyvinyl Chloride

This is one of the most widely used of all plastics. With the resin mixed with stabilizers, lubricants, fillers, pigments, and plasticizers, a wide range of properties is possible from flexible to hard types, in transparent, opaque, and colored forms. It is tough, strong, with good resistance to chemicals, good low-temperature characteristics and flame-retardant properties. PVC does not retain good mechanical performance above 80°C. It is used for electrical conduit and trunking, junction boxes, rainwater pipes and gutters, decorative profile extrusions, tanks, guards, ducts, etc.

Polycarbonate

Polycarbonate is an extremely tough thermoplastic with outstanding strength, dimensional stability, and electrical properties, high heat distortion temperature and low-temperature resistance (down to –100°C). It is available in transparent optical, translucent, and opaque grades (many colors). Polycarbonates have only fair resistance to chemicals as evidenced by the stress cracking caused by many solvents. The weathering tendencies can be stabilized against ultraviolet radiation by the use of proper additives. Polycarbonate compounds are used for injection moldings and extrusions for glazing panels, helmets, face shields, dashboards, window cranks, and gears. Polycarbonate is an important engineering plastic.

Polypropylene

Polypropylene is a low-density, hard, stiff, creep-resistant plastic with good resistance to chemicals, good wear resistance, low water absorption, and is relatively low cost. Polypropylene can be spun into filaments, converted into weaves, injection molded, and is commonly produced in a large variety of forms. Glass-filled polypropylene is widely used for its enhanced mechanical properties. It is used for food and chemical containers, domestic appliances, furniture, car parts, twine, toys, tubing, cable sheath, and bristles.

Polyphenylene Sulfide

Polyphenylene sulfide is a high-temperature plastic useful up to 260°C. Ambient temperature properties are similar or superior to those of nylon. It has good chemical resistance and is suitable for structural components subject to heat. Glass filler improves strength and enables very high heat resistance to 300°C. Uses are similar to those of nylon, but for higher temperatures.

Polyphenylene Oxide

This is a rigid engineering plastic similar to polysulfone in uses. It can be injection molded and has mechanical properties similar to those for nylon. It is used for automotive parts, domestic appliances, and parts requiring good dimensional stability. Frequently, the commercially available product is blended (or "alloyed") with polystyrene which acts as a cost-effective extender.

Thermosetting Polymers

Alkyds

There are two main groups of alkyds: diallyphthalate (DAP) and diallylisopthalate (DIAP). These have good dimensional stability and heat resistance (service temperature 170°C; intermittent use 260°C), excellent electrical properties, good resistance to oils, fats, and most solvents, but limited resistance to strong acids and alkalis. The mechanical properties are improved by filling with glass or minerals. The main uses are for electrical components and encapsulation. A wide range of colors and fast-curing grades are available.

Amino Resins

These are based on formaldehyde reacted with urea or melamine and are formulated as coatings and adhesives for laminates, impregnated paper textiles, and molding powders. The resins are usually compounded with fillers of cellulose, wood flour, and/or other extenders. As composites with open-weave fabric, they are used for building panels. Uses also include domestic electrical appliances and electric light fittings; the melamine type is used for tableware. The strength is high enough for use in stressed components, but the material is brittle. Electrical, thermal, and self-extinguishing properties are good.

Epoxies

Epoxy resins are used extensively across industry as engineering polymers and as adhesives. They can be cold cured without pressure using a "hardener" or may be heat cured. Inert fillers, plasticizers, flexibilizers, and extenders give a wide range of properties from soft flexible to rigid solid materials. Bonding to nearly all materials, e.g., wood, metal, glass, is excellent as are the mechanical, electrical, and chemical properties. Epoxies are used in all branches of engineering, including large castings, electrical parts, circuit boards, potting, glass and carbon fiber structures, flooring, protective coatings, and adhesives. Importantly, they exhibit little or no shrinkage on cure.

