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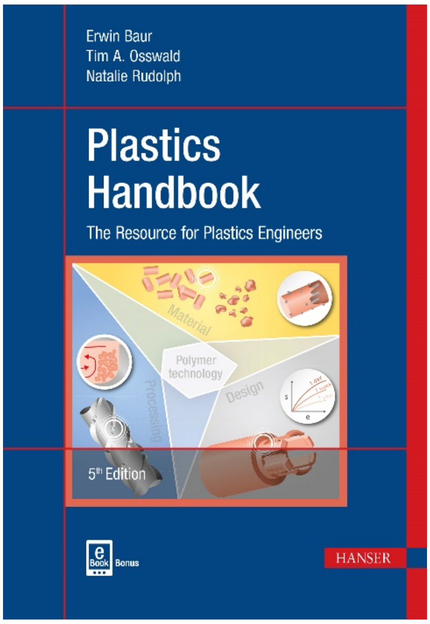

Sample Pages

Plastics Handbook

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Preface

This new and completely reworked edition of the *Plastics Handbook* finds its roots in the German Plastics Handbook *(Saechtling Kunststoff Taschenbuch)*, first published in 1936, and now in its 31st edition. After years of working back and forth between the German and English language editions, updating the processing and materials chapters as well as upgrading the figures into color, we have finally achieved two synchronized handbooks, each designed for their specific geographical market. We realize that the plastics field is constantly in flux, with changes driven by major factors such as energy conservation, new materials, and new manufacturing techniques, such as additive manufacturing. Therefore, we know that this handbook is a never-ending project that will organically change over time. We look forward to the developments our industry will bring in the years to come, and to the work we will do together to bring you the next version of this handbook. It would have been impossible to produce this new edition without the irreplaceable contributions from Dr. Christine Strohm who helped with the translations, as well as those from Tobias Mattner who reworked all the figures. We thank both for their steadfast dedication. We are also thankful to Dr. Mark Smith for his meticulous work while combing through the whole manuscript and to Jörg Strohbach for his production work to generate a version that is so pleasing to the eye. We are grateful to our families for their unconditional love and support.

Winter 2018 *Erwin Baur, Tim A. Osswald, and Natalie Rudolph*

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Common Acronyms in Plastics Technology

The plastics industry typically categorizes plastic materials by their chemical family and assigns material acronyms with respect to this family. While this is common practice, it does not reflect reality in the plastics industry, because the materials are sold under their trade names, each with a very specific property spectrum. In fact, the trade name is the only criterion for identification (similar to an order number). Standards defining the properties of specific material classes, such as are common practice for metals, have been introduced for thermosetting materials only. The materials within one family typically exhibit a wide range of properties.

However, in order to structure our knowledge of these materials, it is necessary to categorize them in a logical and comprehensible way.

We will introduce the common method of assigning acronyms in this book. Here, a compromise needs to be struck between an unambiguous classification that follows strict rules and the popular notations commonly used. Although there are several standards regarding plastic material notations, they are inconsistent and contradictory, sometimes even within the same standard.

Table I summarizes the acronyms of the plastic materials covered in this book, preferably considering the chemical composition of the polymers and avoiding additional specifications that relate to physical properties or processing technologies. However, in light of the fact that notations such as “A” for amorphous or “B” for block copolymers are often used in the literature, they are used here at times as well. We discourage using them though because they lack general validity and often cause contradictions.

Table I contains bold listings, indicating that they are standardized. They are based on suggestions made in connection with the plastics data base CAMPUS. Here, the current ISO-standards are reflected; however, exceptions are permitted as long as they are widely used. This approach allowed for CAMPUS to define a list of so-called base polymers that covers almost the entire plastic materials market. This list is routinely reviewed and expanded when necessary.

Table I A provides the acronyms for plastics and rubbers, while Table I B (page 9) provides acronyms for *plasticizers*.

1.1 Table I: Alphabetical List of Plastics Acronyms, Chemical Notation

A: Plastics and Rubbers

Acronym	Chemical notation	Page #
*	Pyrrone	501
*	Polycyclone	502
*	Polyphenylene (polyarylene)	501
*	Polytriazine	493
ABS	Acrylonitrile-butadiene-styrene copolymer	376
ACM	Acrylate rubber (AEM, ANM)	573
ACS	Acrylonitrile-chlorinated polyethylene-styrene	376
AECM	Acrylic ester-ethylene rubber	572
AEM	Acrylate ethylene polymethylene rubber	573
AES	Acrylonitrile ethylene propylene diene styrene copolymer	376
AFMU	Nitroso rubber	577
AMMA	Acrylonitrile methyl methacrylate	415
APE-CS	see ACS	
ASA	**Acrylonitrile styrene acrylic ester copolymer**	376
AU	Polyester urethane rubber	577
BIIR	Bromobutyl rubber	570
BR	Butadiene rubber	569
CA	Cellulose acetate	520
CAB	Cellulose acetobutyrate	520
CAP	Cellulose acetopropionate	520
CF	Cresol formaldehyde	538, 557
CH	Hydrated cellulose, cellulose film	520
CIIR	Chlorobutyl rubber	570
CM	Chlorinated polyethylene rubber	573
CMC	Carboxymethyl cellulose	520
CN	Cellulose nitrate, celluloid	520
CO	Epichlorohydrin rubber	574
COC	**Cyclic polyolefin copolymers**	348
COP	COC copolymer	358
CP	Cellulose propionate	520
CR	Chloroprene rubber	569
CSF	Casein formaldehyde, artificial horn	548
CSM	Chlorosulfonated polyethylene rubber	573
CTA	Cellulose triacetate	520

* There are no known acronyms for these plastic materials.

Acronym	Chemical notation	Page #
E/P	**Ethylene propylene copolymer**	348
EAM	Ethylene vinyl acetate rubber	572
EAMA	Ethylene acrylic acid ester maleic acid anhydride copolymer	348
EB	Ethylene butene	348
EBA	Ethylene butyl acrylate	348
EC	Ethyl cellulose	520
ECB	Ethylene copolymer bitumen blend	348
ECO	Epichlorohydrin rubber	574
ECTFE	Ethylene chlorotrifluoroethylene	407
EEA	Ethylene ethyl acrylate copolymer	348
EIM	Ionomer copolymer	348
EMA	Ethylene methacrylic acid ester copolymer	348
EP	**Epoxy resin**	538
EP(D)M	see EPDM	572
EPDM	Ethylene propylene diene rubber	572
EPM	Ethylene propylene rubber	572
ET	Polyethylene oxide tetrasulfide rubber	577
ETER	Epichlorohydrin ethylene oxide rubber (terpolymer)	574
ETFE	Ethylene tetrafluoroethylene copolymer	408
EU	Polyether urethane rubber	577
EVAC	**Ethylene vinyl acetate copolymer**	348
EVAL	Ethylene vinyl alcohol, old acronym EVOH	348
FEP	Polyfluoroethylene propylene	408
FF	Furan formaldehyde	538
FFKM	Perfluoro rubber	574
FKM	Fluoro rubber	573
FPM	Propylene tetrafluoroethylene rubber	574
FVMQ	Fluorosilicone rubber	575
HCR	Hydrocarbon resin	564
HNBR	Hydrated NBR rubber	571
ICP	Intrinsically conductive polymers	527
IIR	Butyl rubber (CIIR, BIIR)	570
IR	Isoprene rubber	569
LCP	**Liquid crystal polymer**	497
LSR	Liquid silicone rubber	576
MABS	**Methyl methacrylate acrylonitrile butadiene styrene**	411
MBS	**Methacrylate butadiene styrene**	411
MC	Methylcellulose (cellulose derivate)	520
MF	**Melamine formaldehyde**	538
MFA	Tetrafluoroethylene perfluoromethyl vinyl ether copolymer	410
MFQ	Methylfluoro silicone rubber	575

Acronym	Chemical notation	Page #
MMAEML	Methyl methacrylate-exo-methylene lactone	418
MPF	**Melamine phenolic formaldehyde**	538
MPQ	Methylphenylene silicone rubber	575
MQ	Polydimethyl silicone rubber	575
MS	see PMS	
MUF	Melamine urea formaldehyde	538
MUPF	Melamine urea phenolic formaldehyde	538
NBR	Acrylonitrile butadiene rubber	570
NCR	Acrylonitrile chloroprene rubber	570
NR	Natural rubber	568
PA	Polyamide (other notations see Section 5.8)	430
PA 11	**Polyamide from aminoundecanoic acid**	430
PA 12	**Polyamide from dodecanoic acid**	430
PA 46	**Polyamide from polytetramethylene adipic acid**	430
PA 6	**Polyamide from ε-caprolactam**	430
PA 610	**Polyamide from hexamethylene diamine sebacic acid**	430
PA 612	**Polyamide from hexamethylene diamine dodecanoic acid**	430
PA 66	**Polyamide from Hexamethylene diamine adipic acid**	430
PA 69	**Polyamide from hexamethylene diamine azelaic acid**	430
PAA	Polyacrylic acid ester	410
PAC	Polyacetylene	527
PAEK	**Polyarylether ketone**	483
PAI	Polyamide imide	494
PAN	Polyacrylonitrile	410
PANI	Polyaniline, polyphenylene amine	528
PAR	Polyarylate	472
PARI	Polyarylimide	494
PB	Polybutene	370
PBA	Polybutyl acrylate	410
PBI	Polybenzimidazole	493
PBMI	Polybismaleinimide	493
PBN	Polybutylene naphthalate	474
PBO	Poly(p-phenylene-2,6-benzobisoxazole)	619
PBT	**Polybutylene terephthalate**	470
PC	**Polycarbonate (from bisphenol-A)**	456
PCTFE	Polychlorotrifluoro ethylene	401
PDAP	Polydiallylphthalate resin	544
PDCPD	Polydicyclopentadiene	374

2

Introduction

■ 2.1 Economic Significance of Plastics

Plastics in general have gained significant technological and economic importance alongside metals and ceramics. Globally, plastics represent a larger production volume today than steel or aluminum, thanks to the considerable growth of this material class (Fig. 2.1).

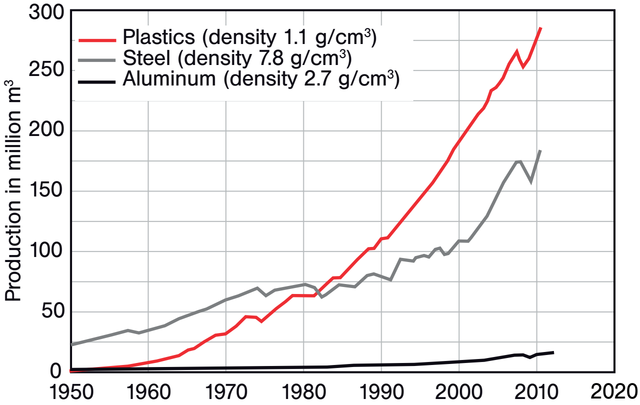


Figure 2.1 Production volume of various materials. Source: Plastics Europe, World Steel Association, The International Aluminium Association

Figure 2.2 provides an overview of the fast-paced growth in plastics production in different global regions between 1990 and 2011. Undoubtedly, we have entered the "age of plastics" in the 21st century. This material class is an integral foundation for technological development and an indicator of the economic growth in an industrial society.

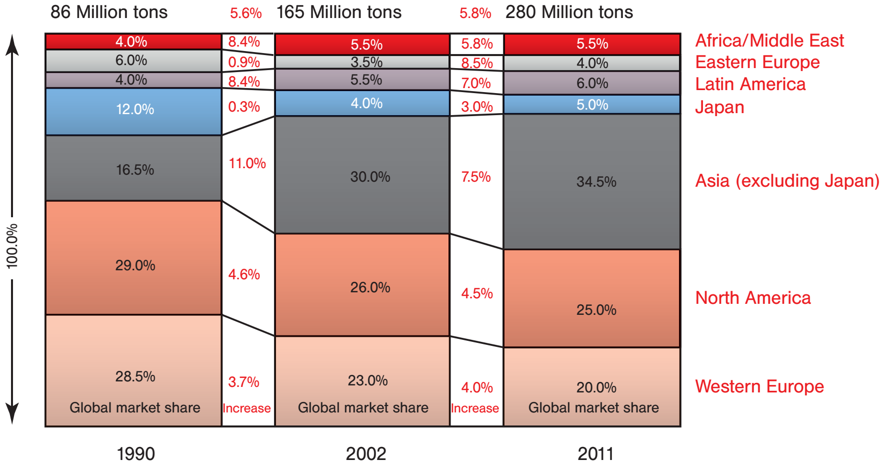


Figure 2.2 Global plastic production since 1990. Source: Plastics Europe

There is a clear correlation between plastic production and the economic and technological performance of a region.

Analyzing the main application areas for plastics in Europe in 2012 (Fig. 2.3) exemplifies the variety of plastic utilization. The “Other” applications, totaling 26% in Figure 2.3 include applications in agriculture, furniture, home appliances, leisure, sport, medicine, and machine construction. Although medical applications have been increasing significantly, their overall share of the plastics market is still only 1%. Plastics have gained entrance into all sectors of industrial production. That their application is profitable is not necessarily a result of their specific properties, such as their potential for lightweight construction or their good insulation properties, but the ability to use economic processing technologies for the manufacture of plastic parts and components. For example, injection molding allows for the manufacture of highly complex components within cycle times ranging from a few seconds to several minutes. The majority of the costs of such manufacturing technologies can be attributed to the depreciation of machine and molds and the cost for raw materials and energy. However, with increasing number of units produced, even highly sophisticated manufacturing equipment becomes profitable quickly.

