

PLASTICS MATERIALS AND PROCESSES

A CONCISE ENCYCLOPEDIA

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**PLASTICS MATERIALS
AND PROCESSES**
A Concise Encyclopedia

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A Concise Encyclopedia

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 **WILEY-INTERSCIENCE**

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PREFACE

Plastics Materials and Processes: A Concise Encyclopedia defines the important concepts of the plastics industry in a single-volume encyclopedia. Materials, processes, properties, test methods, and other information that is used commonly throughout the industry are defined without great involvement in detail and in a manner that is straightforward and efficient. This book is aimed at meeting the needs of general managers, executives, purchasing and manufacturing personnel, supervisors, engineers, students, and all others that are working in the field of plastics or have interest in these important materials. It is expected that in today's robust working environment the time burdens on these individuals are greater than ever. When this limited time frame is coupled with the universe of exploding polymer technology, the resulting pressures may make it difficult to maintain an overall grasp of the information required to efficiently perform.

The selection of information provided in this book has been made with a view toward giving the reader an efficient, intelligent overall insight without having to wade through voluminous texts or handbooks in specific areas. It is not the purpose of the book to provide an exhaustive treatise on any subject, as it is assumed that the reader will consult more comprehensive and detailed texts, journals, and even the producers of materials and processing equipment for such specific and in-depth information. However, this book should make the journey to acquire such information easier and more efficient.

As the goal of this book is to provide a sourcebook of practical information for all ranges of interest, its organization is aimed primarily at reader convenience. The main body, therefore, consists of a concise encyclopedia of knowledge useful in today's plastics industry. It contains an extensive array of materials information and property and performance data presented in an alphabetical format. In addition, it presents all-important application guidelines, process method trade-offs, and design, finishing, and performance criteria. It also summarizes chemical, structural, and other basic polymer considerations.

This main body of information is preceded by a brief introduction to polymers and plastics that may be used to provide the reader with a "glue" to hold the individual snippets of information together. This initial section covers the nature of polymers, and it offers an introduction to the material and process descriptions that follow.

After the encyclopedia, are several appendices containing valuable property data and other detailed information. Here plastics and other materials commonly used in the industry are compared to one another, and guidance is offered regarding their processing methods and final applications. Finally, there is a completely

cross-referenced and easy-to-use index that is provided as a road map for the preceding information and as a method of linking subjects and information together.

The result of this compilation is a concise, yet valuable reference to the broad amount of information required to function in the plastics industry. It will be a useful first-source to anyone involved in all aspects of product design, development, application, manufacturing, marketing, or other peripheral function in the plastics industry. The authors hope that this book will be the most worn book in the reader's reference library as a result of being the first choice for information.

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EDWARD M. PETRIE

Table IN.1 Typical Tradenames and Suppliers of Thermosetting Plastics (Note: these are but a few, see Appendix N for an expanded listing.)

Plastic	Typical trade names and suppliers
Alkyd	Plaskon (Allied Chemical) Durez (Hooker Chemical) Glaskyd (American Cyanamid)
Diallyl phthalates	Dapon (FMC) Diall (Allied Chemical) Durez (Hooker Chemical)
Epoxies	Epon (Shell Chemical) Epi-Rez (Celanese) D.E.R. (Dow Chemical) Araldite (Ciba) ERL (Union Carbide)
Melamines	Cymel (American Cyanamid) Plaskon (Allied Chemical)
Phenolics	Bakelite (Union Carbide) Durez (Hooker Chemical) Genal (General Electric)
Polybutadienes	Dienite (Firestone) Ricon (Colorado Chemical Specialties)
Polyesters	Laminac (American Cyanamid) Paraplex (Rohm and Haas) Selectron (PPG)
Silicones	DC (Dow Corning)
Ureas	Plaskon (Allied Chemical) Beetle (American Cyanamid)

Plastic materials included in the thermosetting plastic category and discussed separately in the following sections of this book include alkyds, diallyl phthlate, epoxies, melamines, phenolics, polyesters, silicones, and ureas. A list of typical tradenames and suppliers of the more common plastics is given in Table IN.1.

