ENGINEERED MATERIALS HANDBOOK

Volume 2

ENGINEERING PLASTICS

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ENGINEERED MATERIALS HANDBOOK™

Volume 2

ENGINEERING PLASTICS

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Foreword

In 1984, ASM INTERNATIONAL, then still known as the American Society for Metals, in response to needs expressed by many of its members, undertook a major commitment to expand its technical purview. In addition to all metals and metalworking processes, ASM would extend its scope to all engineered materials. This expansion would include composite materials, plastics, adhesives and sealants, ceramics and glasses, etc., and their related processes. In 1987, as a first major step toward fulfilling this commitment, the Society published *Volume 1: Composites* of this new *Engineered Materials Handbook* series.

The series is designed to provide, for these new materials, the same kind of definitive coverage that ASM's *Metals Handbook* has afforded metals and metalworking for more than 60 years. The *Metals Handbook*, presently nearing completion of its 17-volume Ninth Edition, is widely acknowledged as the technical bible of metals and processes relating to them.

Publication of *Volume 2: Engineering Plastics* of the *Engineered Materials Handbook* is another major step toward fulfilling the Society's commitment to this technical expansion.

It is also a signal achievement, in that it represents the first attempt, worldwide, to publish a comprehensive, definitive, exhaustively peer-reviewed handbook of practical information on engineering plastics, oriented specifically to engineers in user companies. Each of the articles in this Volume has been authored by a recognized expert in its subject area. Each has been scrutinized by at least three peers, to ensure its completeness, technical accuracy, and impartiality.

Expressions of appreciation for this achievement are in order. We are pleased to offer our warmest thanks, on behalf of ASM INTERNATIONAL, to all of the many professionals who contributed to this book. These individuals gave freely of their time and expertise, as authors, reviewers, section chairmen, and members of the Editorial Steering Committee. We are grateful to the organizations with which they are affiliated for their support in this effort. We thank the members of our Handbook Committee, for their guidance, helpful suggestions, vigilance, and infinite patience in assisting with the review process. And, of course, we also thank ASM's own professional editorial staff, for their untiring efforts to attain in this Volume the standard of excellence established by its predecessors.

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Policy on Units of Measure

By a resolution of its Board of Trustees, ASM INTERNATIONAL has adopted the practice of publishing data in both metric and customary U.S. units of measure. In preparing this Handbook, the editors have attempted to present data primarily in metric units based on Système International d'Unités (SI), with secondary mention of the corresponding values in customary U.S. units. The decision to use SI as the primary system of units was based on the aforementioned resolution of the Board of Trustees, the widespread use of metric units throughout the world, and the expectation that the use of metric units in the United States will increase substantially during the anticipated lifetime of this Handbook.

For the most part, numerical engineering data in the text and in tables are presented in SI-based units with the customary U.S. equivalents in parentheses (text) or adjoining columns (tables). For example, pressure, stress, and strength are shown both in SI units, which are pascals (Pa) with a suitable prefix, and in customary U.S. units, which are pounds per square inch (psi). To save space, large values of psi have been converted to kips per square inch (ksi), where 1 ksi = 1000 psi. Some strictly scientific data are presented in SI units only.

To clarify some illustrations, only SI units are presented on artwork. References in the accompanying text to data in the illustrations are presented in both SI-based and customary U.S. units. On graphs and charts, grids correspond to SI-based units, which appear along the left and bottom axes; where appropriate, corresponding customary U.S. units appear along the top and right axes.

Both nanometers (nm) and angstrom units (Å) are used (1 nm = 10 Å), the former to measure light wavelengths, and the latter as a unit of measure in x-ray crystallography. Data obtained according to standardized test methods for which the standard recommends a particular system of units are presented in the units of that system. Wherever feasible, equivalent units are also presented.

Conversions and rounding have been done in accordance with ASTM Standard E 380, with careful attention to the number of significant digits in the original data. For example, an annealing temperature of 1570 °F contains three significant digits. In this instance, the equivalent temperature would be given as 855 °C; the exact conversion to 854.44 °C would not be appropriate. For an invariant physical phenomenon that occurs at a precise temperature (such as the melting of pure silver), it would be appropriate to report the temperature as 961.93 °C or 1763.5 °F. In many instances (especially in tables and data compilations), temperature values in °C and °F are alternatives rather than conversions.