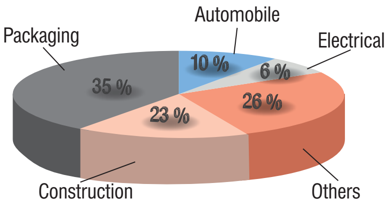


Figure 2.3
Main fields of application for plastics in Europe (2012)
Source: Plastics Europe

The industry branches involved in, and working with, plastics can be distinguished in three categories:

- Plastic production,
- Plastic manufacturing, and
- Plastic machine building industry.

The plastics industry significantly contributes to the world economy in general. For example, it employs almost 900,000 people in the US, and about 1.5 million in the EU countries. Furthermore, there are more than 16,000 plastics industry facilities in the US, in contrast to 60,000 in the EU countries. In the US, $380 billion are created in shipments every year, compared to $400 billion in the 27 European countries.

2.2 Classification of Plastics

Polymers are organic or semi-organic materials with high molecular mass (molecular weight), *i. e.*, they are composed of very large molecules (macromolecules), which significantly determine the distinct characteristics of these materials. Figure 2.4 reflects the classification of plastic materials in the general field of material science. Here, distinguishing characteristics are chemical structure, type of polymerization, and the processing and service properties.

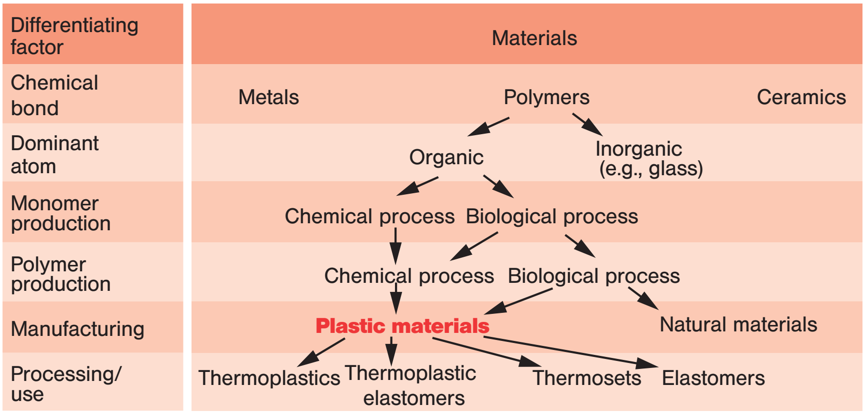


Figure 2.4 Classification of plastic materials in the general field of material science

In this book, the focus will be on thermoplastic materials, reflecting their economic importance. However, many statements made for thermoplastics are valid for all polymeric materials. A clear definition of the terminology used is missing in many texts, *e. g.*, the terms plastic and polymer are often used synonymously. In our view, the term *polymer* is applicable to all materials with a macromolecular structure, whereas the term *plastics* only describes polymers that are modified with additives to meet the requirements of industrial processing technologies, such as processing aids, stabilizers, pigments, fillers, and others.

Despite this clear definition we were not always able to strictly adhere to this terminology. One reason for this shortcoming is the fact that even in the language of science and in economic statistics the differentiation is not consistent. Even in material standards the term polymer is often used when in fact they cover plastic materials. In these cases, it is not an option to change the term *polymer* to *plastics*, because that would make it impossible to retrieve the standard.

The following general statements can be made for plastic materials:

- The variety of plastic material classes and types is unparalleled by any other material class. Plastics represent an extremely large span of property profiles, and the slogan of the early days of plastic material development that euphorically declared them “**tailored materials**” has become reality. In almost every area of modern life plastic materials have established themselves as manufacturing materials of choice or as materials with specific functionalities.
- Their complex chemical and morphological structures together with their wide variety in terms of composition and modifiability result in highly complex **material behaviors** that strongly determine service and processing conditions. Examples of properties to be considered include their visco- and entropy elasticity, non-Newtonian flow, complex aging characteristics, semi-crystallinity, liquid crystallinity, orientation- and modification-dependent anisotropy, stress cracking, and many others. A variety of test procedures is necessary to comprehensively describe plastic properties and to provide meaningful characteristic values (single-point data) or property functions (multiple-point data) (see Chapter 3).
- Plastics technology provides a large number of different **processes** for the compounding, processing, and post-processing of plastic materials. The molding and shaping processes play a dominant role because they offer highly productive and energy efficient material utilization within a minimal number of process steps. In some cases, material shaping and conversion (*e. g.*, tempering, vulcanization) happen simultaneously during processing. The properties of the final product are significantly influenced by the processing conditions. Therefore, process optimization and quality control have to be emphasized appropriately in plastics manufacturing operations (see Chapter 4).
- It is not possible to efficiently **design** plastic components without considering the constraints introduced by material properties and manufacturing processes. This fact, together with the high degree of material and geometry specialization of many manufacturing technologies, requires the consideration of the close interdependence of design, material, and process decisions.

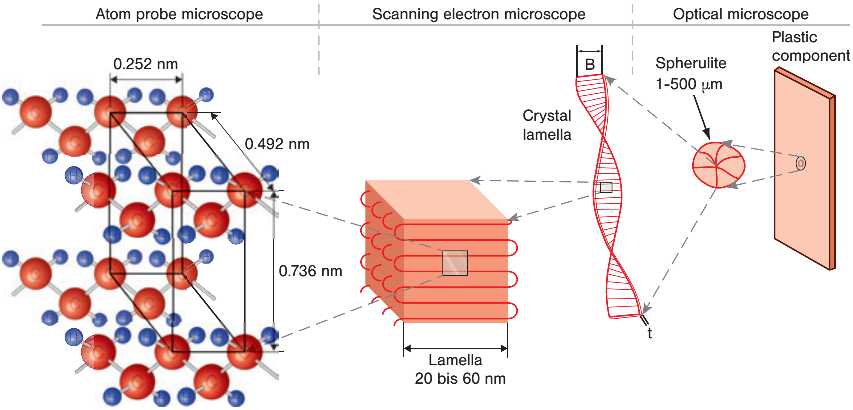


Figure 2.12 Morphology of a semi-crystalline thermoplastic material

Figure 2.13 shows the dynamic shear modulus as a function of temperature for a PE-HD, the most common semi-crystalline plastic material. This curve presents data measured at one test frequency. The figure clearly shows two distinct transitions: one at about −110 °C, the *glass transition temperature*, and one near 140 °C, the melting temperature. Above the *melting temperature*, the shear modulus is negligible and the material will flow. Crystalline arrangement begins to develop as the temperature decreases below the melting point. Between the melting and glass transition temperatures, the material behaves as a leathery solid. Once the temperature decreases below the glass transition temperature, the amorphous regions between the crystalline structures vitrify, resulting in stiff and often also brittle material behavior.

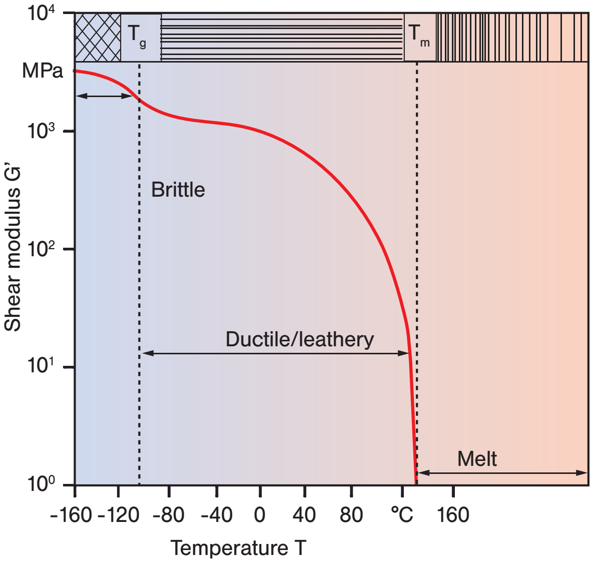


Figure 2.13 Shear modulus of PE-HD as a function of temperature

During processing of plastic materials, inhomogeneous crystal nucleation or differential cooling rates in the material may create locally different crystalline structures, *e. g.*, the fine spherulitic surface layers in injection molded components. This in turn results in anisotropic material properties. The particular characteristics of the molecular structure of semi-crystalline plastics have been tailored in various ways in order to create desired properties:

- Stretching or shearing of macromolecules are used to create molecular rearrangement and the formation of new oriented, crystalline structures, respectively. This results in a significant increase in stability and stiffness, in particular in a desired direction. Examples of such crystalline structures are the fibrils and shish-kebab structures shown in Figure 2.14. A number of processing variations are common in the chemical fiber industry and in plastic engineering, including fiber stretching, biaxial film stretching, and injection- and compression molding stretching. These manipulations result in anisotropic structures with unidirectional or orthogonal orientation.
- Highly homogeneous and fine-grained crystallite structures are obtained by controlling the cooling conditions and/or adding finely dispersed nucleating agents. These structures are advantageous in particular for dimensionally stable and wear resistant components.

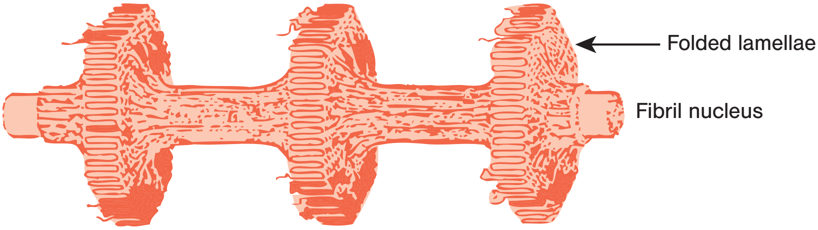


Figure 2.14 Shish-kebab structure

Under common solidification conditions, some polymers are not able to crystallize because of their specific molecular configuration. However, stretching facilitates a partial crystallization by aligning and denser packing of molecular segments *(elongation-induced crystallization)*. This type of structure formation requires a certain level of micro-Brownian molecular mobility, because crystallites can form only by molecular rearrangement during stretching. Elongation-induced crystallization is often seen with rubbers (*e. g.*, NR, IR, IIR, CR). However, the corresponding increase in hardness is not necessarily a welcome side effect in rubber applications.

Crystalline structures in polymers represent the state of highest molecular order in terms of dense molecular aggregation and the corresponding stronger intermolecular forces. Yet, they are still imperfect results of a “frozen” crystallization imbalance so that an increase in temperature will cause melting over a varying

3

Material Properties and Testing Methods

In this chapter we will introduce the characteristic properties of plastics and the testing methods required to determine them. It is our goal to develop and improve a general understanding of this group of materials. Our descriptions will be general and qualitative and the diagrams displaying material characteristics are meant to help gain insight into the behavior of this group of materials. Some tables and figures provide a comparison of selected plastics; however, these comparisons are also only means to foster a general understanding.

It should be noted that plastics are almost always modified by functional or other additives. The properties of commercially available plastic materials may vary from the “average values” provided here. Before selecting a specific plastic material, it is recommended to verify properties through the manufacturer. Another highly recommended source of material property information is CAMPUS, a free database provided by 30 plastic material producers. This database contains material data for materials under their respective tradenames. Both space and timeliness are prohibitive factors for a printed work to provide the plethora of information available. More detailed information regarding the CAMPUS database and free downloads can be found at www.CAMPUSplastics.com.

Figure 3.1 compares the stress/strain diagrams of unfilled PBT grades to exemplify the wide variation of plastic characteristics (data according to CAMPUS). Large differences in property profiles can be found even within one plastic class.

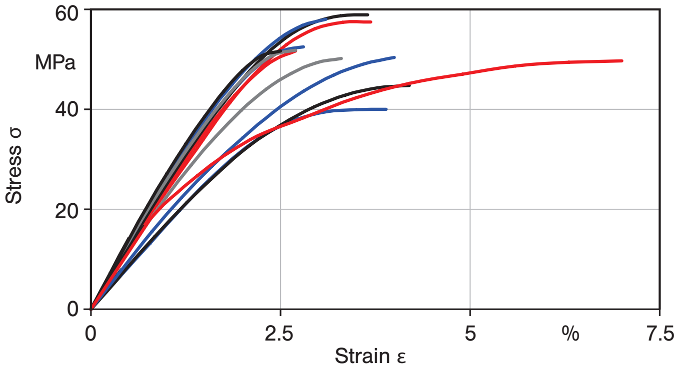


Figure 3.1 Range of stress-strain diagrams for PBT at 23 °C

3.1 Significance of Characteristic Values

Material characteristics are the determining factors during all phases of development and design. They affect the initial, conceptual design steps, material selection, and dimensioning of molded components. In order to meet these requirements, material characteristics have to be

- comparable,
- meaningful, and
- determined by a rational process.

Databases and material data sheets provide up to 200 different characteristics of a product. This large amount of information makes it difficult if not impossible to gain and maintain a comprehensive overview.

In order to select meaningful characteristics here, we refer to a globally respected source: ISO 10350: “Plastics – Acquisition and presentation of comparable single-point data, molding materials” (see Table 3.1). The reference to this standard will also determine the order in which we will describe specific characteristics in this chapter. Another important standard is ISO 11403: “Plastics – Acquisition and presentation of comparable multipoint data, mechanical properties” (see Table 3.2).