THERMOPLASTICS

Thermoplastics differ from thermosets in that they do not cure or set under heat as do thermosets. Thermoplastics merely soften or melt when heated to a flowable state, and under pressure they can be forced or transferred from a heated cavity into a cool mold. On cooling in a mold, thermoplastics harden and take the shape of the mold. Because thermoplastics do not cure or set, they can be remelted and then rehardened by cooling. Thermal aging, brought about by repeated exposure to high temperatures required for melting, causes eventual

Table IN.2 Typical Tradenames and Suppliers of Thermoplastics (Note: these are but a few, see Appendix N for an expanded listing.)

Thermoplastic	Typical trade names and suppliers
ABS	Marbon Cycholac (Borg-Warner) Abson (B. F. Goodrich) Lustran (Monsanto)
Acetals	Delrin (E. I. du Pont) Celcon (Celanese)
Acrylics	Plexiglas (Rohm and Haas) Lucite (E. I. du Pont)
Aramids	Nomex (E. I. du Pont)
Cellulosics	Tenite (Eastman Chemical) Ethocel (Dow Chemical) Forticel (Celanese)
Ionomers	Surlyn A (E. I. du Pont) Bakelite (Union Carbide)
Low-permeability thermoplastics	Barex (Vistron/Sohio) NR-16 (E. I. du Pont) LPT (Imperial Chemical Industries)
Nylons (see also Aramids)	Zytel (E. I. du Pont) Plaskon (Allied Chemical) Bakelite (Union Carbide) Parylene (Union Carbide)
Parylenes	Arylon T (Uniroyal)
Polyaryl ether	Astrel (3M)
Polyaryl sulfone	Lexan (General Electric)
Polycarbonates	Merlon (Mobay Chemical) Valox (General Electric) Celanex (Celanese) Celanar Film (Celanese) Mylar Film (E. I. du Pont) Tenite (Eastman Chemical)
Polyesters	Polyethersulphone (Imperial Chemical Industries) Alathon Polyethylene (E. I. du Pont) Petrothene Polyethylene (U.S.I.) Hi-Fax Polyethylene (Hercules) Pro-Fax Polypropylene (Hercules) Bakelite Polyethylene and Polypropylene (Union Carbide) Tenite Polyethylene and Polypropylene (Eastman)
Polyethersulfone	Irradiated Polyolefin (Raychem)
Polyethylenes, polypropylenes, and polyallomers	Vespel SP Polyimides (E. I. du Pont) Kapton Film (E. I. du Pont) Pyralin Laminates (E. I. du Pont) Keramid/Kinel (Rhodia) P13N (Ciba-Geigy) Torlon Polyamide-Imide (Amoco) TPX (Imperial Chemical Industries)
Polyimides and polyamide-imides	
Polymethyl pentene	

Table IN.2 (Continued)

Thermoplastic	Typical trade names and suppliers
Polyphenylene oxides	Noryl (General Electric)
Polyphenylene sulfides	Ryton (Phillips Petroleum)
Polystyrenes	Styron (Dow Chemical)
	Lustrex (Monsanto)
	Dylene (Koppers)
	Rexolite (American Enka)
Polysulfones	Ucardel (Union Carbide)
Vinyls	Pliovic (Goodyear Chemical)
	Diamond PVC (Diamond Alkali)
	Geon (B. F. Goodrich)
	Bakelite (Union Carbide)

degradation of the materials and so limits the number of reheat cycles. Most of the common thermoplastics materials are discussed in detail in the following section.

Specific data on a variety of thermoplastics can be found in the following sections of this book. In general, thermoplastic materials tend to be tougher and less brittle than thermosets so that they can be applied without the use of filler. However, although some are very tough, others do tend to craze or crack easily, so each case must be considered on its individual merits. Traditionally by virtue of the basic polymer structure, thermoplastics have been much less dimensionally and thermally stable than thermosetting plastics. Hence, thermosets have offered a performance advantage, although the lower processing costs for thermoplastics have given the latter a cost advantage. However, three major trends put both thermoplastics and thermosets on a competitive performance consideration basis.

