Erwin Baur
Tim A. Osswald
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Plastics Handbook

The Resource for Plastics Engineers

5th Edition

HANSER

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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*

Contents

1 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

Acronym	Chemical notation	Page #
PE	**Polyethylene**	338
PE-HD	Polyethylene-high density	338
PE-HMW	Polyethylene-high molecular weight	338
PE-LD	Polyethylene-low density	338
PE-LLD	Polyethylene-linear low density	338
PE-MD	Polyethylene-medium density	338
PE-UHMW	Polyethylene-ultra high molecular weight	338
PE-ULD	Polyethylene-ultra low density	338
PE-VLD	Polyethylene-very low density	338
PE-X	Polyethylene, cross-linked	346
PEA	Polyester amide	497
PEDT	Polyethylenedioxythiophene	528
PEEEK	Polyether ether ether ketone	483
PEEK	Polyether ether ketone	483
PEEKEK	Polyether ether ketone ether ketone	483
PEEKK	Polyether ether ketone ketone	483
PEI	**Polyetherimide**	495
PEK	Polyether ketone	483
PEKEEK	Polyether ketone ether ether ketone	483
PEKK	Polyether ketone ketone	483
PEN	**Polyethylene naphthalate**	474
PEOX	Polyethylene oxide	483
PESI	Polyester imide	497
PES	Polyether sulfone	478
PET	**Polyethylene terephthalate**	464
PET-G	**Polyethylene terephthalate, glycol modified**	464
PF	**Phenolic formaldehyde resin**	538, 557
PFA	Perfluoroalkoxy	408
PFMT	Polyperfluorotrimethyl triazine rubber	578
PFU	Polyfuran	528
PHA	Polyhydroxyalkanoate	526
PHB	Polyhydroxybutyrate	526
PHV	Polyhydroxy valeric acid	526
PI	**Polyimide**	488
PIB	Polyisobutene	370
PISO	Polyimide sulfone	495
PK	**Polyketone**	530
PLA	Polylactide	526
PMA	Polymethylacrylate	410
PMI	Polymethacrylimide	496

Acronym	Chemical notation	Page #
PMMA	**Polymethylmethacrylate**	411
PMMI	Polymethacrylmethylimide	416, 497
PMP	Poly-4-methylpentene-1	373
PMPI	Poly-m-phenylene isophthalamide	497
PMS	Poly-α-methylstyrene	375
PNF	Fluoro-phosphazene rubber	578
PNR	Polynorbornene rubber	571
PO	Polypropylene oxide rubber	575
PO	General notation for polyolefins, polyolefin-derivatives and -copolymers	337
POM	**Polyoxymethylene (polyacetal resin, polyformaldehyde)**	418
PP	**Polypropylene**	360
PPA	Polyphthalamide	453
PPB	Polyphenylene butadiene	528
PPE	**Polyphenylene ether, old notation PPO**	480
PPMS	Poly-para-methylstyrene	375
PPOX	Polypropylene oxide	483
PPP	Poly-para-phenylene	528
PPS	**Polyphenylene sulfide**	475
PPSU	**Polyphenylene sulfone**	478
PPTA	Poly-p-phenylene terephthalamide	497
PPV	Polyphenylene vinylene	528
PPY	Polypyrrole	528
PPYR	Polyparapyridine	528
PPYV	Polyparapyridine vinylene	528
PS	**Polystyrene**	375
PSAC	Polysaccharide, starch	520
PSU	**Polysulfone**	478
PT	Polythiophene	528
PTFE	**Polytetrafluoroethylene**	404
PTHF	Polytetrahydrofuran	483
PTT	Polytrimethylene terephthalate	472
PUR	**Polyurethane**	503
PVAC	Polyvinyl acetate	399
PVAL	Polyvinyl alcohol	399
PVB	Polyvinyl butyral	399
PVC	**Polyvinyl chloride**	385
PVDC	Polyvinylidene chloride	399