Table 3.1 CAMPUS Characteristic Data Catalog According to ISO 10350

Property	Symbol	ISO-(IEC)-standard	Specimen (in mm)	Unit	Notes
Rheological characteristics					
Melt volume rate	MVR	1133	Compound	$cm^3/10$ min	
Mold shrinkage *parallel*	S_{Mp}	294-4 (thermoplastics) 2577 (thermosets)	60 · 60 · 2	%	See ISO 294-3, thermoplastics and ISO 10724-2, thermosets
Mold shrinkage *normal*	S_{Mn}				
Mechanical characteristics, 23 °C					
Tensile modulus	E_t	527-1/2	ISO 3167 (multi-purpose specimen)	MPa	Elongation 0.05 to 0.25%
Yield stress	σ_y			MPa	
Yield strain	ε_y			%	
Nominal strain at break	ε_{tB}			%	After yield
Stress at 50% strain	σ_{50}			MPa	For specimens without σ_y up to $\varepsilon = 50\%$
Stress at break	σ_B			MPa	For specimen without yield
Strain at break	ε_B			%	For specimen without yield
Tensile creep modulus: 1 h	E_{tc} 1	899-1		MPa	Elongation 0.5%
Tensile creep modulus: 1000 h	E_{tc} 10^3				
Charpy impact strength, unnotched at + 23 °C	a_{cU} + 23	179/1eU	80 · 10 · 4 (general purpose specimen)	kJ/m^2	
at − 30 °C	a_{cU} − 30				
Charpy impact strength, notched at + 23 °C	a_{cA} + 23	179/1eA			
at − 30 °C	a_{cA} − 30				
Tensile impact strength at + 23 °C	a_t 1	8256/1	80 · 10 · 4 (multi-purpose specimen) with double V-notch	kJ/m^2	When Charpy impact strength cannot be determined

Table 3.1 CAMPUS Characteristic Data Catalog According to ISO 10350 (continued)

Property	Symbol	ISO-(IEC)-standard	Specimen (in mm)	Unit	Notes
Puncture impact properties at + 23 and − 30 °C	F_M	6603-2	60 · 60 · 2	N	
Max. force at + 23 and − 30° C	W_P			J	
Thermal characteristics					
Melting temperature	T_m	11357-1 and -3	Material	°C	Temperature increase 10 K/min
Glass transition temperature	T_g	11357-1 and -2			
Temperature of deflection under load at 1.8 MPa	T_f 1.8	75-1/2	80 · 10 · 4 (multi-purpose specimen)	°C	Select 1.8 MPa and a second load level
at 0.45 MPa	T_f 0.45				
at 8.0 MPa	T_f 8.0				
Vicat softening temperature	T_v 50/50	306	≥ 10 · 10 · 4 (multi-purpose specimen)	°C	Temperature increase 10 K/min, load increase 50 N
Coefficient of linear thermal expansion, parallel	α_p	11359-1/2	Center of 80 · 10 · 4 (multi-purpose specimen)	E -6/K	Increase in elongation between 23 and 55 °C
Normal	α_n				
Burning behavior, 1.5 mm thickness	B50/1.5 B500/1.5	60695-11-10	125 · 13 · 1.5 ≥ 150 · 150 · 1.5	Class	Classes for B50: V-0, V-1, V-2, HB Classes for B500: 5VA, 5VB, N
-.- mm thickness	B50/-.- B500/-.-	60695-11-10/-20	125 · 13 · 1.5 ≥ 150 · 150 · 1.5		
Oxygen index	OI23	4589-1/2	80 · 10 · 4 (multi-purpose specimen)	%	Method A: Ignition at upper surface

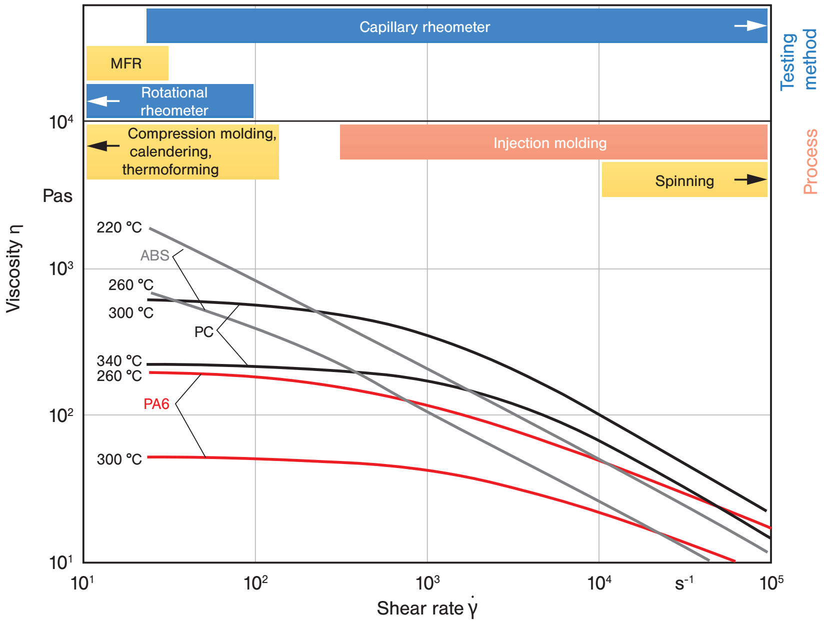


Figure 3.2 Melt viscosity of selected thermoplastics at normal upper and lower permissible melt temperature, respectively

Temperature also influences viscosity: with decreasing temperature the viscosity will increase. Figure 3.2 also shows the shear rate ranges encountered in different processing technologies and identifies the testing methods used for their determination. Figure 3.3 shows the order of magnitude of possible variations in the viscosity curves for ABS at constant temperature. Flow path calculations based on these viscosity curves resulted in variations of up to 30%. This example shows that caution is warranted when operating with averaged values for rheological data. They should be used exclusively for comparisons between material classes – never as the basis for design or dimensioning.

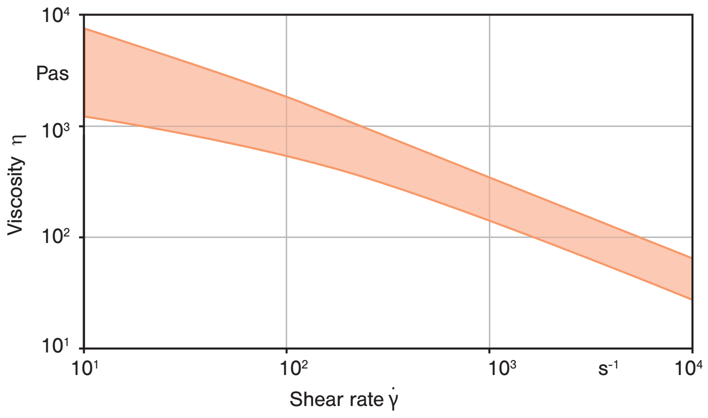
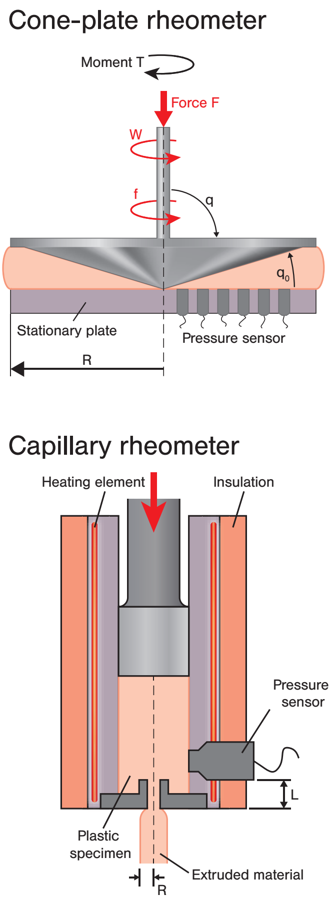


Figure 3.3 Viscosity curve range for ABS at 240 °C

Figure 3.4 shows the two most commonly used rheometer designs and their areas of application. Rotational rheometers, such as the depicted cone-plate system, facilitate measurements at low shear rates. These typically complex measurements allow for the fundamental analysis of rheological phenomena, such as principal stress differences and the derivation of rheological models, because they detect changes on the molecular level. Shear viscosity, which is a processing relevant parameter, is typically measured using capillary rheometers. It is determined at constant temperature by measuring the material exiting a capillary at a specific pressure.



Shear rate range that can be experimentally measured	Material functions to be determined
$(10^{-6}$ to $10^{2})s^{-1}$	Rotating operation: $\tau, \eta = f(T, p, \dot{\gamma}, t)$ Oscillating operation: $\eta', \eta''; G', G''$
$(10^{1}$ to $10^{6})s^{-1}$	$\tau, \eta, \sigma = f(p, T, \gamma)$

T	= Temperature	°C
t	= Time	s
p	= Pressure	Pa
σ	= Tensile stress	Pa
τ	= Shear stress	Pa
γ	= Shearing	m
$\dot{\gamma}$	= Shear rate	$m \cdot s^{-1}$
η	= Viscosity	Pa · s
G	= Shear modulus	Pa
η'; G'	= Elastic part	Pa · s
h''; G''	= Viscous part	Pa · s

Figure 3.4 Rheometer types

Online- and inline rheometers help monitor both injection molding and extrusion processes. While in the past partial flows were sampled from the volume flow (bypass principle), today viscosity is measured directly in the main volume flow. In order to do this, pressure and temperature sensors are placed along the flow length that allow to calculate the viscosity taking into consideration the time of contact with the flow front, the pressure drop, and the geometric dimensions of the cavity. However, this approach is possible only at the shear rate predetermined by the process.

Figure 3.5 shows the flow curves of different plastics with Fig. 3.5 a) showing the viscosity curves of polyolefins with different flow behaviors. The easy flowing grades exhibit lower viscosities. Many plastics contain additives, such as flow promoters or color pigments, which affect processing behavior as well as product properties (*e. g.*, color). As seen in Fig. 3.5 b), the addition of white pigments (TiO_2) increases the viscosity of the compound [1]. The data also indicate that this effect is more pronounced for particles with larger diameters. The increase in viscosity caused by the addition of fillers is also dependent on the viscosity of the plastic itself: the lower the viscosity, the higher the increase in viscosity. This is further illustrated in Fig. 3.5 c) in the case of an easy flowing PE-LD [1]. The viscosity of plastic grades that are offered by the manufacturer already compounded with color pigments typically matches that of the base (uncolored) grade. For master batches however, the processing conditions have to be adjusted accordingly by the processor. Figure 3.5 d) illustrates the effect of fillers with even larger particles, such as fibers or the copper platelets shown here, as a function of temperature [2]. At high temperatures the filler content has less influence than at lower temperatures.

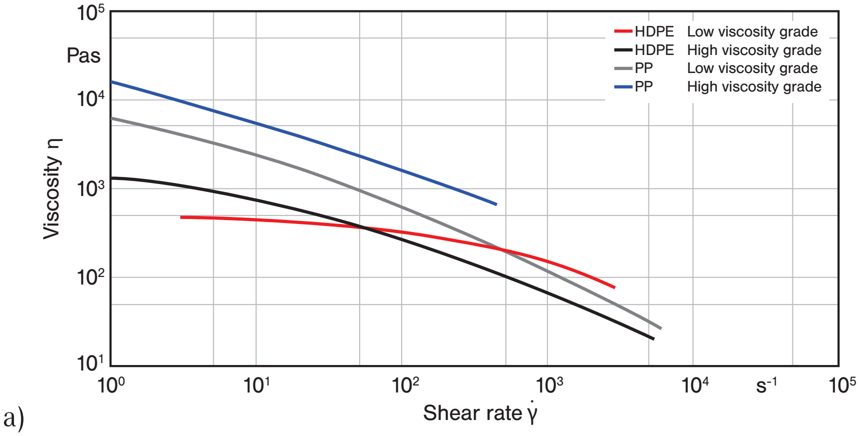


Figure 3.5 Flow curves of selected plastics

This model can be used over a wide range of shear rates because it also covers the shear rate-independent behavior at low shear rates. In its more complex variation, the model may also be used to represent the second Newtonian plateau. At high shear rates the completely stretched molecular chains also exhibit shear-independent behavior. Given the fact that this case is not relevant in industrial practice, simulation uses the model in the form presented in Eq. 3.2.

Cross Model

Another model that is able to represent the transition from zero shear to shear thinning viscosity is the Cross model:

$$\eta(\dot{\gamma}) = \frac{\eta_0}{1 + \left[\frac{\eta_0}{\tau}\dot{\gamma}\right]^{1-n}} \tag{3.3}$$

where η_0 is zero shear viscosity, τ describes the transition to the shear thinning region, and n is the flow exponent. Both models are used interchangeably in common simulation programs.

Temperature Dependency

The fact that viscosity is dependent on temperature is taken into consideration by two different approaches. For semi-crystalline plastics at high processing temperatures ($T > T_g + 100\,°C$), the Arrhenius approach is used:

$$a_T(T) = \exp\left(\frac{E_0}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right) \tag{3.4}$$

where E_0 is the activation energy, R is the universal gas constant, and T_0 is the reference temperature. For amorphous thermoplastics and lower temperature ranges between processing temperature and T_g, the Williams-Landel-Ferry (WLF) equation is used:

$$a_T(T) = \exp\left(\frac{-C_1(T - T_0)}{C_2 + T - T_0}\right) \tag{3.5}$$

where C_1 and C_2 are material constants and T_0 is the reference temperature. In both models, the shift factors are multiplied with the respective values of the zero shear viscosity. Both models also recognize the pressure dependency of the viscosity, a factor that is the particular focus of scientific research. However, because there are only few experimental characteristic data available, the pressure shift factor is typically not considered.