1. Much has been done in the development of reinforced, fiber-filled thermoplastics, greatly increasing stability in many areas.
2. Much has been achieved in the development of so-called engineering thermoplastics, or high-stability, higher-performance plastics, that can also be reinforced with fiber or fillers to increase their stability further.
3. Lower-cost processing methods for thermosetting plastics have been developed, especially the screw-injection molding technology.

All of these options should be considered in optimizing the design, fabrication, and performance of plastic parts.

A list of typical tradenames and suppliers of the more common thermoplastics is given in Table IN.2, and a list of so-called advanced thermoplastic materials is

Table IN.3 Advanced Thermoplastic Materials

Matrix systems	Abbreviation	Trade names and suppliers
Polyphenylene sulfide	PPS	Ryton (Phillips Petroleum)
Polysulfone	PSF	Udel (Union Carbide)
Polyetheretherketone	PEEK	APC (Imperial Chemical Industries)
Polyethersulfone	PES	Victrex (Imperial Chemical Industries)
Polyetherimide	PEI	Ultem (General Electric)
Polyamide-imide	PAI	Torlon (Amoco)
Polyetherketone	PEK	(Imperial Chemical Industries)
Polyamide	PA	J-2 (E. I. du Pont)
Polyimide	PI	K-III (E. I. du Pont)
Polyarylene sulfide	PAS	PAS-2 (Phillips Petroleum)
Polyarylene ketone	—	HTA (Imperial Chemical Industries)
Polyetherketoneketone	PEKK	(E. I. du Pont)

presented in Table IN.3. Specific data and information for a variety of thermoplastics are given in the main body of this book.

Glass Fiber-Reinforced Thermoplastics

Basically, thermoplastic molding materials are developed and can be used without filler, as opposed to thermosetting molding material, which are more commonly used with filler incorporated into the compound. This is primarily because shrinkage, hardness, brittleness, and other important processing and use properties necessitate the use of filler in thermosets. Thermoplastics, on the other hand, do not suffer from the same shortcomings as the thermosets and hence can be used as molded products without fillers. However, thermoplastics do suffer from creep and dimensional stability problems, especially under elevated temperature and load conditions. Because of this shortcoming, most designers find it difficult to match the techniques of classical stress-strain analysis with the nonlinear, time-dependent, strength modulus properties of thermoplastics. Glass fiber-reinforced thermoplastics (FRTPs) help to simplify these problems. For instance, 40 percent glass fiber-reinforced nylon outperforms its unreinforced version by exhibiting 2-1/2 times greater tensile and Izod impact strengths, 4 times greater flexural modulus and only 1/5 of the tensile creep.

Thus FRTPs fill a major materials gap in providing plastic materials that can be reliably used for strength purpose and which in fact can compete with metal die castings. Strength is increased with glass fiber reinforcement, as are stiffness and dimensional stability. The thermal expansion of FRTPs is reduced, creep is substantially reduced, and molding precision is much greater.

The fundamental concept of the diffusion theory is that adhesion arises through the interdiffusion of molecules in the adhesive and the adherend. The diffusion theory is primarily applicable when both the adhesive and the adherend are polymeric, having long-chain molecules capable of movement. Bonds formed by solvent or heat welding of thermoplastics result from the diffusion of molecules.

weak boundary layer theory According to the weak boundary layer theory, when bond failure seems to be at the interface, usually a cohesive break of a weak boundary layer is the real event. Weak boundary layers can originate from the adhesive, the adherend, the environment, or a combination of any of the three.

Weak boundary layers can occur on the adhesive or adherend if an impurity concentrates near the bonding surface and forms a weak attachment to the substrate. When bond failure occurs, it is the weak boundary layer that fails, although failure seems to occur at the adhesive/adherend interface.