Acronym	Chemical notation	Page #
PVDF	**Polyvinylidene fluoride**	401
PVF	Polyvinyl fluoride	401
PVFM	Polyvinyl formal	399
PVK	Polyvinyl carbazole	399
PVME	Polyvinyl methyl ether	399
PVMQ	Polymethylsiloxane phenyl vinyl rubber	575
PVP	Polyvinyl pyrrolidone	399
PZ	Phosphazene rubber with phenoxy groups	578
RF	Resorcinol formaldehyde resin	538, 557
SAN	**Styrene acrylonitrile copolymer**	376
SB	**Styrene butadiene**	376
SBMMA	Styrene butadiene methyl methacrylate	376
SBR	Styrene butadiene rubber	569
SBS	Styrene butadiene styrene	376
SCR	Styrene chloroprene rubber	569
SEBS	Styrene ethene butene styrene	376
SEPS	Styrene ethene propene styrene	376
SI	Silicone, silicone resin	538
SIMA	Styrene isoprene maleic acid anhydride	376
SIR	Styrene isoprene rubber	571
SIS	Styrene isoprene styrene block copolymer	376
SMAB	Styrene maleic acid anhydride butadiene	376
SMAH	**Styrene maleic acid anhydride**	376
TCF	Thiocarbonyldifluoride copolymer rubber	577
TFEHFPVDF	Tetrafluoroethylene hexafluoropropylene vinylidene fluoride	407
TFEP	Tetrafluoroethylene hexafluoropropylene	408
TOR	Polyoctenamer	571
TPA	**Thermoplastic elastomers based on polyamide**	532
TPC	**Thermoplastic elastomers based on copolyester**	532
TPE	Thermoplastic elastomers	532
TPE-A	see TPA	532
TPE-C	see TPC	532
TPE-O	see TPO	532
TPE-S	see TPS	532
TPE-U	see TPU	532
TPE-V	see TPV	532
TPO	**Thermoplastic elastomers based on olefins**	532
TPS	**Thermoplastic elastomers based on styrene**	532
TPU	**Thermoplastic elastomers based on polyurethane**	532

Acronym	Chemical notation	Page #
TPV	**Thermoplastic elastomers based on cross-linked rubber**	532
TPZ	**Other thermoplastic elastomers**	532
UF	Urea formaldehyde resin	538
UP	**Unsaturated polyester resin**	538
VCE	Vinyl chloride ethylene	397
VCEMAK	Vinyl chloride ethylene methyl methacrylate	397
VCEVAC	Vinyl chloride ethylene vinyl acetate	397
VCMAAN	Vinyl chloride maleic acid anhydride acrylonitrile	397
VCMAH	Vinyl chloride maleic acid anhydride	397
VCMAI	Vinyl chloride maleic imide	397
VCMAK	Vinyl chloride methacrylate	397
VCMMA	Vinyl chloride methyl methacrylate	397
VCOAK	Vinyl chloride octylacrylate	397
VCPAEAN	Vinyl chloride acrylate rubber - acrylonitrile copolymer	397
VCPE-C	Vinyl chloride-chlorinated ethylene	397
VCVAC	Vinyl chloride vinyl acetate	397
VCVDC	Vinyl chloride vinylidene chloride copolymer	397
VCVDCAN	Vinyl chloride vinylidene chloride acrylonitrile copolymer	397
VDFHFP	Vinylidene chloride hexafluoropropylene copolymer	410
VE	Vinyl ester resin	538
VF	Vulcanized fiber	520
VMQ	Polymethylsiloxane vinyl rubber	575
VU	Vinyl ester urethane	542
XBR	Butadiene rubber, containing carboxylic groups	569
XCR	Chloroprene rubber, containing carboxylic groups	569
XF	Xylene formaldehyde resin	538,557
XNBR	Acrylonitrile butadiene rubber, containing carboxylic groups	570
XSBR	Styrene butadiene rubber, containing carboxylic groups	569

B: Common Plasticizers

Acronym	Chemical notation	Acronym	Chemical notation
ASE	Alkylsulfone acid ester	DODP	Dioctyldecyl phthalate
BBP	Benzyl butyl phthalate	DOP, DEHP	Dioctyl phthalate
DBA	Dibutyl adipate	DOS	Dioctyl sebacate
DBP	Dibutyl phthalate	DOZ	Dioctyl azelate
DBS	Dibutyl sebacate	DPCF	Diphenyl cresyl phosphate
DCHP	Dicyclohexyl phthalate	DPOF	Diphenyl octyl phosphate
DEP	Diethyl phthalate	DPP	Dipropyl phthalate
DHXP	Dihexyl phthalate	ELO	Epoxidized linseed oil
DIBP	Diisobutyl phthalate	ESO	Epoxidized soybean oil
DIDP	Diisodecyl phthalate	ODA	Octyl decyl adipate
DINA	Diisononyl adipate	ODP	Octyl decyl phthalate
DMP	Dimethyl phthalate	PO	Paraffin oil
DMS	Dimethyl sebacate	TBP	Tributyl phosphate
DNA	Dinonyl adipate	TCEF	Trichloroethyl phosphate
DNODP	Di-n-octyl-n-decyl phthalate	TCF	Tricresyl phosphate
DNOP	Di-n-octyl phthalate	TIOTM	Tri-iso-octyl trimellitate
DNP	Dinonyl phthalate	TOF	Trioctyl phosphate
DOA (DEHA)	Dioctyl adipate, also diethylhexyl adipate, DEHA no longer used	TPP	Triphenyl phosphate