3.2.1.3 Melt Volume Flow Rate (MVR) and Melt Mass Flow Rate (MFR)

The melt volume flow rate (MVR) is used as a comparative index for the flow behavior of a melt; however, it is not suitable for its calculation. It is defined as the volume of melt exiting a capillary with defined dimensions within 10 minutes (cm^3/10 min) under given temperature and pressure conditions (Fig. 3.7). Also commonly used is the melt mass flow rate, also called melt flow index, which is determined under the same conditions, but measured in g/10 min. The respective values can be easily converted using the melt density. When comparing such data, it is important to make sure they were determined under the same conditions, *i. e.*, under the same temperature and pressure.

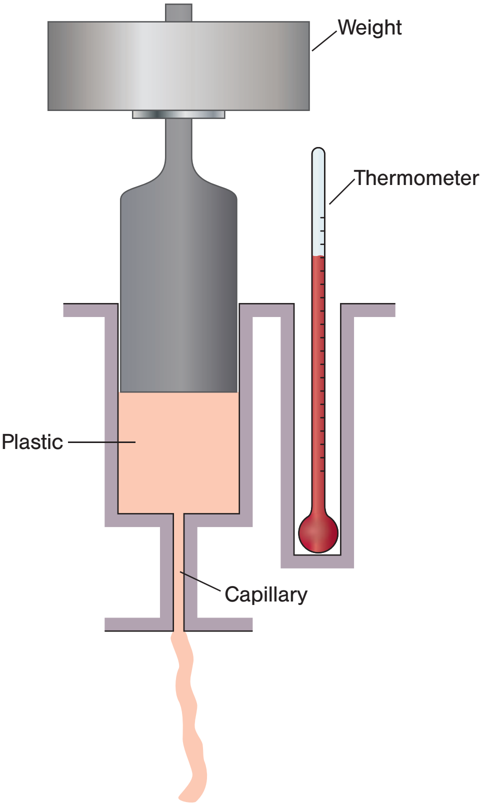


Figure 3.7
Schematic of melt volume flow measurement (flow indexer)

3.2.2 Solidification Behavior

3.2.2.1 Sealing Time

In industrial practice, the time until a molded component is solidified is determined by weight. Here, a series of tests is used to determine the duration of holding time after which the component weight no longer increases. It is not easy to haze number is a measure for haze. It is the ratio of scattered light reflected by the specimen at an angle of 80° to the axis of the incident ray to the almost perpendicularly impinging primary light. According to another definition (ASTM D 1003) haze is the portion of light transmitted by the specimen that deviates from the direction of incident light by more than 2.5°.

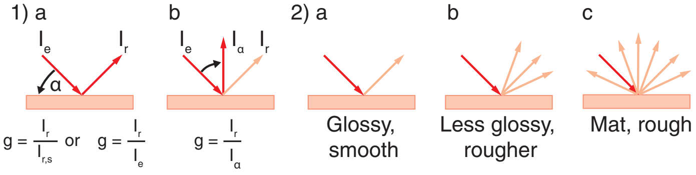


Figure 3.72 Left: Schematic illustration of different gloss measurement methods on plastic surfaces (1a and b); right: different types of surface reflection (2a: directed, 2b: dispersed, and 2c: diffused)

3.6.3 Color

3.6.3.1 Fundamentals

Color is a visual impression of a surface gained by an observer. In order to understand why a surface appears colored, the concepts of light, color, and complementary color have to be explained.

Visible light is comprised of electromagnetic waves with wavelengths ranging from 400 nm to 800 nm, and it is only a small region in the overall spectrum of electromagnetic waves. Every wavelength in this "visible region" corresponds to a specific color. "White light" is the composition of all wavelengths in the visible range.

Two colors are called complementary when their combination results in white light. A color circle can be used to determine the respective complimentary color. The color circle is filled with all possible color transitions.

When "white light" impinges on a colored surface, certain wavelengths are absorbed by the surface and free and/or bonding electrons in the pigments are excited so that the surface appears in its complementary color. The coloring effect of pigments is based on this phenomenon.

3.6.3.2 Colorimetry

Objective measuring methods are required to characterize color, *e.g.*, in quality control. For this purpose, the CIE-Lab system (Commission international de l'éclairage) is globally accepted. The intensity of the reflected light is recorded as a function of wavelength in so-called radiance curves. The colors are arranged in a horizontal plane similar to the color circle (with the only difference that we now know that the circle is in fact a quasi-elliptical), see Fig. 3.73. Here, all colors are represented in their maximum saturation. The additional z-axis represents the color intensity, shown in Figure 3.74. The perceivable color is defined by the coordinates L, a, and b.

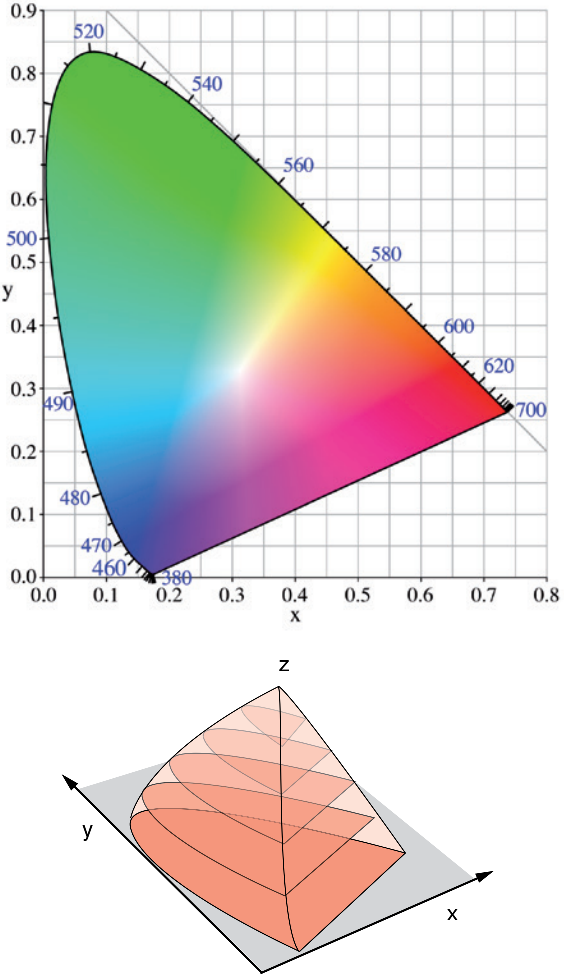


Figure 3.73 Above: CIE-standard chromaticity table; below: three-dimensional illustration of intensity

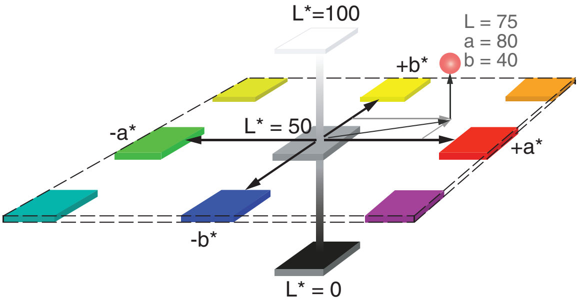


Figure 3.74 CIE-Lab system for color characterization

According to the theory of complimentary colors, green (a = −127) and red (a = +127) are opposite each other on the a*-axis. The b*-axis represents the complimentary colors blue (b = −127) and yellow (b = +127). The L*-axis is perpendicular to this plane and represents color intensity. Black (L = 0) and white (L = 100) are the terminal points, with shades of gray as intermediate values. If the a-component equals 0, only colors ranging from blue to yellow can be represented with intensities ranging from white to black. Analogously, colors from red to green are represented when the b-component equals 0.

3.6.4 Index of Refraction, Birefringence

When light passes from one medium into another, *e. g.*, from air into a plastic material, it is refracted. The degree of light refraction is characterized by the relative index of refraction of medium 2 with respect to medium 1.

$$n_{21} = \frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2} \tag{3.27}$$

where α and β are the angles that a light ray will form in the first and second medium with the axis of incidence, and c_1 and c_2 are the respective rates of propagation of light in these media. In general, indices of refraction refer to vacuum as the first medium. The speed of light c_0 in a vacuum is higher than in any other medium. Assuming the speed of light in a medium is *c*, and the index of refraction with respect to vacuum is *n*, we can calculate for light passing from a vacuum into a medium:

$$n = \frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2} \tag{3.28}$$

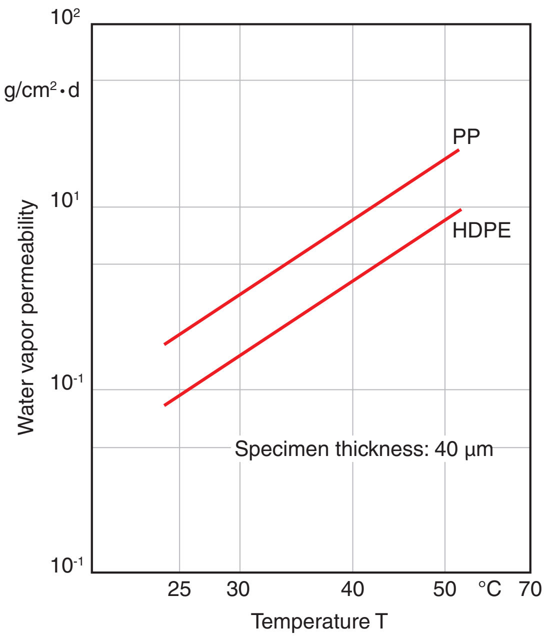


Figure 3.91
Water vapor permeability as a function of temperature

3.7.7.2 Gas Permeability

The gas permeability q is defined as the gas volume (reduced to standard conditions) that permeates through 1 m^2 of a plastic film within 24 h at a specified temperature and pressure differential:

$$q \text{ in} \left[\frac{\text{cm}^3}{\text{m}^2 \cdot 24\text{h} \cdot \text{bar}} \right] \quad \text{(ISO 2556)}$$

Again, the specimen thickness has to be specified. The permeability coefficient Q for gases is the permeability in relation to specimen thickness and pressure differential:

$$\text{Q in} \left[\frac{\text{cm}^3\text{(NTP)}}{\text{cm} \cdot \text{s} \cdot \text{mbar}} \right]$$

Permeability characteristics increase sharply with increasing temperature (Fig. 3.92) and depend strongly both on the measurement conditions and the kind and condition of the tested film. Published permeability values therefore offer only a qualitative standard of comparison. In critical applications, measurements of the actual product are required. Sometimes, different units are used for permeability values and permeability coefficients, see Table 3.10.

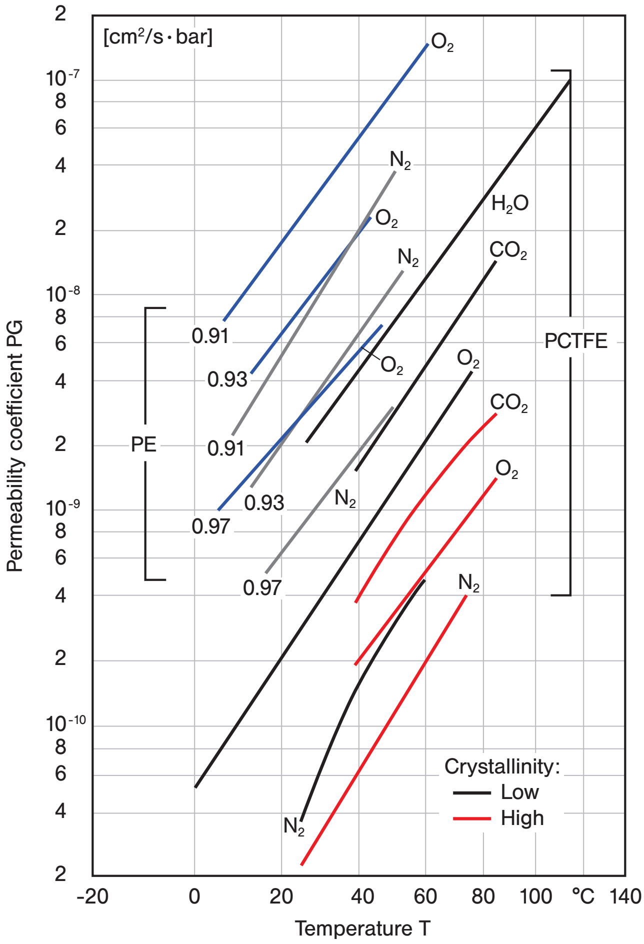


Figure 3.92 Permeability coefficients for selected PE and PCTFE as a function of temperature

Table 3.10 Conversion Table for the Permeability Characteristics of Gases and Water Vapor

Parameter	Recommended unit	Conversion factor
Permeability coefficient	$1\,\dfrac{\text{cm}^3\cdot 100\ \mu\text{m}}{\text{m}^2\cdot\text{d}\cdot\text{bar}} \triangleq$	$10^{-2}\,\dfrac{\text{cm}^3\cdot 100\ \mu\text{m}}{\text{dm}^2\cdot\text{d}\cdot\text{bar}}$ $10^{-9}\,\dfrac{\text{cm}^2}{\text{d}\cdot\text{mbar}}$ $1.5\cdot 10^{-14}\,\dfrac{\text{cm}^2}{\text{s}\cdot\text{Torr}}$ $1.2\cdot 10^{-11}\,\dfrac{\text{cm}^2}{\text{s}\cdot\text{bar}}$ $10^{-11}\,\dfrac{\text{cm}^2}{\text{d}\cdot\text{Pa}}$
Gas permeability	$1\,\dfrac{\text{cm}^3}{\text{m}^2\cdot\text{d}\cdot\text{bar}} \triangleq$	$1.2\cdot 10^{-9}\,\dfrac{\text{cm}}{\text{s}\cdot\text{bar}}$ $12\cdot 10^{-6}\,\dfrac{\text{cm}^3}{\text{m}^2\cdot\text{s}\cdot\text{bar}}$ $10^{-4}\,\dfrac{\text{cm}}{\text{d}\cdot\text{bar}}$ $10^{-9}\,\dfrac{\text{cm}}{\text{d}\cdot\text{Pa}}$ $1.3\cdot 10^{-7}\,\dfrac{\text{cm}}{\text{d}\cdot\text{Torr}}$
Water vapor permeability	$1\,\dfrac{\text{g}}{\text{m}^2\cdot\text{d}} \triangleq$	$12\cdot 10^{-6}\,\dfrac{\text{g}}{\text{m}^2\cdot\text{s}}$ $12\,\dfrac{\mu\text{g}}{\text{m}^2\cdot\text{s}}$

Figure 3.93 provides an example for gas permeability showing the oxygen permeation of films; Fig. 3.94 shows the effect of temperature on gas permeability.