Two examples of a weak boundary layer effect are polyethylene and metal oxides. Conventional grades of polyethylene have weak, low-molecular-weight constituents evenly distributed throughout the polymer. These weak elements are present at the interface and contribute to low failing stress when polyethylene is used as an adhesive or adherend. Certain metal oxides are weakly attached to their base metals. Failure of adhesive joints made with these adherends will occur cohesively within the weak oxide layer. Weak boundary layers can be removed or strengthened by various surface treatments.

Weak boundary layers formed from the shop environment are also very common. When the adhesive does not wet the substrate, a weak boundary layer of air is trapped at the interface, causing lowered joint strength. Moisture from the air may also form a weak boundary layer on hydrophilic adherends.

adhesive An adhesive is a substance capable of holding at least two surfaces together in a strong and permanent manner. Adhesives can be made of organic or inorganic material. They are chosen for their bonding and holding power. They are generally materials having high shear and tensile strength.

Structural adhesive is a term generally used to define an adhesive whose strength is critical to the success of the assembly. This term is usually reserved for adhesives with high shear strength (generally in excess of 1000 psi) and good environmental resistance. Structural adhesives are usually expected to last the life of the product to which they are applied. Examples of structural adhesives are epoxy, thermosetting acrylic, and urethane systems.

Nonstructural adhesives are adhesives with lower strength and permanence. They are generally used for temporary fastening or to bond weak substrates such as paper and foam. Examples of nonstructural adhesives are pressure-sensitive tapes, wood glue, elastomers, and sealants. These adhesives are sometimes used for temporary fastening or sealing.

Adhesives can also be broadly classified as being *thermoplastic*, *thermosetting*, *elastomeric*, and *alloy blends*. These four adhesive classifications can be further divided by specific chemical composition, as shown in Appendix K.

The types of resins that make up thermosetting and alloy adhesives are noted for their high strength, creep resistance, and resistance to environments such as heat, moisture, solvents, and oils. Their physical properties are well suited for structural adhesive applications. Elastomeric and thermoplastic adhesive classes are not used in applications requiring continuous load because of their tendency to creep under high stress. Many common service environments also degrade them. These adhesives find greatest use in nonstructural, low-strength applications such as pressure-sensitive tape, sealants, and hot-melt products.

Adhesives may also be classified by the way they are applied or cured. Hence, *anaerobic adhesives* are adhesives that set only in the absence of air, for instance, when confined between plates or sheets. A *contact adhesive* is one that is apparently dry to the touch but will adhere to itself instantaneously on contact (also called *contact bond adhesive* and *dry bond adhesive*). A *heat-activated adhesive* is a dry adhesive film that is made tacky or fluid by application of heat or heat and pressure to the assembly. A *pressure-sensitive adhesive* is a viscoelastic material that in solvent-free form remains permanently tacky. Such materials will adhere instantaneously to most solid surfaces with the application of very slight pressure. *Room-temperature setting adhesives* are those that set in the temperature range of 20–30°C. These are usually two-component adhesives that must be mixed before application. A *solvent adhesive* is an adhesive that has a volatile organic liquid as a vehicle and sets or becomes tacky after the solvent has evaporated. A *solvent-activated adhesive* is a dry adhesive film that is rendered tacky just before use by application of a solvent.

There are many types and suppliers of adhesives. The major suppliers of formulated adhesives range from large international businesses to very small regional shops. The major source of information regarding adhesives and adhesive bonding processes can be either the adhesive supplier or the supplier of the substrate material that is to be bonded. For example, most polymeric material suppliers are experts on the types of adhesives and processes that can be used to assemble products made with their materials.

See also structural adhesive; individual resins.

adhesive bonding Adhesive bonding is the process of joining two substrates (or *adherends*) with a third substance, usually an organic or inorganic resin. The resin or *adhesive* is applied in the liquid state and hardens after application and joining of the parts.