The policy on units of measure in this Handbook contains several exceptions to strict conformance to ASTM E 380; in each instance, the exception has been made to improve the clarity of the Handbook. The most notable exception is the use of MPa $\sqrt{m}$ rather than $MN \cdot m^{-3/2}$ or $MPa \cdot m^{0.5}$ as the SI unit of measure for fracture toughness. Other examples of such exceptions are the use of "L" rather than "l" as the abbreviation for liter and the use of g/cm^3 rather than kg/m^3 as the unit of measure for density (mass per unit volume).

SI practice requires that only one virgule (diagonal) appear in units formed by combination of several basic units. Therefore, all of the units preceding the virgule are in the numerator and all units following the virgule are in the denominator of the expression; no parentheses are required to prevent ambiguity.

Preface

Natural polymers, such as rosin, tortoise shell, ivory, bone, horn, rubber, and others, have been a part of man's world of materials for time spans measured in centuries. By contrast, the synthetic polymers we call "plastics," introduced in the late 19th and early 20th centuries, were man's first new engineering materials since the advent of metals in ancient times. In its short lifetime, beginning with celluloid, the first commercially successful plastic (1870), and Bakelite, the first moldable thermoset (1901), the plastics industry has grown exponentially. By 1987, when work on this Volume first began, the U.S. plastics industry had become the country's fourth largest.

Reliable forecasts indicate that worldwide plastics use will double in the next two decades, with polymer production assuming the position of the world's largest industry. While engineering plastics constitute only a small segment of this industry, it is the fastest growing segment of the world's fastest growing technology.

By definition, a growth industry is not a mature one. One of the characteristics of immature technologies is that their vocabularies are more fluid, their terminologies less precise, their definitions more subject to variable interpretation, than their more mature counterparts. For this reason, an attempt will be made here to clarify some basic terminology used in this book.

In common usage, the words "plastic," "polymer," and "polymeric material" are often used as interchangeable nouns. In this Volume, "plastic" used as a noun means a material which has as its principal constituent one or more polymer resins, and which is capable of being formed or molded into an end-use shape. Use of the word "polymer" for such a material is avoided here, for two major reasons: (1) Polymer resins are only infrequently used in their "neat" form (i.e., without other constituents) as plastics. Almost universally, most plastics contain other constituents (extenders, fillers, reinforcements, plasticizers, colorants, etc.). (2) Discussing the various engineering plastics requires frequent reference to the individual polymers that are their principal constituents. To avoid confusion, use of the noun "polymer," meaning a material consisting of molecules which contain many ("poly") repetitions of a single, smaller unit ("mer"), is reserved for the synthetic resins from which plastics are made.

In the plastics industry, the term "engineering plastic" is subject to a variety of interpretations. For the purposes of this Volume, it has been defined to mean a synthetic polymer resin based material that is capable of being molded into load-bearing shapes, and that has high-performance properties which permit it to be used in the same manner as metals and ceramics. By intention, this definition includes thermoset, as well as thermoplastic, resins. Concomitantly, it includes continuous fiber reinforced resins (often termed "composite materials," especially when used for structural applications), as well as the short-fiber and/or particulate-reinforced plastics commonly used for parts and components. Because composites are, by this definition, a subset of engineering plastics, the reader will find some limited treatment of them in this Volume, although they are addressed in much greater detail in *Volume 1: Composites* of this Handbook series.

This present Volume is intended as a comprehensive basic reference source for engineers in user companies who must make informed day-to-day decisions involving the use of engineering plastics. In recognition of the fact that many of these readers may have little or no basic knowlege of plastic materials, the first section of the book is designed to furnish general background and overview information. Section 1, "General Design Considerations," offers a glossary of engineering plastics terminology and definitions, along with introductory articles designed for orientation of the novice with little or no experience in plastics technology.

Section 2, "Guide to Engineering Plastics Families," also intended in part as a backgrounding section, should be useful to novice and expert alike. It contains short articles that describe the major thermoplastic and thermoset engineering plastics families in sufficient detail to acquaint the reader with their general characteristics and uses, including the important similarities and differences among them, special processing considerations, major applications, etc. These articles are written to a common outline, to facilitate cross-comparisons between resin families.

The remaining sections of the Volume contain more detailed discussions of the important topics and issues in the major subject areas of interest to users of engineering plastics.

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SECTION 1

General Design Considerations

Chairman: L.C. Roy Oberholtzer, Rockwell International, Collins Avionics Division

Introduction

THE SCOPE OF THIS VOLUME is engineering plastics, which the dedicated efforts of scientists, engineers, technicians, and marketers have created and maintained as one of the most dynamic and responsive industries in the world. This Section of the Volume presents general background information directed to those engineers not generally familiar with plastics technology. Therefore, the articles in this Section are primarily overviews to promote an understanding of the more detailed articles in the remainder of the Volume.