4.1.1 Mixing Processes

The properties of the finished product in almost all polymer processes depend in part on how well the material was mixed, and all processing methods include a mixing step of the base materials. For example, an integral part of a screw extruder is a mixing zone. In fact, most twin screw extruders are primarily used as mixing devices. Hence, a better understanding of the mixing process helps to optimize processing conditions and increase part quality.

The process of polymer blending or mixing is accomplished by distributing or dispersing a minor or secondary component within a major component serving as a matrix. The major component can be thought of as the continuous phase and the minor components as distributed or dispersed phases in the form of droplets, filaments, or agglomerates. When creating a polymer blend, one must always keep in mind that the blend will probably be re-melted in subsequent processing or shaping processes. Coalescence may compromise the finely dispersed structure created during compounding by causing phase separation. To avoid this problem, compatibilizers, which are macromolecules used to ensure compatibility in the boundary layers between the two phases, are common.

We distinguish between three general categories of polymer blends (for examples see Table 4.1):

- Homogeneous mixtures of compatible polymers,
- Single-phase mixtures of partly incompatible polymers, and
- Multi-phase mixtures of incompatible polymers.

The mixing process itself is defined by three fundamental mechanisms:

- Distributive mixing,
- Dispersive mixing, and
- Coalescence.

Table 4.1 Common Polymer Blends

Blends of compatible plastic materials	Natural rubber and polybutadiene Polyamides (*e.g.*, PA 6 and PA 66) Polyphenylene ether and polystyrene
Blends of partially incompatible plastic materials	Polyethylene and polyisobutene Polyethylene and polypropylene (< 5% PE in PP) Polycarbonate and polyethylene terephthalate
Blends of incompatible plastic materials	Polystyrene and polyethylene Polyamide and polystyrene Polypropylene and polystyrene

Distributive or laminar mixing of compatible materials describes the distribution of a component A in a matrix B. This distribution is achieved by imposing large strains on the material. This increases the interfacial area between the two or more phases and decreases the local dimensions, or striation thicknesses, of the secondary phases. Imposing large strains on the blend is not always sufficient to achieve a homogeneous mixture. The type of mixing device and the initial orientation and position of the two or more fluid components play a significant role in the quality of the mixture.

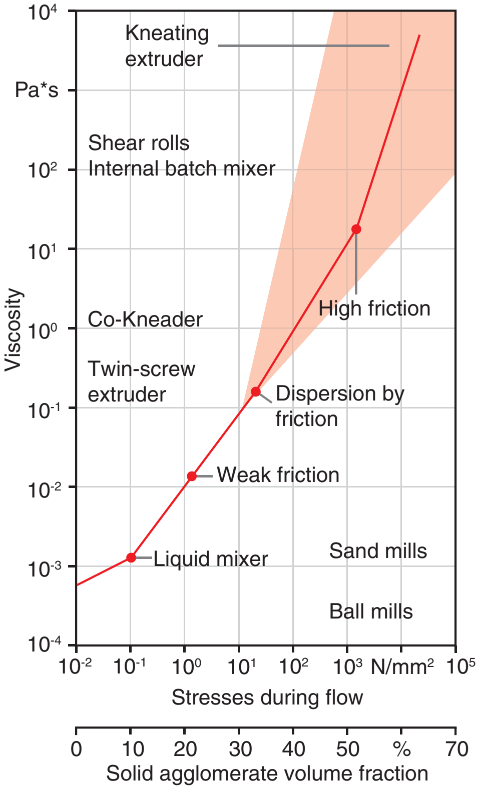


Figure 4.1
Use of dispersive mixing equipment depending on compound viscosity and volume fraction of solid agglomerates

Dispersive mixing in polymer processing involves breaking a secondary immiscible fluid or an agglomerate of solid particles and dispersing them throughout the matrix. Here, the imposed strain is not as important as the imposed stress which causes the system to break up. Hence, the type of flow inside a mixer plays a significant role on the break-up of solid particle clumps or fluid droplets when dispersing them throughout the matrix. The most common example of dispersive mixing of particulate solid agglomerates is the dispersion and mixing of carbon black into a rubber compound. Figure 4.1 relates the viscosity of the compound to the volume fraction of the solid agglomerates and the type of mixing device. When breaking up a polymer melt within a matrix, *i. e.*, when compounding a polymer blend, the droplets inside the incompatible matrix tend to stay or become spherical because of the natural tendency of the drop to maintain the lowest possible surface-to-volume ratio. However, the flow field within the mixer applies a stress on the droplets, causing them to deform. If this stress is high enough, it will eventually cause the drops to elongate and finally break up. This phenomenon of dispersion and distribution continues to repeat itself until the stresses caused by the flow field can no longer overcome the surface tension of the ever smaller droplets that are formed.

The dispersion of solid agglomerates or melt droplets is most effectively achieved by stretching or elongational flow. Hence, devices that stretch the melt, instead of shearing it, lead to more effective mixers while significantly lowering energy consumption.

Coalescence describes the coming together of single drops, *e. g.*, by collision in the flow field. In essence, it is the opposite of dispersion. Depending on filler content and surface tension, coalescence may predominate dispersion. In this case, mixing will cause a coarsening of the blend morphology.

4.1.1.1 Mixing Devices

We generally distinguish between two categories of mixers:

- Discontinuous mixers and
- Continuous mixers.

Rotating Solid Particulate Mixers

The different designs have varying types of mixing drums and thus rely on different kinds of mixing mechanism. There are simple roll drums, drum hoop mixers, tumbling mixers (for larger volumes), double conical mixers, and V-mixers. They are used as pre-mixers for free flowing materials and additives to be further processed on screw kneaders, extruders, or injection molding machines. They are also used to post-mix and homogenize charges of final compounds and for subsequent drying operations.

Solid Particulate Mixers with Rotating Elements

This mixer type comes in a wide variety of designs. The internal impeller speeds range from less than 2 m/s to speeds up to 50 m/s. As the speed increases, so does the energy input and dispersion of the mixed components. However, that also makes the mixing process less gentle. These types of mixers can be discontinuous (Fig. 4.2) or continuous (Fig. 4.3). In continuous systems, the mixing impellers also impose a conveying action on the particulates or mixture.

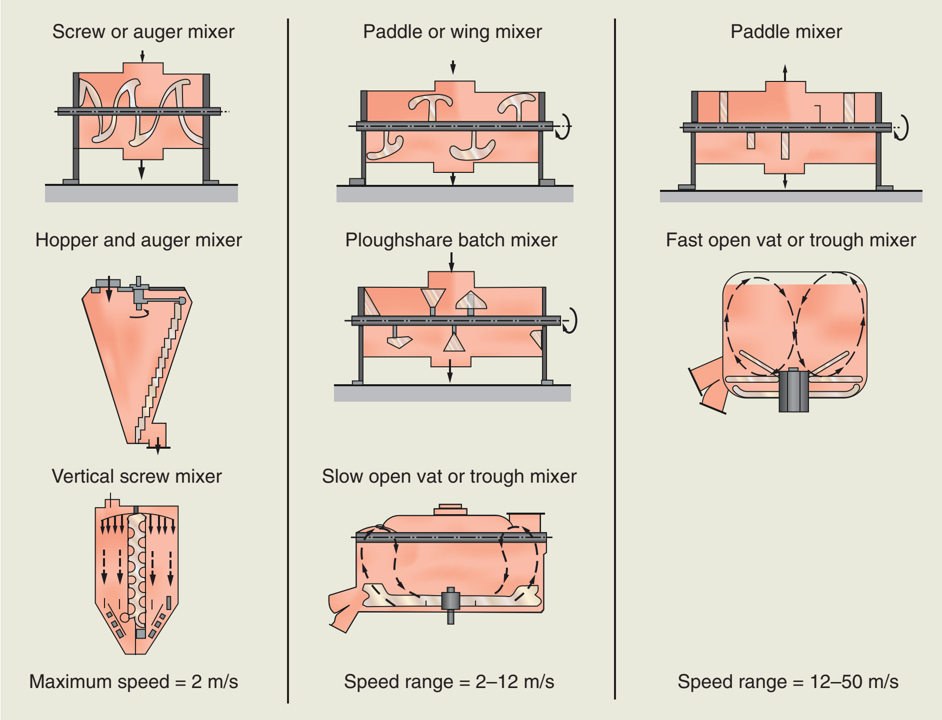


Figure 4.2 Solid particulate (discontinuous) batch mixing devices

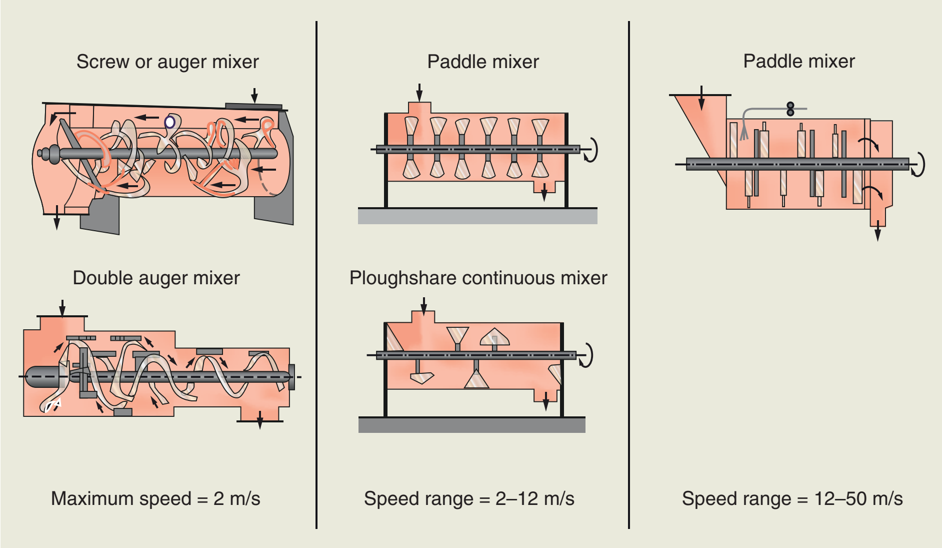


Figure 4.3 Solid particulate continuous mixing devices

products and thus improve product properties by introducing molecular and/or crystallite orientation in the direction of drawing. It is also possible to proceed with thermoforming operations immediately after the manufacture of plastic sheets or films, thus eliminating a heating process.

4.12 Plastic Joining

4.12.1 Plastic Welding

Plastic welding is defined as the joining of thermoplastic materials under heat and pressure (either with or without filler materials). The joining surfaces are heated to a temperature above the melt temperature and then joined under pressure to ensure a homogeneous joint. In general, only thermoplastics and thermoplastic elastomers can be welded because thermosets and crosslinked elastomers are not fusible and cannot flow. However, a material can still be welded if the crosslink density is not too high, *e.g.*, semi-crystalline crosslinked polyethylene. In this case, the bond is formed through crystallization across the joining area. Joining partners belonging to different plastic material types can only be welded if they have a certain chemical compatibility and if their melting temperatures are within a certain range.

When assessing the quality of welded joints, both leak tightness (pipes, containers, bags, packaging) and weld strength have to be considered. While leak tightness is typically determined using practical tests with welded components, test specimens are used to determine short- and long-term welding factors (quality factors). These factors provide the ratio of weld strength to strength of the parent material, and they range between 0.3 and 1. Weld quality factors always have to be listed together with the test procedure that was used to determine them because these procedures significantly influence the values of the factors. Common testing procedures are tensile, bending, flexural bending, flexural impact, tensile impact, and creep rupture tests, *e.g.*, of pipe joints under internal pressure. A welded joint may introduce a notch effect into the component. The heat introduced locally into the weld seam creates local changes in residual stresses which significantly affect the service life of a welded joint and may require testing of the long-term properties of a welded component. The quality of a welded joint is also affected by material and processing properties (residual stresses, crystallization, orientation) of the joining partners.