Adhesive bonding presents several distinct advantages over other methods of fastening substrates (Table A.6). Bonding, as a method of assembly, is often preferred when different types of substrates (e.g., metals to plastics) need to be joined, when high-volume production is necessary, or when the design of the finished part prohibits the use of mechanical fasteners.

Although there are various ways of joining plastics to themselves or to other materials, adhesive bonding has often proved to be the most effective assembly method. In many applications the use of adhesives rather than metal fasteners reduces product cost and the weight of the assembly, in some cases providing longer service life. Adhesive bonding can also be used very effectively in prototypes and with large or intricate assemblies that for economic or design reasons cannot be

Table A.6 Advantages and Disadvantages of Adhesive Bonding

Advantages	Disadvantages
1. Provides large stress-bearing area.	1. Surfaces must be carefully cleaned.
2. Provides excellent fatigue strength.	2. Long cure times may be needed.
3. Damps vibration and absorbs shock.	3. Limitation on upper continuous operating temperature (generally 350°F).
4. Minimizes or prevents galvanic corrosion between dissimilar metals.	4. Heat and pressure may be required.
5. Joins all shapes and thicknesses.	5. Jigs and fixtures may be needed.
6. Provides smooth contours.	6. Rigid process control usually necessary.
7. Seals joints.	7. Inspection of finished joint difficult.
8. Joins any combination of similar or dissimilar materials.	8. Useful life depends on environment.
9. Often less expensive and faster than mechanical fastening.	9. Environmental, health, and safety considerations are necessary.
10. Heat, if required, is too low to affect metal parts.	10. Special training sometimes required.
11. Provides attractive strength-to-weight ratio.	

molded or processed as a single part. *Solvent* and *heat welding* may be considered, in the case of plastic substrates, as a type of adhesive bonding process in which the adhesive is actually a part of the substrate itself.

However, the joining of plastics with adhesives can be made difficult because of their low surface energy and poor wetting, the presence of contaminants such as mold release agents and low-molecular-weight internal components (e.g., flexibilizers, UV inhibitors, and processing aids), and possible susceptibility to moisture and other environmental factors. Fortunately, numerous adhesives and processing methods are available for the joining of plastic materials and have been successfully used in many applications. Many of these products and applications are described in articles and handbooks on the subject. The plastic resin manufacturer is generally the leading source of information on the proper methods of joining a particular plastic.

See also adhesion; solvent cementing; heat welding.

adhesive failure Adhesive failure occurs when there is rupture of an adhesive bond such that the separation appears to be at the adhesive/adherend interface. When rupture occurs within one of the materials (either the adhesive or the adherend), the failure is said to be a *cohesive failure*.

See also adhesion theory.

adhesive joint The adhesive joint is the location at which two adherends are held together with a layer of adhesive. It is the general area of contact for a bonded structure. Generally, the adhesive joint is made up of components other than the adhesive and adherend. Metal oxides, contamination, mold release agent, moisture, and other such components may also be present at the adhesive joint area.

See also interphase; joint design (adhesive bonding).

dielectric curing or heating Dielectric curing of a synthetic thermosetting resin can be accomplished by simply placing the part in a high-frequency electric field. Such a field is produced by radio frequency or microwave ovens. Dielectric curing is very difficult to control, and there is a significant risk of overheating and burning the part.

Dielectric heating can be used to preheat powder, pellets, or preforms to remove water before processing the material. Dielectric heating can also be used to generate the heat necessary for curing polar, thermosetting adhesives, and it can be used to quickly evaporate water from a water-based adhesive formulation.

Dielectric processing of water-based adhesives is commonly used in the furniture industry for very fast drying of wood joints in furniture construction. Common wood adhesives, such as polyvinyl acetate emulsions, can be dried in seconds with dielectric heating processes.

dielectric heat sealing/welding Dielectric sealing can be used on most thermoplastics except those that are relatively transparent to high-frequency electric fields. This method is used mostly to seal vinyl sheeting such as automobile upholstery, swimming pool liners, and rainwear. An alternating electric field is imposed on the joint, which causes rapid reorientation of polar molecules. As a result, heat is generated within the polymer by molecular friction. The heat causes the polymer to melt, and pressure is applied to the joint. The field is then removed, and the joint is held until the weld cools. The main difficulty in using dielectric heating as a bonding method is in directing the heat to the interface. Generally, heating occurs in the entire volume of the polymer that is exposed to the electric field.