Engineering plastics all have, as their principal constituent, one or more synthetic polymer resins, and almost universally have other constituents, such as fillers, plasticizers, and colorants. Because this Handbook is intended for users of engineering plastics, rather than suppliers, the use of the term plastics is deemed more appropriate than the term polymers, which is much in vogue with some writers in the field.

The most fundamental question a design engineer must address is whether it is appropriate to consider the use of engineering plastics for a given application. The characteristics of plastics that render them advantageous in many applications include thermal and electrical insulation, low density, self-lubrication, atmospheric-corrosion resistance, chemical resistance, inherent color, and design freedom.

In a free-enterprise economy, cost must be a prime adjunct to the technical considerations involved in materials selection and application. However, materials selection and application that are based solely on cost considerations can have devastating results. This practice, which was very popular in the 1950s and 1960s, caused the disenchantment of the general public with plastic materials because their plastic products failed soon after purchase. To this day, the term plastic still retains a residual connotation of poor quality. Therefore, in the interest of corporate financial health and industry reputation, sound engineering judgment must prevail in material selection, product design, and production parameters.

Conversely, a design engineer should immediately disqualify engineering plastics if the application requires maximum efficiency of heat transfer or electrical conductivity, or nonflammable properties. Although some plastics can be formulated to retard flames, their organic nature makes them inherently flammable. Applications under constant stress for which a close tolerance must be held need to be scrutinized in terms of the effects of creep at the application temperature. The design engineer also must be cognizant of the poor ultraviolet (UV) resistance of most, though not all, engineering plastics, and the resulting requirement for a UV absorber. It is also incumbent upon the design engineer to realize the greatest reliability of a part at a tolerable cost. Practitioners of failure analysis will affirm that most part failures result from a lack of attention during design, either to the relatively high coefficient of expansion of unfilled engineering plastics or to the chemical compatibility of the plastic with another material it will be in contact with. The articles "Cost Considerations" and "Characteristics Crucial to the Application of Engineering Plastics" will expand on this topic.

Material selection is now more complex by virtue of the great number of engineering plastics available to the design engineer. It would be too time consuming to research all the literature for every new application. The design engineer risks application failure or unnecessary cost by deciding on a formulation strictly because it was previously used in a similar application. The use of computer data banks to reduce the options to a practical number is encouraged. After a complete analysis, which is described in the article "Design Approach for Engineering Plastics," if there is still more than one option, a data bank that includes material costs can provide a fast and accurate means of ranking the candidates in terms of value. It cannot be inferred that the computer makes the decision. It provides information that allows the design engineer to make a sound decision. Thus, there can be discrete reasons for not selecting the candidate with the highest value rating. Although commercial data banks are available, many large companies have elected to develop their own.

In this dynamic electronic age of rapid information dissemination, many practitioners need to remember the importance of a triangular flow of information between the design engineer, the tool designer, and the material converter. Procedures at some companies assume that the drawings, notes, and referenced specifications provided by a design engineer enable a purchasing department to manage vendor relationships completely. There are also converters who have a similar relationship with tool makers. Each party has options unknown to the other two parties, and each wants to select from among his own options those that will result in a product with the lowest cost and highest reliability. Only direct communication among the three can bring about the best possible choice among all options available, and thus ensure the success of a given application.

*Glossary of Terms**

A

A. The symbol for a repeating unit in the polymer chain.

ABA copolymers. Block copolymers with three sequences, but only two domains.

A-basis. The "A" mechanical property value is the value above which at least 99% of the population of values is expected to fall, with a confidence of 95%. Also called A-allowable. See also *B-basis, S-basis,* and *typical-basis.*

abhesive. A material that resists adhesion. A film or coating applied to surfaces to prevent sticking, heat sealing, and so on, such as a parting agent or mold release agent.

ablation. A self-regulating heat and mass transfer process in which incident thermal energy is expended by sacrificial loss of material.

ablative plastic. A material that absorbs heat (with a low material loss and char rate) through a decomposition process (pyrolysis) that takes place at or near the surface exposed to the heat. This mechanism essentially provides thermal protection (insulation) of the subsurface materials and components by sacrificing the surface layer. Ablation is an exothermic process.

ABL bottle. An internal pressure test vessel about 460 mm (18 in.) in diameter and 610 mm (24 in.) long used to determine the quality and properties of the filament-wound material in the vessel.