1.2 Table II: Common Units, ISO- and US-Units

Length

		mm	m	km	in	ft	yd	mile
1 mm	=	1	10^{-3}	10^{-6}	0.0394	0.0033	–	–
1 m	=	10^{3}	1	10^{-3}	39.37	3.281	1.094	–
1 km	=	10^{6}	10^{-3}	1	39,370	3281	1094	0.6214
1 inch	=	25.40	0.0254	–	1	0.0833	0.0278	–
1 foot	=	304.8	0.3048	–	12	1	0.3333	–
1 yard	=	914.4	0.9144	–	36	3	1	–
1 statute mile	=		1609	1.609	–	5280	1760	1

Area

		cm^2	m^2	a	ha	km^2	in^2	ft^2	yd^2
1 cm^2	=	1	10^{-4}	–	–	–	0.155	–	–
1 m^2	=	10^4	1	0.01	10^{-4}	10^{-6}	1550	10.76	1.196
1 a	=	–	100	1	0.01	10^{-4}	–	1076	119.6
1 ha	=	–	10^4	100	1	0.01	–	–	–
1 km^2	=	–	10^6	10^4	100	1	–	–	–
1 square inch	=	6.452	–	–	–	–	1	–	–
1 square foot	=	929	0.0929	–	–	–	144	1	0.1111
1 square yard	=	8361	0.8361	–	–	–	1256	9	1

Volume

		cm^3	dm^3	m^3	in^3	ft^3	yd^3	gal (US)
1 cm^3	=	1	10^{-3}	10^{-6}	0.061	–	–	–
1 dm^3 [1)]	=	10^3	1	10^{-3}	61.02	0.0353	–	0.2642
1 m^3	=	10^6	10^3	1	61023	35.31	1.308	264.2
1 cubic inch	=	16.39	0.0164	–	1	–	–	–
1 cubic foot	=	–	28.32	0.0283	1728	1	0.037	7.841
1 cubic yard	=	–	764.6	0.7646	46656	27	1	202
1 gallon (US)	=	3785	3.785	–	281	0.1337	–	1

[1)] 1 Liter (l) = 1.0 dm^3

Force

			N	dyn^2	kp	
Newton	1 N	=	1	10^5	0.101972	
Kilopond [1)]	1 kp	=	9.80665	980 665	1	
Pound-force	1 lbf	=	4.44822		0.4536	kilogram-force (kgf) = kp

[1)] Unit no longer approved

Mass

		g	kg	t	oz	lb
1 g	=	1	10^{-3}	10^{-5}	0.0353	
1 kg	=	10^3	1	10^{-3}	35.27	2.205
1 t	=	10^6	10^3	1	–	2205
1 ounce (oz)	=	28.35	0.0284	–	1	0.0625
1 pound (lb)	=	453.6	0.4536	–	16	1

Metric carat 1 ct = 0.200 g for gemstones. For gold alloys, 1 carat represents $^1/_{24}$ mass fraction gold;
grain 1 gr = ($^1/_{700}$) lb = 0.0648 g

Pressure

Rounded values. The unit for pressure is Pascal (Pa)

	Pa = N/m^2	bar	kp/cm^2 = at	atm	Torr	lbf/in^2	
1 Pa = 1 N/m^2 =	1	10^{-5}	$10.2 \cdot 10^{-6}$	$9.869 \cdot 10^{-6}$	$7.5 \cdot 10^{-3}$	$145.05 \cdot 10^{-6}$	–
1 bar =	10^5	1	1.02	0.987	750	14.505	1 µbar = 1 dyn/cm^2 [1]
1 kp/cm^2 = 1 at = (techn. atmosph.)[1]	98 100	0.981	1	0.968	735.5	14.224	1 at = 10 m WS (4 °C)
1 atm = (phys. atmosph.)[1]	101 325	1.013	1.033	1	760	14.7	1 Torr = 1/760 atm
1 Torr[1] =	133.32	$1.333 \cdot 10^{-3}$	$1.36 \cdot 10^{-3}$	$1.316 \cdot 10^{-3}$	1	0.01934	1 Torr = 1 mm Hg (0 °C)
1 lbf/in^2 =	6894.8	0.6895	0.0703	0.06804	51.715	1	–

[1] Unit no longer approved

Energy (work, heat)