Phenolics (Phenol Formaldehyde, PF)

PF, the original "Bakelite," is usually filled with 50 to 70% wood flour for molded nonstressed or lightly stressed parts. Other fillers are mica for electrical parts, asbestos for heat resistance, glass fiber for strength and electrical properties, nylon, and graphite. Phenolics represent one of the best polymers for low-creep applications. Moldings have good strength, good gloss, and good temperature range (150°C wood filled; intermittent use 220°C), but are rather brittle. Applications include electrical circuit board, gears, cams, and car brake linings (when filled with asbestos, glass, metal powder, etc.). The cost is low and the compressive strength very high.

Polyester

Polyester resins can be cured at room temperature with a hardener or alone at 70 to 150°C. It is used unfilled as a coating, for potting, encapsulation, linings, thread locking, castings, and industrial moldings. It is used mostly for glass-reinforced-plastic (GRP) moldings.

Polyimides

Polyimides are noted for their unusually high resistance to oxidation and service temperatures up to 250°C (400°C for intermittent use). The low coefficient of friction and high resistance to abrasion make them ideal for nonlubricated hearings. Graphite or molybdenum disulfide filling improves these properties. They are used for high-density insulating tape. Polyimides have high strength, low moisture absorption, and resist most chemicals, except strong alkalis and ammonia solutions.

Silicones

These may be cold or heat cured and are used for high-temperature laminates and electrical parts resistant to heat (heat distortion temperature 450°C). Unfilled and filled types are used for special-duty moldings. Organosilicones are used for surface coatings and as a superior adhesive between organic and nonorganic materials.

Laminated Polymer Structures

A wide range of composite structures are prepared from polymer resins combined with fibers. The reader is referred to Section 12.6 for a more extensive discussion of polymer composites. Laminated polymer structures consist of layers of fibrous material impregnated with and bonded together usually by a thermosetting resin to produce sheets, bars, rods, tubes, etc. The laminate may be "decorative" or "industrial," the latter being of load-bearing mechanical or electrical grade.

Phenolics

Phenolic plastics can be reinforced with paper, cotton fabric, asbestos paper fabric or felt, synthetic fabric, or wood flour. They are used for general-purpose mechanical and electrical parts. They have good mechanical and electrical properties.

Epoxies

These are used for high-performance mechanical and electrical duties. Fillers used are paper, cotton fabric, and glass fiber.

Tufnol

"Tufnol" is the trade name for a large range of sheet, rod, and tube materials using phenolic resin with paper and asbestos fabric and epoxy resin with glass or fabric.

Polyester

This is normally used with glass fabric (the cheapest) filler. The mechanical and electrical properties are inferior to those of epoxy. It can be rendered in self-colors.

Melamine

Fillers used for melamine are paper, cotton fabric, asbestos paper fabric, and glass fabric. Melamines have a hard, nonscratch surface, superior electrical properties, and can be rendered in self-colors. They are used for insulators, especially in wet and dirty conditions, and for decorative and industrial laminates.

Silicone

Silicone is used with asbestos paper and fabric and glass fabric fillers for high-temperature applications (250°C; intermittent use 300°C). It has excellent electrical but inferior mechanical properties.

Polyimide

Polyimide is most often used with glass fabric as filler. Polyimides have superior thermal and electrical properties with a service temperature similar to that for silicones but with two to three times the strength and flexibility.

Foam and Cellular Polymers

Thermoplastics

Polyurethane Foams. The "flexible" type is the one most used. It is "open cell" and used for upholstery, underlays, thermal and vibration insulation, and buoyancy. It can be generated *in situ*. The rigid type has "closed cells" and is used for sandwich construction, insulation, etc. Molded components may be made from rigid and semirigid types.

Expanded Polystyrene. This material is produced only in rigid form with closed cells. It can be formed *in situ*. The density is extremely low, as is the cost. Chemical resistance is low and the service temperature is only 70°C. It is used for packaging, thermal and acoustic insulation, and buoyancy applications.