Variables in the bonding operation are the frequency generated, dielectric loss of the plastic, the power applied, pressure, and time. The materials most suitable for dielectric welding are those that have strong dipoles. These can often be identified by their high electrical dissipation factors. Materials most commonly welded by this process include polyvinyl chloride, polyurethane, polyamide, and thermoplastic polyester. Because the field intensity decreases with distance from the source, this process is normally used with thin polymer films.

There are basically two forms of dielectric welding: radio frequency welding and microwave welding. Radio frequency welding uses high frequency (13–100 MHz) to generate heat in polar materials, resulting in melting and weld formation after cooling. The electrodes are usually designed into the platens of a press. Microwave welding uses high-frequency (2–20 GHz) electromagnetic radiation to heat a susceptor material located at the joint interface. The heat generated melts thermoplastic materials at the joint interface, producing a weld on cooling. Heat generation occurs in microwave welding through absorption of electrical energy similar to radio frequency welding.

Polyaniline doped with an aqueous acid, such as hydrochloric acid, is used as a susceptor in microwave welding. This introduces polar groups and a degree of conductivity into the molecular structure. It is these polar groups that preferentially generate heat when exposed to microwave energy. These doped materials are used to produce gaskets, which can be used as an adhesive in dielectric welding.

Solvents used with synthetic resins and elastomers are generally organic in nature. Often a mixture of solvents is required to achieve the desired properties. Polar solvents are required with polar resins; nonpolar solvents with nonpolar resins. Water is sometimes used as a solvent for water-soluble resins. Certain polymers are also available as a water-based emulsion or latex formulation.

When solvents are used in the adhesive or coating formulation, they must be completely evaporated from the bondline before cure. Otherwise, bubbles could form in the bond line, causing a weak joint. In the early 1970s, during the time of the petroleum crisis, water-based adhesives were thought of as a possible replacement for solvent-based adhesives systems. However, water-based adhesives never met the lofty expectations, primarily because of the time and energy required to remove water from the bond line, the corrosion that the water causes in drying ovens, and the poor moisture resistance of the final product.

solvent cementing Solvent cementing is the simplest and most economical method of joining noncrystalline thermoplastics. In solvent cementing, the application of the solvent softens and dissolves the substrate surfaces being bonded. The solvent diffuses into the surface, allowing increased freedom of movement of the polymer chains. As the parts are then brought together under pressure, the solvent-softened plastic flows. van der Waals attractive forces are formed between molecules from each part, and polymer chains from each part intermingle and diffuse into one another. The parts then are held in place until the solvent evaporates from the joint area.

Solvent-cemented joints of like materials are less sensitive to thermal cycling than joints bonded with adhesives because there is no stress at the interface caused by differences in thermal expansion between the adhesive and the substrate. When two dissimilar plastics are to be joined, adhesive bonding is generally desirable because of solvent and polymer compatibility problems. Solvent-cemented joints are as resistant to degrading environments as the parent plastic. Bond strength greater than 85 percent of the parent plastic can generally be obtained. Solvents provide high-strength bonds quickly because of rapid evaporation rates.

Solvent bonding is suitable for all amorphous plastics. It is used primarily on ABS, acrylics, cellulose, polycarbonates, polystyrene, polyphenylene oxide, and vinyls. Solvent welding is not suitable for crystalline thermoplastics. It is not effective on polyolefins, fluorocarbons, or other solvent-resistant polymers. Solvent welding is moderately effective on nylon and acetal polymers. Solvent welding cannot be used to bond thermosets.