	J	kWh	kpm	PSh	kcal	Btu	Details
1 J = 1 Ws = 1 Nm = 1 kg m^2/s^2	1	$277.8 \cdot 10^{-9}$	0.101972	$377.5 \cdot 10^{-9}$	$238.8 \cdot 10^{-6}$	$984 \cdot 10^{-6}$	1 J = 1 Nm = 10^7 erg 1 eV = $1.602 \cdot 10^{-19}$ J
1 kWh =	$3.6 \cdot 10^6$	1	$367 \cdot 10^3$	1.360	859.8	3412	
1 kpm[1] =	9.80665	$2.724 \cdot 10^{-6}$	1	$3.704 \cdot 10^{-3}$	$2.342 \cdot 10^{-3}$	$9.294 \cdot 10^{-3}$	
1 PSh [1] =	$2.648 \cdot 10^6$	0.7355	$270 \cdot 10^3$	1	632.4	2509	
1 kcal [1] =	4186.8	$1.163 \cdot 10^{-3}$	426.9	$1.581 \cdot 10^{-3}$	1	3.968	
1 Btu = (British Thermal Unit)	1055	$293 \cdot 10^{-6}$	107.6	$398.5 \cdot 10^{-6}$	0.252	1	

[1] Unit no longer approved

Power

	W	kW	kpm/s	PS	hp	
1 W =	1	10^{-3}	0.101972	$1.36 \cdot 10^{-3}$	$1.341 \cdot 10^{-3}$	1 W = 1 J/s = 10^7 erg/s
1 kW =	10^3	1	101.975	1.36	1.341	
1 kpm/s[1] =	9.80665	$9.80665 \cdot 10^{-3}$	1	0.0133	0.0131	
1 PS[1] =	735.5	0.7355	75	1	0.986	
1 hp (horsepower) =	745.7	0.746	76.04	1.014	1	1 hp = 550 ft lbf/s

[1] Unit no longer approved

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).

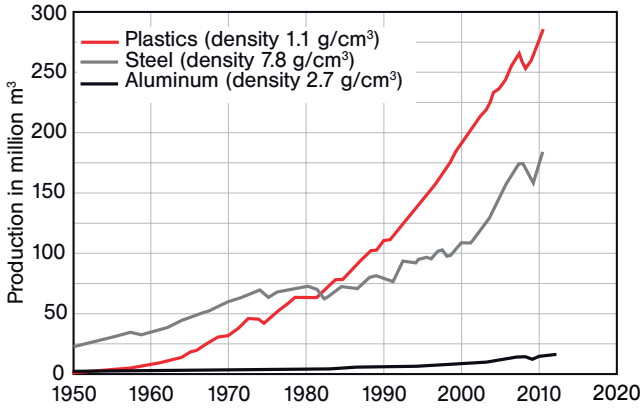

Figure 2.1 Production volume of various materials. Source: Plastics Europe, World Steel Association, The International Aluminium Association

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.

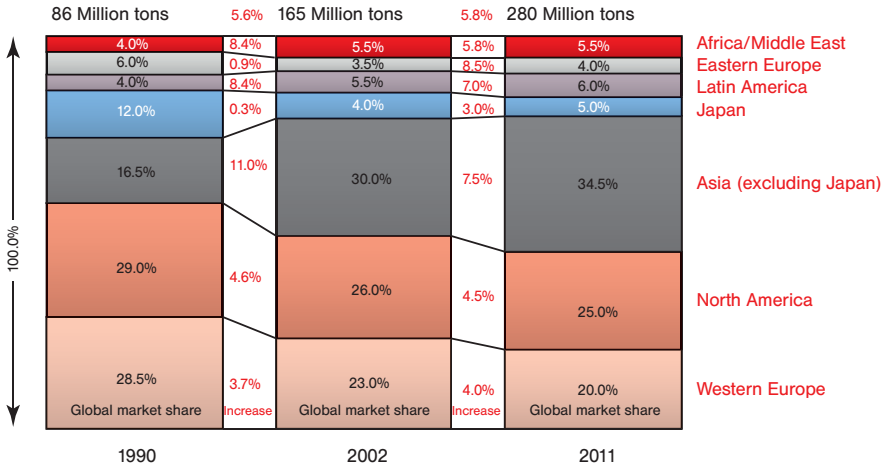

Figure 2.2 Global plastic production since 1990. Source: Plastics Europe

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.

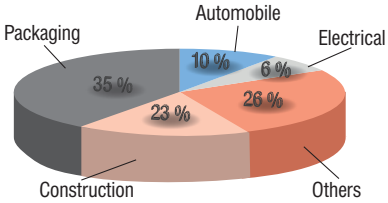

Figure 2.3
Main fields of application for plastics in Europe (2012)
Source: Plastics Europe

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.