Cellular Polyvinyl Chlorides. The low-density type is closed cell and flexible. It is used for sandwich structures, thermal insulation, gaskets, trim, to provide buoyancy, and for insulating clothing. The moderate- to high-density open-cell type is similar to latex rubber and is used as synthetic leather cloth. The rigid closed-cell type is used for structural parts, sandwich construction, thermal insulation, and buoyancy. Rigid open-cell PVC (microporous PVC) is used for filters and battery separators. In general, cellular PVC has high strength, good flame resistance, and is easy to work.

Polyethylene Foams. The flexible type is closed cell and has low density with good chemical resistance and color availability, but is a poor heat insulator and is costly. The flexible foams are used for vibration damping, packaging, and gaskets. The rigid type has high density and is used for filters and cable insulation. A structural type has a solid skin and a foam core.

Ethylene Vinyl Acetates. These are microcellular foams similar to microcellular rubber foam, but are much lighter with better chemical resistance and color possibilities.

Other Types. Other types of thermoplastics include cellular acetate, which is used as a core material in constructions; expanded acrylics, which have good physical properties, thermal insulation, and chemical resistance; expanded nylon (and expanded ABS), which are low-density, solid-skin constructions; expanded PVA, which has similar properties to expanded polystyrene; and expanded polypropylene, which gives high-density foams.

Thermosets

Phenolics. These can be formed *in situ*. They have good rigidity, thermal insulation, and high service temperature, but are brittle.

Urea Formaldehyde (UF) Foam. This is readily formed *in situ* and has good thermal insulation. It has open pores and is used for cavity-wall filling.

Expanded Epoxies. These have limited use because of their high cost. They give a uniform texture and good dimensional stability and are used for composite forms, e.g., with polystyrene beads.

Silicon Foams. These are rigid and brittle with a high service temperature (300°C; 400°C intermittent use). Their use is limited to high-temperature-resistant sandwich constructions. The flexible closed-cell type is costly but will operate up to 200°C and is used for high-temperature seals and gaskets.

Elastomers

Cellular Rubbers. There are three types: *sponge*, solid rubber blown to give an open-cell structure, *foam*, a liquid rubber expanded to form open or closed cells which is stiffer than sponge; and *expanded*, a solid rubber blown with mainly closed cells, also it is stiffer than sponge. Uses include gaskets, seals, thermal insulation, cushioning, shock absorption, sound and vibration damping, buoyancy, and sandwich constructions.

Elastomers

Elastomers, or rubbers, are essentially amorphous polymers with linear chain molecules with some cross-linking, which ensures elasticity and the return of the material to its original shape when a load is removed. They are characterized by large strains (typically 100%) under stress. The synthetic rubber styrene butadiene is the most-used elastomer, with natural rubber a close second. The following describes the commonly used elastomers and gives some applications and properties.

Natural Rubbers (Polyisoprene, NR)

These elastomers have high strength, flexibility, and resilience, but have poor resistance to fuels, oils, flame, and sunlight aging. They are more costly than synthetic rubbers, which often replace them. “Soft-rubber” contains 1 to 4% sulfur as a vulcanizer. Wear resistance is increased by inclusion of fillers such as carbon black, silicon dioxide, clay, and wood flour. “Hard rubber” may contain up to 25% sulfur. Applications include vehicle tires and tubes, seals, antivibration mountings, hoses, and belts. Full vulcanization of 45% produces ebonite. Shore hardness: 30 to 90. Temperature range: –55 to 82°C.

Synthetic Rubbers

Styrene Butadiene Rubbers (SBR, GRS, BUNAS). These are similar to natural rubbers in application, but are usually inferior in mechanical properties, although cheaper. They are used in car brake hydraulic systems and for hoses, belts, gaskets, and antivibration mountings. Shore hardness: 40 to 80. Temperature range: –50 to 82°C.

Butadiene Rubbers (Polynutadiene, BR). These are used as substitutes for natural rubber, but are generally inferior. They have similar applications as natural rubber. Shore hardness: 40 to 90. Temperature range: –100 to 93°C.

Butyl Rubbers (Isobutylene Isoprene, GR 1). These are extremely resistant to water, silicon fluids and grease, and gas permeation. They are used for puncture-proof tires, inner tubes, and vacuum seals. Shore hardness: 40 to 90. Temperature range: –45 to 150°C.