A disadvantage of solvent welding is that many solvents are flammable and/or toxic and must be handled accordingly. Proper ventilation must be provided when bonding large areas or for high-volume production. The bonded part should not be packaged or stressed until the solvent has adequate time to escape from the joint. Complete evaporation of solvent may not occur for hours or days. Some solvent-joined parts may have to be "cured" at elevated temperatures to encourage the release of solvent before packaging.

Table S.1 Typical Solvents for Solvent Cementing of Plastics (Ref: Raia, D.C., "Adhesives-King of Fasteners", Plastic World, June 1975)

Solvents for bonding plastics															
ABS	Acetic acid (glacial)														
Cellulose acetate	Acetone														
Cellulose acetate butrate	Acetone: ethyl acetate: R (40:40:20)														
Cellulose propionate	Acetone: ethyl lactate (90:10)														
Ethyl cellulose	Acetone: methoxyethyl acetate (80:20)														
Nylon	Acetone: methyl acetate (70:30)														
Polycarbonate	Butyl acetate: acetone: methyl acetate (50:30:20)														
Polymethyl methacrylate	Butyl acetate: methyl methacrylate (40:60)														
Polyphenylene oxide	Chloroform														
Polystyrene	Ethyl acetate														
Polysulfone	Ethyl acetate: ethyl alcohol (80:20)														
Polyvinyl chloride	Ethylene dichloride														
SAN	Ethylene dichloride: methylene chloride(50:50)														
Styrene butadiene	Methyl acetate														

(Continued)

Table S.1 (Continued)

Solvents for bonding plastics												
	Methylene chloride											
	Methylene chloride: methyl methacrylate (60:40)											
	Methylene chloride: methyl methacrylate (50:50)											
	Methylene chloride: thrichloroethylene (85:15)											
	Methyl ethyl ketone											
	Methyl isobutyl ketone											
	Methyl methacrylate											
	Tetrachloroethylene											
	Tetrachloroethane											
Tetrahydrofuran: cyclohexanone (80:20)												
Toluene												
ABS												
Cellulose acetate												
Cellulose acetate butrate												
Cellulose propionate												
Ethyl cellulose												
Nylon												
Polycarbonate												
Polymethyl methacrylate												
Polyphenylene oxide												
Polystyrene												
Polysulfone												
Polyvinyl chloride												
SAN												
Styrene butadiene												

Table S.1 (Continued)

Solvents for bonding plastics						
	Toluene: ethyl alcohol (90:10)					
	Toluene: methyl ethyl ketone (50:50)					
	Trichloroethane					
	Trichloroethylene					
	Xylene					
	Xylene: methyl isobutyl ketone (25:75)					
ABS						
Cellulose acetate						
Cellulose acetate butrate						
Cellulose propionate						
Ethyl cellulose						
Nylon						
Polycarbonate						
Polymethyl methacrylate						
Polyphenylene oxide						
Polystyrene						
Polysulfone						
Polyvinyl chloride						
SAN						
Styrene butadiene						

Solvent cements should be chosen with approximately the same solubility parameter as the plastic to be bonded. Table S.1 lists typical solvents used to bond major plastics. Solvents used for bonding can be a single pure solvent, a combination of solvents, or a solvent(s) mixed with resin. It is common to use a fast-drying solvent with a less volatile solvent to prevent crazing. The cement can be bodied up to 25 percent by weight with the parent plastic to increase viscosity. These bodied solvent cements can fill gaps and provide less shrinkage and internal stress than when only pure solvent is used.

solvent molding Solvent molding is a process for forming thermoplastic articles by dipping a male mold in a solution or dispersion of the resin and drawing off the solvent to leave a layer of plastic film coated on the mold. When the solvent evaporates and the coating hardens, the product can be removed from the mold.