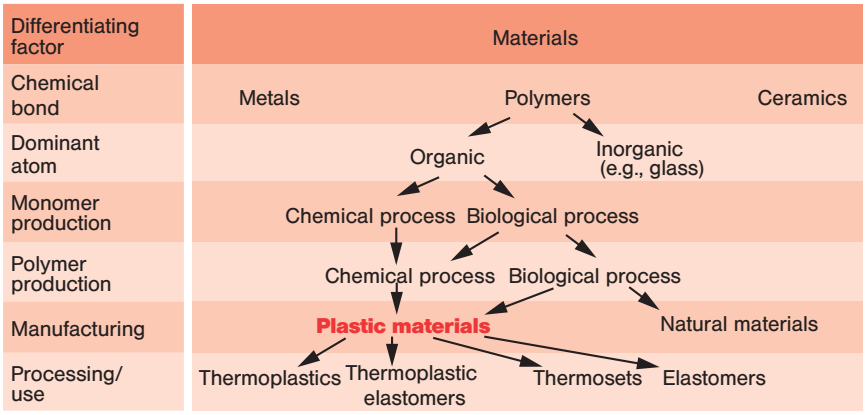

Figure 2.4 Classification of plastic materials in the general field of material science

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.

- The manufacturing costs of plastic parts are significantly determined by **material costs**. In addition to economic goals, ecological requirements are increasingly considered during material selection (see Chapter 5). Appropriate material selection and material-saving designs are effective approaches to achieve economic production and ecologically expedient plastic applications. Integration of functionalities also facilitates the reduction of processing steps and thus processing costs. Component design that allows for easy recycling offers additional benefits.

The majority of plastic materials are used in systems in which they perform structural, protective, or separating roles. Here, the mechanical properties of plastics materials play a dominant role.

Plastic materials are increasingly used as functional materials, *e.g.,* they are selected for specific applications because of their optical, electrical, or specific mechanical properties. These materials include UV-curing resins, photo-addressable macromolecules, and electrically switchable polymers. Generally, these materials are referred to as functional polymers (more precisely: functional plastics). They are locally placed in the component, *e.g.,* in layers or punctiform arrangements, and assume specific functions (*e.g.,* data storage). Growing importance is predicted for this group of materials in the future. Because they are currently used only in rather specific applications, these materials will not be covered in this book.

Historically, textiles are not covered in the field of plastics, because textile manufacturing traditionally utilized natural materials only. However, over the course of time, textile technology adapted manufacturing technologies geared towards plastic materials.

Also historically based is the differentiation between thermoplastic and thermoset materials on the one hand and elastomers on the other. However, the development of thermoplastic elastomers revealed that there was no technical rationale for this differentiation

In plastic processing we distinguished between three characteristic phases:

- Compounding,
- Processing,
- Post-processing and finishing.

During the compounding phase, the plastic raw materials or precursors are transformed into processable molding compounds. If a chemical reaction occurs during the processing phase, the molding material is a reactive precursor and fundamentally different from the final molding material. A second processing step is used, if necessary, to shape, machine, or weld semi-finished plastic parts into final products or to assemble components and/or semi-finished parts into finished products. During post-processing the parts may be finished (*e.g.,* by deflashing), surface

treated (*e.g.,* by printing, flocking, metal coating), or their material properties may be changed (conditioning, tempering), depending on application requirements. Molding compounds are available in different types and conditions: powder, chips, dry blends, agglomerates, pellets, prepregs, premix, paste (plastisol), solution, suspension, emulsion, and latex, among others.

2.3 Composition of Plastics

A material's properties are defined by its structure. Plastic materials offer the most structural variety of all materials used by man. Both synthetically produced plastics, plastics resulting from material conversion, as well as bio-plastics, such as proteins and carbohydrates, follow the same structural principles. Elementary knowledge of polymeric structure is necessary in order to navigate the field of plastics and rubbers and to assess material properties. In the following, we will present this knowledge in a concise but simple way that does not claim to be complete or go into academic depth. In the subsequent chapters, more detailed information on structure-property relationships will be provided.

2.3.1 Chemical Structure (Constitution and Configuration of Macromolecules)

Polymers are organic macromolecules consisting of many repeating units. They are synthesized from low-molecular units *(monomers)* by different polymerization reactions. The predominant types of chemical bonds in polymers are atomic bonds (covalent bonds). In very few cases we also see ionic bonds (electrovalence). If the concentration of ions results in water-soluble polymers, the ionic polymers are called *polyelectrolytes;* they are called ionomers if the concentration of ionic dissociated bonds leads to non-water-soluble polymers.