Nitrile Rubbers (Butadiene Acrylonitrile, BUNA, N.NBR). These have good physical properties and good resistance to fuels, oils, solvents, water, silicon fluids, and abrasion. They are used for O rings and other seals, petrol hoses, fuel-pump diaphragms, gaskets, and oil-resistant shoe soles. Shore hardness: 40 to 95. Temperature range: –55 to 82°C.

Neoprene Rubbers (Polychloroprene, Chloroprene). These are some of the best general-purpose synthetic rubbers. They have excellent resistance to weather aging, moderate resistance to oils, and good resistance to refrigerants and mild acids. Shore hardness: 40 to 95. Temperature range: –40 to 115°C.

Chlorosulfonated Polyethylene Rubbers (CSM). These have poor mechanical properties but good resistance to acids and heat with complete resistance to ozone. They are used in chemical plants, tank linings, and high-voltage insulation. Shore hardness: 45 to 100. Temperature range: –100 to 93°C.

Ethylene Propylene Rubbers (EP, FPM). These specialized rubbers are especially resistant to weather aging heat, many solvents, steam, hot water, dilute acids and alkalis, and ketones, but not petrol or mineral oils. They are used for conveyor belts, limited automotive applications, silicone fluid systems, and electrical insulation. Shore hardness: 40 to 90. Temperature hardness: –50 to 177°C.

Fluorocarbon Rubbers. These comprise a wide range of rubbers with excellent resistance to chemical attack, heat, acids, fuels, oils, aromatic compounds, etc. They have a high service temperature. They are particularly suitable for vacuum applications. Shore hardness: 60 to 90. Temperature hardness: –23 to 260°C.

Isoprenes (Polyisoprene, IR). These are chemically the same as natural rubber but are more costly. The properties and applications are similar to those of natural rubber. Shore hardness: 40 to 80. Temperature hardness: –50 to 82°C.

Polyacrylic Rubbers (ACM, ABR). This is a group of rubbers with properties midway between nitrile and fluorocarbon rubbers with excellent resistance to mineral oils, hypoid oils, and greases and good resistance to hot air and aging. The mechanical strength is low. They are often used for spark plug seals and transmission seals. Shore hardness: 40 to 90. Temperature hardness: –30 to 177°C.

Polysulfide Rubbers. These have poor physical properties and heat resistance, but good resistance to oils, solvents, and weathering and are impermeable to gases and moisture. They are used for caulking and sealing compounds and as a casting material. Shore hardness: 40 to 85. Temperature hardness: –50 to 121°C.

Polyurethane Rubbers. These have exceptional strength and tear and abrasion resistance (the best of all rubbers), low-temperature flexibility, and good resistance to fuels, hydrocarbons, ozone, and weather. Resistance to solutions of acids and alkalis, hot water, steam, glycol, and ketones is poor. They are used for wear-resistant applications such as floor coverings. Shore hardness: 35 to 100. Temperature hardness: –53 to 115°C.

Silicone Rubbers (SI). These have exceptionally high service-temperature ranges, but the mechanical properties and chemical resistance are poor. They cannot be used in applications which expose them to fuels, light mineral oils, or high-pressure steam. They are used for high- and low-temperature seals, high-temperature rotary seals, cable insulation, hydraulic seals, and aircraft door and canopy seals. Shore hardness: 30 to 90. Temperature hardness: –116 to 315°C (380°C for intermittent use).

Fluorosilicone Rubbers. These are similar to silicone rubbers but have better oil resistance and a lower temperature range. Shore hardness: 40 to 80. Temperature hardness: –64 to 204°C.

12.3 Adhesives

Richard L. Lehman

Introduction

Adhesives are substances capable of holding materials together in a useful manner by surface attachment. The principal attribute of adhesives is their ability to form strong bonds with surfaces of a wide range of materials and to retain bond strength under expected use conditions. Although most adhesives do not have excellent bulk properties and it is therefore important to keep adhesive films thin, some materials such as epoxies have bulk properties which qualify them as engineering materials and thus can be used in multifunctional applications.