Table S.2 Solvents that Affect Plastics (Ref: Izzo, C.P., "Decorative and Protective Coatings", *Handbook of Plastics, Elastomers, and Composites*, 3rd ed., C.A. Harper, ed. McGraw-Hill, New York, 1996)

Resin	Heat-distortion Point, °F	Solvents that Affect Surface
Acetal	338	None
Methyl methacrylate	160-195	Ketones, esters, aromatics
Modified acrylic	170-190	Ketones, esters, aromatics
Cellulose acetate	110-209	Ketones, some esters
Cellulose propionate	110-250	Ketones, esters, aromatics, alcohols
Cellulose acetate butyrate	115-227	Alcohols, ketones, esters, aromatics
Nylon	260-360	None
Polyethylene:		
High density	140-180	
Med. density	120-150	None
Low density	105-121	
Polypropylene	210-230	None
Polycarbonate	210-290	Ketones, esters, aromatics
Polystyrene (G.P. high heat)	150-195	Some aliphatics, ketones, esters, aromatics
Polystyrene (impact, heat-resistant)	148-200	Ketones, esters, aromatics, some aliphatics
ABS	165-225	Ketones, esters, aromatics, alcohol

solvent resistance Solvents affect thermoplastics, rubber, and thermosets in different ways. Thermoplastics usually dissolve in an adequate solvent. Solvent molecules separate the chains, forming a solution. Drying will return the thermoplastic to its normal state. Table S.2 shows the solvents that will affect surfaces of certain plastics.

Rubber generally swells as the solvent penetrates between the chains. The chemical bonds between polymer chains (due to crosslinking or vulcanization) are

joints, etc. Heat flow is determined by monitoring the surface temperature of a test piece a short time after external heating or cooling has been applied. Subsurface anomalies will alter the heat flow pattern and thereby affect the surface temperature. The surface temperature difference can be detected by thermometers, thermocouples, or heat-sensitive coatings. Liquid crystals applied to the joint can make voids visible if the substrate is heated.

Thermal transmission testing is an excellent way for detecting various types of anomalies such as surface corrosion under paint before the corrosion becomes visually evident. Thin single-layer structures, such as aircraft skin panels, can be inspected for surface and subsurface discontinuities. This test is simple and inexpensive, although materials with poor heat transfer properties are difficult to test and the joint must be accessible from both sides.

For nonmetallic materials, the defect diameter must be on the order of four times its depth below the surface to obtain a reliable thermal indication. For metals, the defect diameter must be approximately eight times its depth. Some bright surfaces, such as bare copper and aluminum, do not emit sufficient infrared radiation and may require a darkening coating on their surface.

With thermal surface impedance testing, heat is injected into the test object's surface from a hot gas pulse. The resulting surface temperature transient is analyzed to determine the part's quality in nearly real time. The surface temperature transients are sensed using an innovative noncontacting, emissivity independent infrared sensor. This method is not adversely affected by surface blemishes or roughness.

thermal welding Welding by application of heat or thermal welding provides an advantageous method of joining many thermoplastics that do not degrade rapidly at their melt temperature. It is a method of providing fast, relatively easy, and economical bonds that are generally 80–100 percent the strength of the parent plastic.

Thermal welding process can be of two kinds: direct and indirect. With *direct welding*, the heat is applied directly to the substrate in the form of either a heated tool or hot gas. *Indirect heating* occurs when some form of energy other than thermal is applied to the joint. The applied energy, which causes heating at the interface or in the plastic as a whole, is generally in the form of friction, high-frequency electrical fields, electromagnetic fields, or ultrasonic vibration. Because the heating is localized at the bonding surface, indirect heating processes are very energy efficient, generally resulting in bonds that are stress free and of higher strength than those made by direct welding methods.

See also heated tool welding; hot gas welding; spin welding; induction welding; ultrasonic welding; vibration welding; and dielectric heat sealing/welding.

thermoforming Thermoforming is the process of creating a formed article from a flat sheet by combinations of heat and pressure. This process first softens the sheet by application of heat and then forms the sheet into some three-dimensional shape. *Thermoforms* are the products that result from a thermoforming operation.

Thermoforming is one of the simplest, most economical plastic-forming processes. There are numerous variations of the thermoforming process, but most involve heating

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