The atomic building blocks of polymers are primarily the non-metallic elements carbon (C), hydrogen (H), and oxygen (O). Nitrogen (N), chlorine (Cl), fluorine (F), and sulfur (S) *(heteroatoms)* are also recurrent elements in polymers. The so-called semi-organic polymers contain the metalloid elements silicon (Si) (in silicone and polysiloxane) and boron (B). Although other elementary compositions can sometimes be found in polymers, we will not discuss them in more detail here because of their very specific nature. The structural characteristics of the mentioned elemental building blocks define the properties common to all organic polymers:

- Low electrical conductance (electrical insulators),
- Low thermal conductance (thermal insulators),

- Low specific weight (density 0.8 to 2.2 g/cm^3),
- Limited thermal resistance, because the splitting of covalent bonds is irreversible.

In addition, the properties of final plastic parts and components are significantly influenced by the conformation configuration of the macromolecules.

2.3.1.1 Conformation

The conformation describes the preferential spatial positions of the atoms in a molecule, which is described by the polarity, flexibility, and regularity of the macromolecule. Typically, carbon atoms are tetravalent, which means that they are surrounded by four substituents in a symmetric, tetrahedral geometry.

The arguably best known example of a molecule with tetrahedral geometry is methane, CH_4, schematically shown in Figure 2.5. The figure shows that the tetrahedral arrangement of the substituents (here hydrogen) creates a bond angle of 109.5°. This angle is maintained between the carbon atoms in the macromolecule, as illustrated in Figure 2.5, right. The figure also shows that each axis of the carbon chain is able to freely rotate.

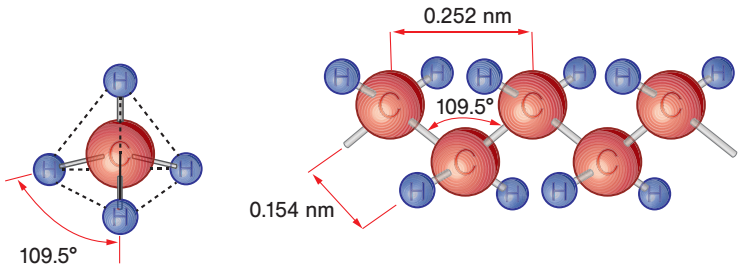

Figure 2.5 Left: schematic illustration of methane (CH_4); right: detail of a polyethylene molecule

2.3.1.2 Configuration

The configuration provides information about the distribution and spatial organization of the molecule. For polymers composed of asymmetric monomers it is possible to place the side groups on the carbon-carbon backbone in different directions during polymerization. The order in which they are arranged is called the tacticity. The polymers whose side groups are all on the same side are called isotactic and are assigned the suffix "I" as in polypropylene: PP-I. The polymers whose side groups are regularly alternating on both sides are called syndiotactic (*e.g.*, PP-S). Irregular arrangement of the side groups is called atactic or random configurations (*e.g.*, PP-R).

Figure 2.6 illustrates the three different tacticity cases for polypropylene. A polymer's tacticity determines the degree of crystallinity that it can reach. For example, polypropylene with a high isotactic content will reach a high degree of crystallinity, and as a result will be stiff, strong, and hard.

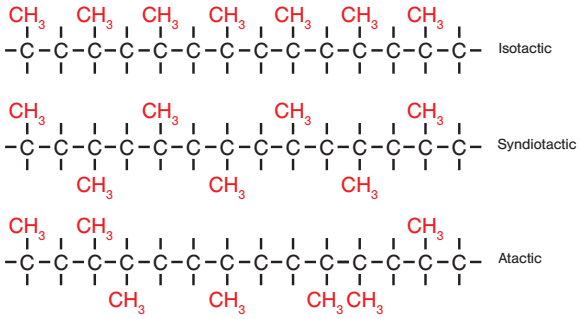

Figure 2.6 Different polypropylene configurations

Another type of geometric arrangement arises with polymers that have double bonds between carbon atoms. Double bonds restrict the rotation of the carbon atoms about the backbone axis, causing the formation of different, so-called stereoisomers. The side groups may be on the same side (cis-) or on opposite sides (trans-) of the chain, as schematically shown in Figure 2.7. The arrangement in a cis-1,4-polybutadiene results in a very elastic rubbery material, whereas the structure of the trans-1,4-polybutadiene results in a leathery and tough material. A cis-1,4-polybutadiene can be used to manufacture the outer tread of an automotive tire. A trans-1,4-polybutadiene can be used to make the outer skin of a golf ball. The same geometric arrangement is found in natural rubber, polyisoprene. The cis-1,4-polyisoprene is the elastic natural rubber used for the body of a tire, and the latex used to manufacture "rubber" gloves and condoms.