The different welding processes are categorized according to their type of external heat input (Fig. 4.119).

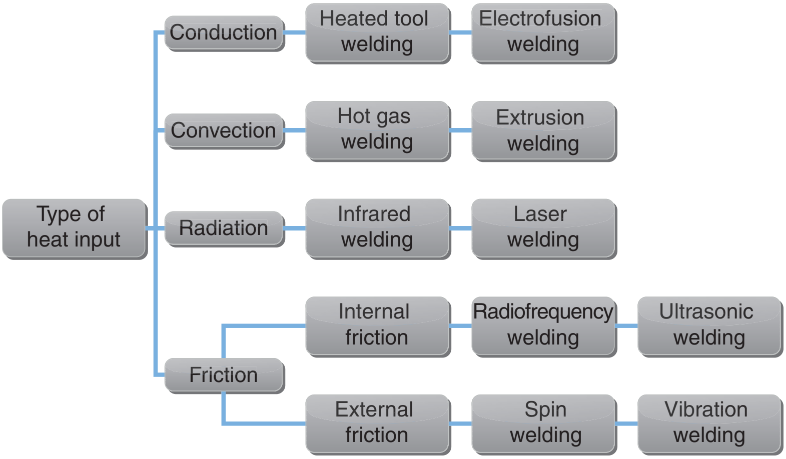


Figure 4.119 Welding of thermoplastics

4.12.1.1 Heated Tool Welding with Contact Heating

The joining areas are brought into direct contact with the metal hot plates (electrically heated to 180–300 °C, in special cases up to 550 °C) and are heated up under light pressure until a bulge of plastic molten material has been formed. After quick removal of the heated tool(s), the joining surfaces are pressed together with a pressure of 0.1 to 2 N/mm^2 so that molten material is pushed out of the joining area. The heating elements (typically made from Al-alloys) match the joining area and for temperatures up to 260 °C are coated with a PTFE anti-stick layer. To prevent scaling, they are either nickel or silver plated. When different materials are to be joined, the surface temperatures of the heated tools are adjusted to match the different melting temperatures of the plastic joining partners. The difference in surface temperature of the heated tools should not exceed 5 K.

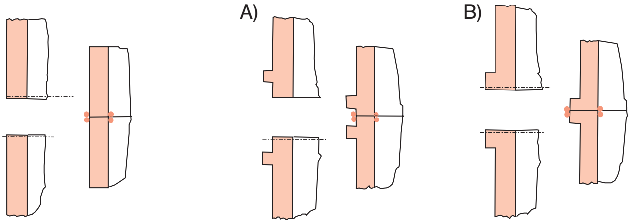
Heated tool welding equipment that can be used both on the shop floor and on-site allow for high quality welded joints. Here, the parts to be joined are clamped and guided, the heat reflectors are automatically swiveled, and the sequence of operations, heat reflector temperature, and contact pressure are controlled. Polyolefin semi-finished products in particular are manufactured this way:

- Welding and edge bending of plastic sheets using heated swords with lengths up to 2 m,
- Butt welding of pipes with diameters up to 1,400 mm,
- Welding of pipe fittings using heated tools that heat interior and exterior surfaces to be welded,
- Welding of components into sheets or pipes (Y-pipes),
- Mitered joints, *e.g.*, of PVC window frames,
- Joining of injection molded parts, *e.g.*, to form hollow parts and intake manifolds.

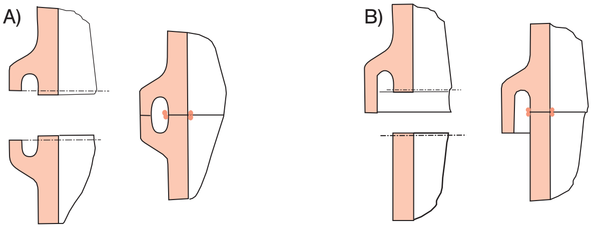
Heating muffles and mandrels are used to form and heat internal and external pipes for welded sleeves in a single operation. Figure 4.120 shows examples of typical joint designs.

1) Simple butt weld

2) Modified butt weld



3) Joint design for hidden butt welds



4) Butt welds for external attachments

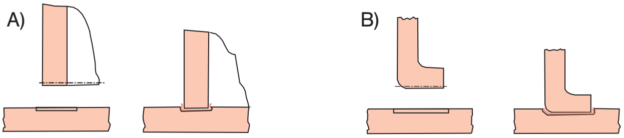


Figure 4.120
Joint design for heated tool welding

Socket welding with arc welding fittings is a special variation of heated tool welding. During injection molding, lost heating coils are internally imbedded in the socket and electrically heated. The plastic material's thermal expansion creates the welding pressure.

Lap joints of flexible sealing membranes for roofing and landfill applications are manufactured continuously by guiding the membranes over heated wedges and subsequently joining them using pressure rollers.

4.12.1.2 Heated Tool Welding with Non-Contact Heating

The processes have been developed in particular for films in the packaging industry. The overlapping films are placed between two tools with either one or both tools being heated. *Heat sealing* processes use constant heating at 150 to 250 °C. The heated tools are covered with PTFE-coated glass fiber fabrics and transfer heat through the film into the weld area. Weld seam quality is optimized by varying welding time and pressure. The fact that the welded seam does not cool while un-

5 Plastic Materials

5.1 General Remarks

Comparisons between different plastic materials will be based on characteristics provided in Table 3.1 in Section 3.1 (see also CAMPUS database or ISO 10350). For example, in general, no values for impact strength will be provided, because these values typically do not contribute significant information to either part design or a part's load bearing capacity, see also Section 3.3.3. As a general rule of thumb it can be assumed that parts made from resin types with a lower modulus of elasticity and a higher elongation at yield (elongation at break) will be more ductile (tougher) under excessive loads.

Unless particularly noted, specific property values are given for generic unmodified material classes. Because in general there will be no data provided for specific trade names, the property values given should be considered an indicating range. Specific material types may vary widely from these ranges, particularly regarding classifications such as "resistant" or "non-resistant" to environmental conditions.

5.2 Polyolefins (PO), Polyolefin Derivatives and Copolymers

Polyolefins are polymers built from hydrocarbons with a double bond and the general chemical structure C_nH_{2n} (ethene, propene, butene-1, isobutene). They include polyethylene, polypropylene, polybutene-1, polyisobutene, poly-4-methylpentene as well as their respective copolymers. Today, the available homo- and copolymeric resins based on ethylene and propylene provide an extraordinarily broad range of properties.

The polyolefin architecture is determined in particular by the catalysts used, with *metallocene catalysts* gaining increasing importance. Polymeric resins made with metallocene catalysts provide a narrow molecular weight distribution and their polymerization allows for a particular sequence and order of their monomer building blocks. In addition, it is possible to incorporate building blocks into the polyolefin structure that could not be incorporated previously by copolymerization.

5.2.1 Polyethylene Standard Homo- and Copolymers (PE-LD, PE-HD, PE-HD-HMW, PE-HD-UHMW, and PE-LLD)

Polyethylenes (PE) are semi-crystalline thermoplastic materials. Their structure, molecular weight, crystallinity, and thus their properties depend to a high degree on the polymerization method used and on possible chain branching options (see Section 2.3). The relative molecular weight and its distribution can be influenced by high thermal or mechanical stresses, which is typically avoided. The degree of crystallinity is determined by the structure of the polymer and the processing conditions. For industrial applications, ISO 1133 categorizes polyethylenes by their different densities, which depend on the respective degree of crystallinity of each specific PE grade. ISO 1872 is used internationally and specifies PE resins mainly by "*density*" and "*melt flow rate (MFR)*"*;* in addition, it uses a system of abbreviations indicating application, processing method, additives, fillers, and reinforcements. However, the characterization by these designations is inadequate in describing the properties and application ranges for the numerous PE grades available and is therefore rarely used in practice.

5.2.1.1 Polymerization, Chemical Constitution

In general, polyethylenes are produced either by high-pressure processes in the presence of radicals (radical polymerization) or by medium- and low-pressure processes with the help of catalyst systems (anionic polymerization). In addition, polyethylenes are classified as suspension-, solution-, gas phase-, or mass polymerization grades depending on their state. High-pressure processes are used for highly branched homopolymers (PE-LD), while medium- and low-pressure processes are used to synthesize linear homo- and copolymers (PE-HD, PE-MD, PE-LLD).

High-pressure process: PE-LD (LD = low density) is synthesized by a *high pressure process* from ethylene (CH_2=CH_2) under a pressure of 1,000 to 3,000 bar at 150 to 275 °C with 0.05 to 0.1% oxygen or peroxides as catalysts; synthesis occurs either discontinuously in stirrer vessels or continuously in pipe reactors. The result is a highly branched PE with side chains of different lengths. Its crystallinity ranges from 40 to 50%, its density from 0.915–0.935 g/cm^3, and it has a molecular weight average up to 600,000 g/mol. With the help of high-performance catalyst systems, PE-LD synthesis equipment can also produce linear low density PE (PE-LLD).

Medium- and low-pressure process: PE-HD (HD = high density) is synthesized by either a *medium-pressure* (Phillips method) or a *low-pressure process* (Ziegler method), both of which are suspension processes. The Phillips method uses pressures from 30 to 40 bar, temperatures from 85 to 180 °C, and chromium oxide or aluminum oxide as catalysts. The molecular weights obtained are approx. 50,000 g/mol. The *Ziegler method* uses pressures from 1 to 50 bar, temperatures from 20 to 150 °C, and titanium halides, titanium esters, or aluminum alkyls as catalysts, obtaining molecular weights ranging from 200,000–400,000 g/mol. PE-HD is almost unbranched and therefore has a higher degree of crystallinity (60–80%) and higher densities (0.94–0.97 g/cm^3) than PE-LD.

PE-HD-HMW (HMW = high molecular weight) with a density of 0.942–0.954 g/cm^3 and *PE-HD-UHMW* (UHMW = ultra-high molecular weight) with a density of 0.93–0.94 g/cm^3 offer high molecular weights together with their high densities. These resins are produced with special catalysts in a low-pressure process. The average molecular weight ranges from 200–500 kg/mol for PE-HD, from 500–1,000 kg/mol for PE-HD-HMW, and from 3,000–6,000 kg/mol for PE-HD-UHMW.

PE-LLD (LLD = linear low density) is polymerized with high-efficiency catalysts (metal complexes) in four different processes: a *low-pressure process* in the gas phase, in solution, in suspension, or in a *modified high-pressure process*. Copolymerization of ethylene with 1-olefins, such as butene-1 or hexene-1, creates short side chains. Compared to linear PE-HD, PE-LLD contains a higher ratio of comonomers. The higher molecular weight and the low number of side chains lead to improved properties of these resins.

PE-VLD (VLD = very low density) with a density of 0.905–0.915 g/cm^3 and *PE-ULD* (ULD = ultra low density) with a density of 0.890–0.905 g/cm^3 exhibit such a high degree of branching caused by their increased comonomer content that their densities decrease below 0.915 g/cm^3.

PE-(M) (polyethylene produced with metallocene catalysts) exhibits a narrow molecular weight distribution and can be produced in a broad range of densities. Although PE-MLLD (M) is of the same composition as “regular” PE-LLD, it shows a different sequence statistic. Transition metal compounds activated by methyl aluminoxanes are used as catalysts, typically with Ti- or Zr-centers linked with cyclopentadienyl residues.

The densities of PE-(M) grades range from

- PE-MLLD: 0.915–0.930 g/cm^3
- PE-MMD: 0.930–0.940 g/cm^3 (medium density)
- PE-MHD: 0.940–0.995 g/cm^3

In addition, it is possible to produce PE-MVLD with densities from 0.863–0.885 g/cm^3 (polyolefin-elastomers) and 0.866–0.915 g/cm^3 (polyolefin-thermoplastics).

5.17.3.2 Rigid Foams (PUR-R)

Rigid foams exhibit relatively high resistance to deformation under compression load. Their most important properties are their very low thermal conductivity caused by the insulating gases in the *closed cells* and their ability to form solid composites with almost any flexible or rigid skin layer. Rigid *foam blocks* are manufactured either continuously or in batch processes as semi-finished products and subsequently cut to measure depending on application. They range in density from 30–90 kg/m^3 and are used for various insulation applications, automotive interiors, and others.

Comparison of properties, see Table 5.48.

Foamed panels with protective outer skins are produced either continuously on double belt lines or discontinuously. The outer skins can be either flexible or rigid. Examples of carrier materials include Kraft paper, aluminum, particle or plaster boards, coiled steel or beaded sheet metal, and coated glass fiber mats. Areas of application are: building/construction as roofing insulation, sheet rock and plaster boards, sandwich elements for industrial buildings and cooling facilities. The core density of the foams ranges from 30–40 kg/m^3. Foams are introduced into hollow parts or hollow spaces as liquid reaction mixtures and fill these spaces after foaming. With densities from 30–60 kg/m^3 they serve as thermal insulators in cooling appliances of all sorts, for hot water boilers and district heating pipes. *In situ* foams for roofing and wall insulation, window- and door installation, and sealing is produced directly on site by mobile foaming machines or by pressure vessels from single- or two-component foam systems. Densities are ≈ 30 kg/m^3; spray foams for roof sealing purposes have densities up to 55 kg/m^3.