ABS. See *acrylonitrile-butadiene-styrene (ABS) resins.*

absolute humidity. The weight of water vapor present in a unit volume of air, such as grams per cubic foot, or grams per cubic meter. The amount of water vapor is also reported in terms of weight per unit weight of dry air, such as grams per pound of dry air, but this value differs from values calculated on a volume basis and should not be referred to as absolute humidity. It is designated as humidity ratio, specific humidity, or moisture content.

absolute viscosity. With respect to a fluid, the tangential force on unit area of either of two parallel planes at unit distance apart when the space between the planes is filled with the fluid in question and one of the planes moves with unit differential velocity in its own plane.

absorption. The penetration into the mass of one substance by another. The process whereby energy is dissipated within a specimen placed in a field of radiant energy. The capillary or cellular attraction of adherend surfaces to draw off the liquid adhesive film into the substrate.

AC. See *acetal (AC) copolymers, acetal (AC) homopolymers,* and *acetal (AC) resins.*

accelerated-life test. A method designed to approximate, in a short time, the deteriorating effect obtained under normal long-term service conditions. See also *artificial aging.*

accelerator. A material that, when mixed with a catalyst or a resin, speeds up the chemical reaction between the catalyst and the resin (usually in the polymerizing of resins or vulcanization of rubbers). Also called promoter.

accumulator. An auxiliary cylinder and piston (plunger) mounted on injection molding or blowing machines and used to provide faster molding cycles. In blow molding, the accumulator cylinder is filled (during the time between parison deliveries, or "shots") with melted plastic coming from the main (primary) extruder. The plastic melt is stored, or "accumulated," in this auxiliary cylinder until the next shot or parison is required. At that time the piston in the accumulator cylinder forces the molten plastic into the dies that form the parison.

acetal (AC) copolymers. A family of highly crystalline thermoplastics prepared by copolymerizing trioxane with small amounts of a comonomer that randomly distributes carbon-carbon bonds in the polymer chain. These bonds, as well as hydroxyethyl terminal units, give the acetal copolymers a high degree of thermal stability and resistance to strong alkaline environments.

acetal (AC) homopolymers. Highly crystalline linear polymers formed by polymerizing formaldehyde and capping it with acetate end groups.

acetal (AC) resins. Thermoplastics (polyformaldehyde and polyoxymethylene resins) produced by the addition polymerization of aldehydes by means of the carbonyl function, yielding unbranched polyoxymethylene chains of great length. The acetal resins, among the strongest and stiffest of all thermoplastics, are also characterized by good fatigue life, resilience, low moisture sensitivity, high solvent and chemical resistance, and good electrical properties. They may be processed by conventional injection molding and extrusion techniques, and fabricated by welding methods used for other plastics.

acid-acceptor. A compound that acts as a stabilizer by chemically combining with acid that may be initially present in minute quantities in a plastic, or that may be formed by the decomposition of the resin.

acrylate resins. See *acrylic resins.*

acrylic plastic. A thermoplastic polymer made by the polymerization of esters of acrylic acid or its derivatives.

acrylic resins. Polymers of acrylic or methacrylic esters, sometimes modified with nonacrylic monomers such as the ABS group. The acrylates may be methyl, ethyl, butyl, or 2-ethylhexyl. Usual methacrylates are methyl, ethyl, butyl, laural, and stearyl. The resins may be in the form of molding powders or casting syrups, and are noted for their exceptional clarity and optical properties. Acrylics are widely used in lighting fixtures because they are either slow burning or self-extinguishing, and do not produce harmful smoke or gases in the presence of flame.

*Numerous abbreviations for plastics families have been used throughout this Volume, as standardized by the American Society for Testing and Materials in ASTM D 1600 and ASTM D 4000.

acrylonitrile. A monomer with the structure (CH_2:CHCN). It is most useful in copolymers. Its copolymer with butadiene is nitrile rubber; acrylonitrile-butadiene copolymers with styrene (SAN) exist that are tougher than polystyrene. It is also used as a synthetic fiber and as a chemical intermediate.

acrylonitrile-butadiene-styrene (ABS) resins. A family of thermoplastics based on acrylonitrile, butadiene, and styrene, combined by a variety of methods involving polymerization, graft polymerization, physical mixing, and combinations thereof. The standard grades of ABS resins are rigid, hard, and tough, but not brittle, and possess good impact strength, heat resistance, low-temperature properties, chemical resistance, and electrical properties.

activation. The (usually) chemical process of making a surface more receptive to bonding with a coating or an encapsulating material.

activator. See *accelerator*.

addition polymerization. A chemical reaction in which simple molecules (monomers) are linked to each other to form long-chain molecules (polymers) by chain reaction.