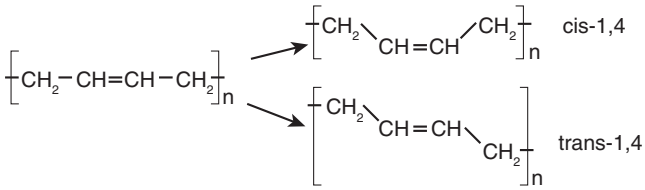

Figure 2.7 Chemical structure of cis-1,4- and trans-1,4-polybutadiene molecules

2.3.1.3 Constitution

Chemical reactions cause chain branching, and the type and length of the branches are determined by the type of polymerization reaction chosen. The chain branches influence the final structure, crystallinity, and thus the properties of the plastic material. Figure 2.8 schematically compares different molecular structures of polyethylene (PE).

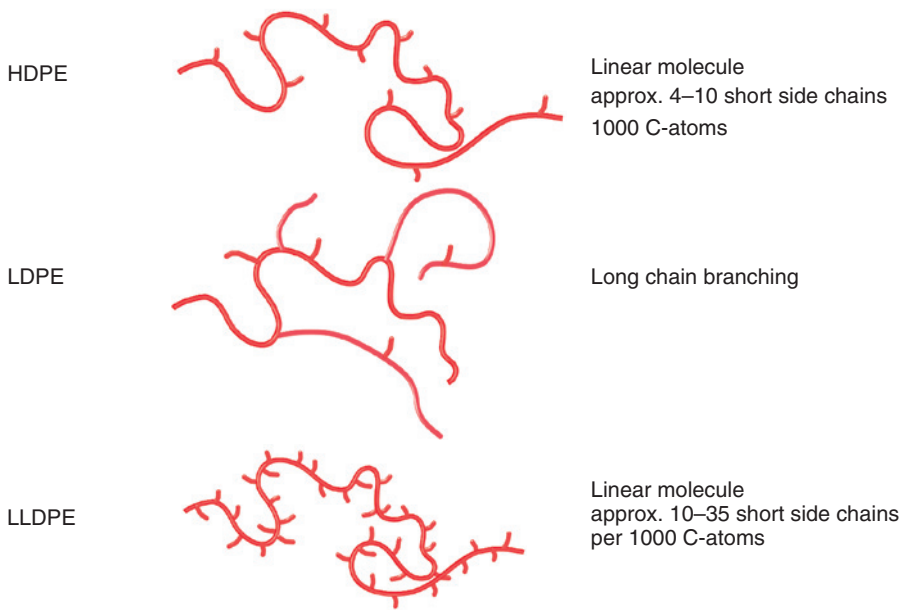

Figure 2.8 Molecular structure of various polyethylenes (schematic)

High density polyethylene (PE-HD) features between 4 and 10 short side chains per 1,000 carbon atoms. Low density polyethylene (PE-LD) has the same number of side chains; however, they are significantly longer and often branched themselves. Linear low density polyethylene (PE-LLD) features between 10 and 35 short side chains per 1,000 carbon atoms. Molecular chains with less and shorter side chains will crystallize more easily and therefore exhibit higher densities.

Other than by their structure, the properties of plastic materials are also determined by the molecular weight of the chains. For example, polystyrene (PS) with a polymerization degree of 1,000 (number of monomer units in the polymer) is stiff and brittle. With a polymerization degree of 10, PS is soft and tacky. Figure 2.9 illustrates the dependence of mechanical and rheological properties on molecular weight. The size of the molecular chains significantly influences the ability of a plastic material to flow in the molten state or in solution. Therefore, there are material characteristic values and functions describing the flow behavior of polymers that are directly correlated to molecular weight.

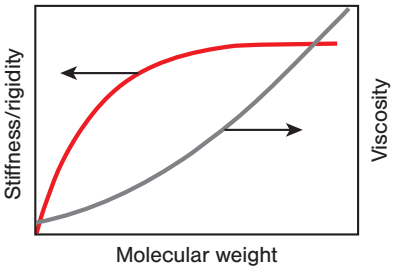

Figure 2.9
Influence of molecular weight on mechanical and rheological properties

High molecular mass imparts higher tensile strength to plastic materials, in particular under impact load. However, this effect is accompanied by higher viscosity, which reduces the material's ability to flow. Therefore, often compromises have to be found between processability (flow behavior) and service properties. In addition, certain processing technologies (*e.g.*, injection molding) require rather narrow molecular weight distributions in order to control the viscosity. Special molding compounds have been developed to meet these requirements.

The size of a macromolecule is an important structural parameter. The polymerization reactions of most synthetic linear polymers result in molecular chains of varying lengths. They consist of molecular fractions of different sizes, also called *polymolecular ("polydisperse") material systems*. There is no uniform molecular size; therefore, the specification of molecular mass (here: relative molecular mass) is always a statistical mean, or average value that depends on the distribution spectrum of the individual molecules and on the way the average value was determined. With the exception of some natural polymers, most polymers exhibit a molecular weight distribution similar to the one shown in Figure 2.10.