5.17.3.3 Integral Foams (PUR-I)

While flexible and rigid foams are fundamentally different in their chemical structure (highly crosslinked/little crosslinked), *integral foams* represent a *variation in production technology:* they are available both as rigid and as flexible *molded foams* only. The liquid, highly reactive mixture is injected into a closed mold, in which foam generation and mold temperature control are used to produce parts with cellular cores and solid skins. The transition from core to skin is not abrupt but rather continuous (see Fig. 5.20). This technique of foaming highly reactive PUR systems with particularly short holding times is generally called *reaction injection molding (RIM)*; it is used to produce both large parts as well as parts with minimum dimensions and with flow length-to-wall thickness ratios of up to 1 : 1000.

Flexible integral foams with densities from 200 to 1100 kg/m^3 are used for exterior body parts, bicycle seats, shoe soles, and others.

Rigid integral foams with comparable densities are used for technical parts, in construction, furniture, and sport- and leisure products of various designs and purposes.

Glass fiber reinforced integral foams (R-RIM) with densities from 1.0–1.4 g/cm^3 are used for automotive body parts and housings.

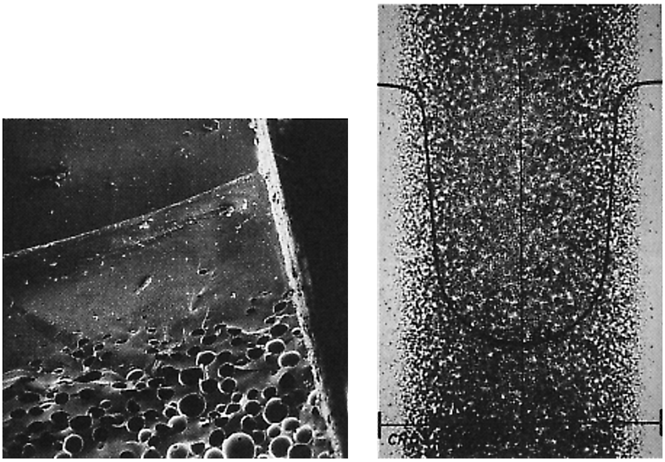


Figure 5.20 Integral foams
Left: Foam structure
Right: Density transition across specimen section

PUR-R-RIM is used to produce stiff, laminar parts, *e.g.*, automotive interior side panels. Long fibers, fabrics, non-woven material, or fiber mats, for which bio-renewable materials such as flax, sisal, or coir (coconut fibers) are increasingly used, are sprayed or impregnated with the PUR mixture and laid into the mold where they are compression molded.

Table 5.49 provides an overview of the properties of various integral foam systems, while Table 5.50 shows the dependency of certain properties on density and provides an example of flexible integral foam properties in automotive applications.

R-RIM parts (with 20–25% wollastonite reinforcement) can be coated in-line, *e.g.*, for exterior automotive panels. The plastic parts are connected to the car body prior to electro-immersion coating. Shrinkage is 0.8 or 0.57%, respectively, for temperature loads of 2 times 45 min at 200 °C. These systems are also suitable for thin-wall technology: automotive door sills with 2 mm thickness and a length of 2 m.

Table 5.49 Property Comparison for PUR Flexible Integral Foam, R-RIM

PUR-System	Filler	Filler content	Density	Shore-hardness	Flexural modulus of elasticity	Tensile strength	Elongation at break	Application, see below
		wt.-%	g/cm^3		MPa	MPa	%	
Flexible		0	1.05–1.10	D 66	500–760	26–33	135–150	A
	Glass flakes	20	1.20	D 75	1550	31	30	A
	Mica	22	1.25	D 75	1720	30	25	A
	Glass fibers, average fiber length 180 µm	15	1.20	D 68	950	31	140	A
		20	1.24	D 70	1400	28	130	A
		25	1.30	D 71	1700	27	120	A
Shoe soles		0	0.55–0.60	A 55–60		8–10	550–460	B
		0	0.60	A 60		25	600	C
Rigid	Glass mat 225 g/cm^2	30	0.25		250	5.8 [1]	2.3	D
	300 g/cm^2	20	0.48		900	25 [1]	2.2	E
	600 g/cm^2	20	1,0		3500	110 [1]	2.2	F
	1800 g/cm^2	32	1.4		650	170 [1]	2.8	G
S-RIM[2]		25	1,05		4200	70	1.9	H
LFI[3]		25–30	0.7–1.0		4500–6000	54–68	2.2–1.8	H

[1] Flexural strength; [2] Structural RIM; [3] Long fiber injection.

A Car panels

B Integral shoe soles

C Shoe soles

D Automotive roof linings

E Automotive roof frames, -columns/door-/seat-/trunk liners, rear window shelf

F Car dashboard frame, consoles, seat frame, seat-back, spare tire and engine cover

G Automotive seat shells and frames, bumper beams

H Sun roof

Table 5.50 Property Comparison of Flexible PUR Integral Foam in Automotive Applications (RIM)

Property	Unit	Application (see below)					
		A		B	C	D	
		Core	Skin				GF 22
Density	g/cm^3	0.120–0.175		0.7	0.95–1.08	1.0–1.1	1.22
Tensile strength	MPa	0.27–0.50	1.7–3.5	5.7	14–31	17–28	23
Flexural modulus	MPa			17	75–720	40–350	1300
Elongation at break	%	220–125	220–120	230	220–140	> 300–230	130
Shore hardness				A 75	D 39–69	D 33–57	D 67

Application: Type A: Motorcycle seats, interior automotive safety equipment
Type B: Bumper skins, door protection strips
Type C: Bumpers, truck splash boards, external automotive body parts
Type D: Car body parts

5.19 Thermoplastic Elastomers (TPE)

Acronyms, see Table 5.56.

Table 5.56 Overview of Thermoplastic Elastomers

Acronym	Chemical description
TPE	**Thermoplastic elastomers**
TPA	**Polyamide TPE**
TPA-EE	TPA, soft segments with ether- and ester bonds
TPA-ES	TPA with polyester soft segments
TPA-ET	TPA with polyether soft segments
TPC	**Copolyester TPE**
TPC-EE	TPC, soft segments with ether- and ester bonds
TPC-ES	TPC with polyester soft segments
TPC-ET	TPC with polyether soft segments
TPO	**Olefin TPE**
TPO-(EPDM+PP)	Ethylene/propylene/diene + polypropylene
TPO-(EVAC+PVDC)	Ethylene/vinyl acetate + polyvinylidene chloride
TPS	**Styrene TPE**
TPS-SBS	Styrene/butadiene block copolymer
TPS-SIS	Styrene/isoprene block copolymer
TPS-SEBS	Styrene/ethene/butene/styrene block copolymer
TPS-SEPS	Styrene/ethene/propene/styrene block copolymer
TPU	**Urethane TPE**
TPU-ARES	Aromatic rigid segments, polyester soft segments
TPU-ARET	Aromatic rigid segments, polyether soft segments
TPU-AREE	Aromatic rigid segments, soft segments with ether and ester bonds
TPU-ARCE	Aromatic rigid segments, polycarbonate soft segments
TPU-ARCL	Aromatic rigid segments, polycaprolactone soft segments
TPU-ALES	Aliphatic rigid segments, polyester soft segments
TPU-ALET	Aliphatic rigid segments, polyether soft segments
TPV	**TPE with crosslinked rubber**
TPV-(EPDM-X+PP)	Highly crosslinked EPDM + PP
TPV-(NBR-X+PP)	Highly crosslinked acrylonitrile/butadiene
TPV-(NR-X+PP)	Highly crosslinked natural rubber + PP
TPV-(ENR-X+PP)	Highly crosslinked epoxidized natural rubber + PP
TPV-(PBA-X+PP)	Crosslinked polybutylacrylate + PP
TPZ	**Other TPEs**
TPZ-(NBR+PVC)	Acrylonitrile/butadiene rubber + polyvinyl chloride

5.19.1 Physical Constitution

TPEs combine the elastomeric properties of crosslinked elastomers with those of rubbers (see Section 5.22) with the advantage of thermoplastic processability.

Their composition allows the classification in two groups:

Polymer blends consist of a “rigid” thermoplastic polymer matrix, into which either non-crosslinked or crosslinked elastomer particles are incorporated as a “flexible phase”. Examples are thermoplastic polyolefin elastomers (TPO or TPV) that consist of PP with up to 65% of incorporated ethylene-propylene-[diene] rubber (EP[D]M).

Graft- or copolymer molecules contain thermoplastic sequences A and elastomeric sequences B. Both components A and B are incompatible and demulsify locally so that the rigid A sequences form physical crosslinking points in the continuous matrix of flexible B sequences. An example is styrene block copolymer TPS, in which blocks of polystyrene (S) and butadiene (B) alternate: SSSSSSSS-BBBBBBBB-SSSSSSSS.

At service temperature, the flexible B sequences are above their glass transition temperature (freezing point); however, the rigid A sequences are below their glass transition temperature (for amorphous polymers) or their melt temperature (for semi-crystalline polymers). Above their transformation temperature, the A sequences soften so that TPEs can be processed like thermoplastics.

5.19.2 Chemical Constitution, Properties, Applications

Compared to rubbers, TPEs offer the following advantages: being suitable for thermoplastic processing and therefore also for recycling, weldability, transparency for some grades, colorability. An important area of application is therefore rigid-flexible combinations in 2-component injection molding (see Section 4.3.5.4) and in coextrusion (see Section 4.2.3.9). Table 5.56 provides an overview of acronyms and chemical designations, while Table 5.57 provides a comparison of properties.

Table 5.57 Property Comparison of Thermoplastic Elastomers (TPE)

TPE	Type	Density	Shore hardness		Service temperature °C			Glass transition temperature T_g	Resistance against[1]				
		g/cm^3	A	D	max. short-term	max. continuous	min. continuous	°C	Wear	Oil	Acid	Alkali	Aging
TPA	PA6	1.0–1.2	> 65	< 75		85	−60	80	2	1	2	2	2
TPA	PA12	1.1–1.3	> 85	< 85	150	120/150	−65	160/220	2	1	3	4	2
TPC[2]		0.9–1.0	> 50	< 70		115	−50	160	4	4	2	1	2
TPO	EVAC-PVDC		> 55	< 80	100		−40						
TPO	PP-EPDM-X	0.94–1.0	> 35	< 75	145	125	−50	160	3	3	1	1	1
TPV	PP-NBR-X		> 45	< 70	110		−40	160					
TPS	SBS	0.9–1.1	> 27	< 50	90	80	−40	95	2	4	2	2	2
TPS	SEBS		> 10	< 75	150	130	−50						
TPU	AREE	1.1–1.3	> 65	< 80	120	100/80	−50	130–200	1	1	3	4	1

[1] 1 = excellent, 2 = good, 3 = adequate, 4 = poor

[2] see also Table 5.30

5.19.2.6 Polyolefin Blends with Crosslinked Rubber (TPV)

These TPEs are crosslinked with flexible rubber segments. They exhibit increased elasticity and resistance. Oil-resistant and foamable grades are available. Applications: door- and window seals, air intake manifolds in automotive applications.

5.19.2.7 Other TPEs, TPZs

This category includes TPEs based on PVC with NBR [TPZ-(NBR + PVC)] or PBA [TPZ-(PBA + PVC)]. They are used for extruded seals. TPEs with crosslinked NBR are considered TPVs.

5.20 Thermosets, Curable Resins, Formaldehyde Molding Resins (PF, RF, CF, XF, FF, MF, UF, MUF, MUPF), Other Resins (UP, VE (PHA), EP, PDAP, SI)

Thermosets is a general term describing polymeric materials consisting of close-meshed, spatially crosslinked macromolecules. In general, these materials are rigid and behave as elastics up to their degradation temperature so that that they cannot be processed like thermoplastics. Molding and forming occurs either at the same time or prior to chemical crosslinking (curing).

Raw materials for thermosets are reaction resins (curable resins), which will react either at room temperature after the addition of curing agents or at elevated temperatures without curing agents. Curing can also be initiated by electron- or UV radiation.

Curable molding compounds are resins that can be processed by compression, transfer molding, extrusion, or (for special resins) by injection molding under simultaneous formation of macromolecules (crosslinking). They are filled and reinforced (some to a high degree). Delivery forms: dust-free grounds, pellets, free-flowing rods, and granules.

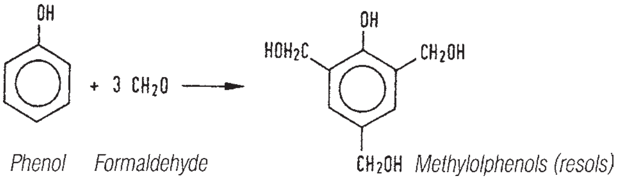
Prepregs (pre-impregnated) are laminar or tape-like materials, into which reinforcement in the form of mats, fabrics, or rovings can be incorporated (possible orientation from anisotropic to uniaxial).