additive. A substance added to another substance, usually to improve properties, such as plasticizers, initiators, light stabilizers, and flame retardants. See also *filler*.

adduct. A chemical addition product.

adherend. A body that is held to another body, usually by an adhesive. A detail or part prepared for bonding.

adhesion. The state in which two surfaces are held together at an interface by mechanical or chemical forces or interlocking action or both.

adhesion promoter. A coating applied to a substrate before it is coated with an adhesive, to improve the adhesion of the plastic. Also called primer.

adhesive. A substance capable of holding two materials together by surface attachment. Adhesive can be in film, liquid, or paste form.

adhesive, anaerobic. See *anaerobic adhesive*.

adhesive, cold-setting. See *cold-setting adhesive*.

adhesive, contact. See *contact adhesive*.

adhesive failure. Rupture of an adhesive bond such that the separation appears to be at the adhesive-adherend interface.

adhesive film. A synthetic resin adhesive, with or without a film carrier fabric, usually of the thermosetting type, in the form of a thin film of resin, used under heat and pressure as an interleaf in the production of bonded structures.

adhesive, gap-filling. See *gap-filling adhesive*.

adhesive, heat-activated. See *heat-activated adhesive*.

adhesive, heat-sealing. See *heat-sealing adhesive*.

adhesive, hot-melt. See *hot-melt adhesive*.

adhesive, hot-setting. See *hot-setting adhesive*.

adhesive, intermediate temperature setting. See *intermediate temperature setting adhesive*.

adhesive joint. The location at which two adherends or substrates are held together with a layer of adhesive. The general area of contact for a bonded structure.

adhesive, pressure-sensitive. See *pressure-sensitive adhesive*.

adhesive strength. The strength of the bond between an adhesive and an adherend.

adhesive, structural. See *structural adhesive*.

adiabatic. Occurring with no addition or loss of heat from the system under consideration. It is used, somewhat incorrectly, to describe a mode of extrusion in which no external heat is added to the extruder although heat may be removed by cooling to keep the output temperature of the melt passing through the extruder constant. The heat input in such a process is developed by the screw as its mechanical energy is converted to thermal energy.

admixture. The addition and homogeneous dispersion of discrete components, before cure.

adsorption. The adhesion of the molecules of gases, dissolved substances, or liquids in more or less concentrated form, to the surfaces of solids or liquids with which they are in contact. The concentration of a substance at a surface or interface of another substance.

advanced composites. Composite materials that are reinforced with continuous fibers having a modulus higher than that of fiberglass fibers. The term includes metal matrix and ceramic matrix composites, as well as carbon-carbon composites, all of which are beyond the scope of this Volume.

afterbake. See *postcure*.

aggregate. A hard, coarse material usually of mineral origin used with an epoxy binder (or other resin) in plastic tools. Also used in flooring or as a surface medium.

aging. The effect on materials of exposure to an environment for a prolonged interval of time. The process of exposing materials to an environment for a prolonged interval of time in order to predict in-service lifetime. Also called bursting strength.

air-assist forming. A method of thermoforming in which air flow or air pressure is employed to preform the sheet partially just before the final pull-down onto the mold using vacuum.

air-bubble void. Air entrapment within a molded item or between the plies of reinforcement or within a bondline or encapsulated area; localized, noninterconnected, and spherical in shape.

air gap. In extrusion coating, the distance from the die opening to the nip formed by the pressure roll and the chill roll.

air ring. A circular manifold used to distribute an even flow of the cooling medium, air, onto a hollow tubular form passing through the center of the ring. In blown tubing, the air cools the tubing uniformly, thereby providing a uniform film thickness.

air-slip forming. A variation of snap-back forming in which the male mold is enclosed in a box such that when the mold moves forward toward the hot plastic, air is trapped between the mold and the plastic sheet. As the mold advances, the plastic is kept away from it by this air cushion until the full travel of the mold is completed, at which point a vacuum is applied, destroying the cushion and forming the part against the plug.

air vent. A small outlet to prevent entrapment of gases in a molding or tooling fixture.

alcohols. Characterized by the hydroxyl (—OH) group they contain, alcohols are valuable starting points for the manufacture of synthetic resins, synthetic rubbers, and plasticizers.

aldehydes. Volatile liquids with sharp, penetrating odors that are slightly less soluble in water than are corresponding alcohols.

aliphatic hydrocarbons. Saturated hydrocarbons having an open-chain structure; for example, gasoline and propane.

alkyd plastic. Thermoset plastic based on resins composed principally of polymeric esters, in which the recurring ester