5.20.1 Chemical Constitution

5.20.1.1 Formaldehyde Molding Resins (PF, RF, CF, XF, FF, MF, UF, MUF, MUPF)

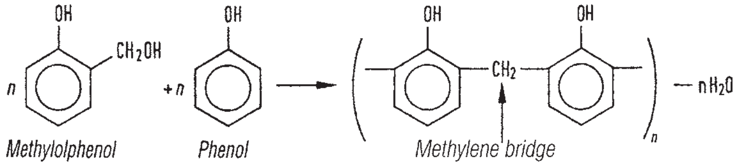
The polycondensation of formaldehyde resins will be exemplified by phenol formaldehyde (PF). It begins with fundamental reactions (see Eq. 5.34 to 5.36), which involve the formation of various cross-linkages during curing:

Addition to phenol alcohols:



(5.34)

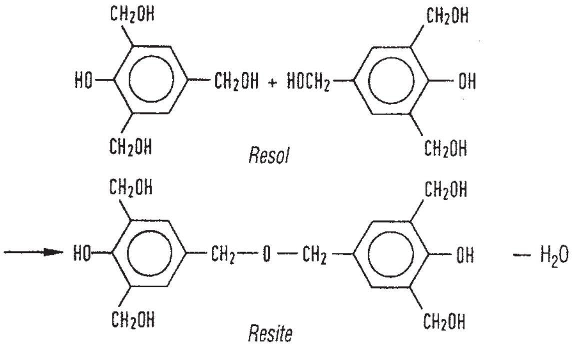
Condensation under elimination of water:



(5.35)

The condensation is performed step-wise to facilitate the escape of volatile reaction products. In stage “A” (resol), the reaction product is still soluble and can be melted. In stage “B” (resistol), the product can only be swelled and softens only at elevated temperatures, while in stage “C” (resite) complete crosslinking has occurred (Eq. 5.36). The product is insoluble and cannot be melted. The manufacturing of molded parts can be based on stage A resins, though mostly it is based on stage B resins.

Condensation with further elimination of water:



(5.36)

ISO 1043-4 classifies different flame retardant groups by code numbers, see Table 6.3. This identification is particularly important for components that are molded from recycled material and must not contain halogen-based flame retardants.

Table 6.3 ISO 1043-4 Codes for Flame Retardants

Code No.	Flame retardant
10–29	Halogen compounds (chlorine, bromine, fluorine)
30–39	Nitrogen compounds
40–49	Organic phosphorus compounds
50–59	Inorganic phosphorus compounds
60–69	Metal oxides, metal hydroxides, metal salts
70–74	Boron compounds and zinc compounds
75–79	Silicon compounds
80–89	Graphite, among others
90–99	Not assigned

6.1.5 Colorants

Colorants for plastics are comprised of specially compounded *insoluble pigments* and of plastic-*soluble dyes*. Figure 6.1 demonstrates the significance of pigments for the coloring of plastics compared to dyes. Pigments are classified as organic or inorganic depending on their chemical constitution. In contrast to pigments for special effects (see below), absorbing pigments reflect only the colors they do not absorb (subtractive color) so that the color impression is created by the complementary color.

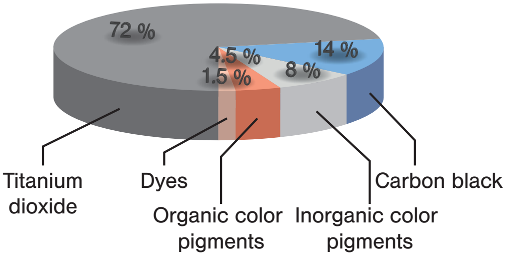


Figure 6.1 Proportions of different colorants in current applications

Because of their irregular form and light absorption, absorbing pigments exhibit only one color (independent of sight angle) and no gloss.

Inorganic pigments (Table 6.4) include metal oxides, sulfides, chromates, and carbon blacks (the latter are categorized as inorganic despite their chemical constitution).

Table 6.4 Inorganic Pigments

Pigment	Chemical family	Temp. resistance in PE-HD, °C	Chemical formula
White	Lithopone (zinc sulfide + barium sulfate)	300	$ZnS \bullet BaSO_4$
	Titanium dioxide (rutile-, anatase modification)	300	TiO_2
	Zinc oxide		ZnO
Black	Carbon blacks		
	Iron oxide black	240	Fe_3O_4, $(Fe,Mn)_2O_3$
	Spinel black	300	$Cu(Cr,Fe)_2O_4$, $Cu(Cr,Mn)_2O_4$, $(Fe,Co)Fe_2O_4$
Yellow/orange	Cadmium yellow1)	300	CdS, $(Cd,Zn)S$
	Chrome yellow1)	260/290	$PbCrO_4$, $Pb(Cr,S)O_4$
	Chrome rutile yellow	300	$(Ti,Sb,Cr)O_2$, $(Ti,Nb,Cr)O_2$, $(Ti,W,Cr)O_2$
	Iron oxide yellow	220/260	α-$FeO(OH)$, χ-$FeO(OH)$
	Nickel rutile yellow	300	$(Ti,Sb,Ni)O_2$, $(Ti,Nb,Ni)O_2$
	Bismuth vanadate/ molybdate	280	$BiVO_4Bi_2MoO_6$
	Zinc ferrite		$ZnFe_2O_4$
Brown	Chrome iron brown	300	$(Fe,Cr)_2O_3$
	Iron oxide(manganese-) brown	260/300	$(Fe,Mn)_2O_3$
	Rutile brown		$(Ti,Mn,Sb)O_2$, $(Ti,Mn,Cr,Sb)O_2$
	Zinc ferrite brown	260	$ZnFe_2O_4$
Red	Cadmium red/orange1)	300	$Cd(S,Se)$ $(Cd,Hg)S$
	Iron oxide red	300 (1200)	α-Fe_2O_3
	Molybdate red	260/300	$Pb(Cr,Mo,S)O_4$
Green/blue	Chrome oxide green	300	Cr_2O_3
	Cobalt (spinel) green	300	$(Co,Ni,Zn)_2(Ti,Al)O_4$
	Cobalt blue	300	$CoAl_2O_4$, $Co(Al,Cr)O_4$
	Ultramarine blue	300	$Na_8(Al_6Si_6O_{24})S_x$
Metallic	Aluminum	300	Al
	Copper	260	Cu/Zn alloys

1) Should be avoided because of Cd, Cr, or Hg content or only pigments with low soluble content should be used.

Azo- and polycyclic pigments among others represent the most significant families of *organic pigments*. All azo-pigments are characterized by their common azo-group (-N=N-), which is responsible for the selective absorption of light. Because the entire molecular structure determines the specific color of an azo-pigment, they cover a wide color spectrum, ranging from yellow, orange, brown, and red to violet. Some azo-pigments contain carcinogenic amine components and may therefore not be used for plastic coloration applications. Polycyclic pigments also cover a wide color spectrum, ranging from orange, brown, red, violet, and blue to green. Important representatives of polycyclic pigments include quinacridones (red) and phthalocyanines (blue/green).

Polyol dyes are used to color PUR foams. Here, chromophores (constituents of a dye with excitable electrons such as conjugated double bonds) are chemically bound to polymer chains with terminal hydroxyl groups that react with isocyanate. The results are homogeneously colored polyurethanes (foams, rigid and rubber-elastic components; the latter can also be manufactured with transparent coloration).

The following properties determine application and processing conditions of pigments: light and weather fastness, heat and chemical resistance. Other undesirable issues to be considered are warpage caused by pigments and migration of pigments to the surface of manufactured components. Pigments may also considerably affect flow, curing, and electrical properties. Compatibility with the plastic is another important criterion for the selection of suitable pigments. The coloration created by pigments is determined by particle size and distribution in the plastic. The smaller the particles, the more vivid the color. Inorganic pigments generally exhibit higher light fastness and better temperature resistance with low migration tendency. Organic pigments offer more luminous colors.

Several plastics yellow under UV exposure and are therefore not light/color fast as such. This results in a darkening, in particular of lighter colors.

Pigments are available in powder form; however, they are difficult to disperse in plastic materials. Therefore, plastics are often colored using pigment pastes with binders and/or plasticizers. These are available either as pelletized masterbatches or in liquid plastics.

Over the past decades, the colorant market has seen continuous increase in products that provide special optical effects in addition to coloring plastics. These products include metal and pearlescent pigments, fluorescent colorants, and last but not least optical brighteners.

Pigments for Special Effects

Pigments that provide metal and pearlescent effects are “special effect” pigments.

Metal pigments consist of small aluminum, bronze, or gold platelets that reflect light like mirrors. Pearlescent pigments are based on silicon or aluminum oxide platelets with thin (few nanometers thick) titanium or iron oxide layers. TiO_2-pearlescent pigments are often used. Pearlescent pigments partially reflect light directly at the smooth surface of the pigment, while another part of the

7

Material Properties

This chapter provides comparisons of the most important properties of plastic materials in table format. When possible, tables and charts referring to specific classes of plastic materials were placed in the respective chapter.

Because material names and properties have already been discussed in the previous chapters, this chapter will not offer additional explanations.

7.1 Processing Characteristics and Tolerances

Table 7.1 Processing-Relevant Characteristics for Selected Plastic Materials (Injection Molding)

Plastic material	Processing temperature °C	Pre-drying °C/h	Mold temperature °C	Shrinkage %	Length of flow path[1] at 2 mm wall thickness
PE-LD	160–220	–	20–60	1.5–5.0	550–600
PE-HD	180–250	–	10–60	1.5–3.0	200–600
EVAC	130–240	–	10–50	0.8–2.2	320
PP	200–270	–	20–90	1.3–2.5	250–700
PB	220–290	–	10–60	1.5–2.6 –	300–800
PIB	150–250	–	50–80	1.5–3.0	
PMP	280–310	–	ca. 70		
PS	170–280	–	10–60	0.4–0.7	200–500 –
SAN	200–260	85/2–4 –	50–80	0.4–0.7	200–500
SB	190–280	70–80/2[2]	10–80	0.4–0.7	320 –
ABS	200–275	70–80/2–4	50–90	0.4–0.7	
ASA	220–260		50–85	0.4–0.7	
PVC-U	170–210	–	20–60	0.4–0.8	160–250
PVC-P	160–190	–	20–60	0.7–3.0	150–500
PMMA	190–270	70–100/2–6	40–90	0.3–0.8	200–500
POM	180–230	110/2[2]	60–120	1.5–2.5	500
PA 6	240–290	80/8–15[2]	40–120	0.8–2.5	400–600
PA 66	260–300	80/8–15[2]	40–120	0.8–2.5	810
PA 610	220–260	80/8–15	40–120	0.8–2.0	–
PA 11	200–250	70–80/4–6	40–80	1.0–2.0	–
PA 12	190–270	100/4[2]	20–100	1.0–2.0	200–500
PA 6-3-T	250–320	80–90/10	70–90	0.5–0.6	–
PC	270–320	110–120/4	80–120	0.6–0.8	150–220
PET	260–300	120/4[2]	130–150	1.2–2.0	200–500
			20[3]	0.2[3]	
PBT	230–280	120/[2]	40–80	1.0–2.2	250–600
PPE + PS	240–300	100/2	40–110	0.5–0.8	260
PSU	340–390	120/5 –	100–160	0.6–0.8	–
PPS	320–380	160/5	20–200	ca. 0.2	–
PES	320–390		100–190	0.2–0.5	–
PVDF	250–270	–	90–100	3–6	–
PTFE	320–360	–	200–230	3.5–6.0	–
PFA	380–400	–	95–230	3.5–5.5	80–120

Table 7.1 Processing-Relevant Characteristics for Selected Plastic Materials (Injection Molding) (continued)

Plastic material	Processing temperature °C	Pre-drying °C/h	Mold temperature °C	Shrinkage %	Length of flow path1) at 2 mm wall thickness
PEEK	350–390	150/3	120–150	ca. 1 –	–
PAI	330–380	180/8	ca. 230	0.4–0.7	–
PEI	340–425	150/4	65–175	ca. 1	–
PEK	360–420	150/3	120–160		–
CA	180–220	80/2–4	40–80	0.4–0.7	350
CP	190–230	80/2–4	40–80	0.4–0.7	500
CAB	180–220	80/2–4	40–80	0.4–0.7	500
PF Type 31	60–80	–	170–190	1.2	–
MF Type 131	70–80	–	150–165	1.2–2	–
MF/PF	60–80	–	160–180	0.8–1.8	–
Type 180/82		–			–
UP Type 802	40–60	–	150–170	0.5–0.8	–
EP Type 891	ca. 70		160–170	0.2	
TPO	180–200	75/2 or 65/3	10–80	1.5–2.0	–
SBS	175–250	–	10–90	0.3–2.2	–
TPA	170–230	110/2–4 or 100/3–6	15–80	1.0–2.0	–
TPC	160–220				–
TPS	180–220				–
TPU	180–220	110/0.5 or 100/2	20–40	0.8–1.5	–

1) At average melt temperature, melt pressure, and injection mold wall temperature.
2) Not necessary when delivered in pre-dried form. 3) For amorphous grades

Additional Shrinkage Information

Plastic material	%	Plastic material	%
PP-GF 20	1.2–2.0	PBT-GF-30	0.5–1.5
PS-HI	0.4–0.7	PPE+PS-GF-30	0.2
SAN-GF 30	0.2–0.3	PSU-GF40	0.2–0.4
ABS-GF 30	0.1–0.3	PPS-GF-40	0.2
POM-GF 30	0.5–1.0	PES-GF-40	0.15
PA 6-GF 30	0.2–1.2	PEK	0.7–0.9
PA 66	0.2–1.2	PEK-GF-30	0.3–0.8
PET-A	0.2	PC-GF-30	0.2–0.4
PET-GF-30	0.2–2.0		

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