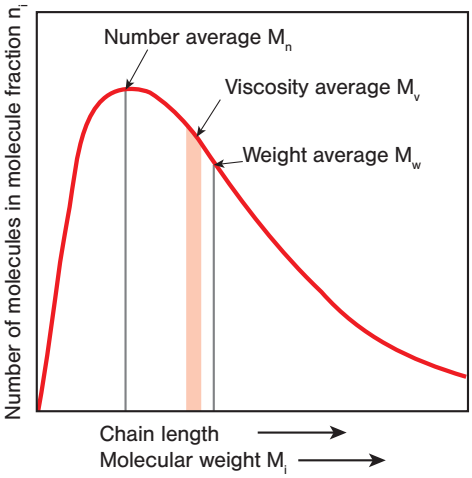

Figure 2.10
Molecular weight distribution of a typical thermoplastic material

For such a distribution function, we can define a number-, weight-, and viscosity average. In practical applications, the weight average (M_w) is more meaningful when investigating property correlations. The number average (M_n) is used when investigating the heterogeneous nature of polymers. It is defined as

$$\bar{M}_n = \frac{\sum m_i}{\sum n_i} = \frac{\sum n_i \cdot M_i}{\sum n_i}$$

where m_i the total mass of all molecules, M_i is the molecular weight, and n_i is the number of molecules with i repeat units. The weight average (M_w) is defined as

$$\bar{M}_w = \frac{\sum n_i \cdot M_i^2}{\sum n_i \cdot M_i} = \frac{\sum m_i \cdot M_i}{\sum m_i}$$

The viscosity average (M_v) is calculated by

$$\bar{M}_v = \left(\frac{\sum m_i \cdot M_i^{\alpha+1}}{\sum m_i} \right)^{1/\alpha}$$

where α is a material constant that relates the *intrinsic viscosity* $[\eta]$ to the molecular weight. This correlation is sometimes identified as the *Mark-Houwink Equation,* written as

$$[\eta] = k\bar{M}_v^{\alpha}$$

For low molecular weight polymers or short chains, this relationship is linear with $\alpha = 1$, and for high molecular weight polymers, which exhibit increasing numbers of entanglements, this relationship follows a Power Law ($\alpha = 3.4$). As seen in Fig. 2.10, most plastic materials consist of chains of different lengths, *i. e.,* they are polydisperse and can be described as follows:

$$\bar{M}_w > \bar{M}_v > \bar{M}_n$$

In the few cases in which a polymer consists of chains of equal lengths (monodisperse polymers), we can say

$$\bar{M}_w = \bar{M}_v = \bar{M}_n$$

A measure of the broadness of a polymer's molecular weight distribution – or the uniformity of its chain lengths – is the polydispersity index defined by

$$PI = \frac{\bar{M}_w}{\bar{M}_n} - 1$$

The broadness of the molecular weight distribution significantly influences the mechanical and rheological properties of plastic materials. Plastic material grades with low polydispersity index values typically exhibit higher strength and better flowability. Table 2.1 provides an overview of the polydispersity of various plastic materials.

Table 2.1 Molecular Dispersity as a Function of Polymerization Method

Polymer	$\frac{\bar{M}_W}{\bar{M}_n}$
Polymers with consistent molecular weight	1
Polycondensation and polyaddition products	2
Vinyl polymers	2–5
Highly branched polymers	20–50

What is the molecular mass that defines a polymer? Considering the minimum molecular size at which entanglements in melts and solutions can be detected, the lower limit for the molecular weight of a polymer can be determined as approx. 10^4 g/mol. Molecular entanglements represent temporary physical cross-links that create qualitatively new material properties (*e.g.*, entropy elasticity) not seen in lower molecular materials. An upper limit to the molecular mass of polymers cannot be determined. Plastics used in technical applications have molecular weights ranging from 10^4 – 10^7, and typically from $5 \cdot 10^4$ – $5 \cdot 10^5$ g/mol. Macromolecules with weights in a transitional range of 10^2 – 10^4 g/mol are also called oligomers.

For a visual representation of the macromolecules of engineering plastics in a disentangled, stretched state, envision 1 mm thick threads with lengths ranging from 2 to 200 m. Specific biopolymers may contain macromolecules with lengths exceeding this by several orders of magnitude.

The different polymerization reactions will be covered in the following. The reactions forming macromolecules are controlled by suitable reaction conditions (temperature, pressure, monomer concentration, reaction medium) and by either activating or inhibiting and structure-controlling additives (catalysts, activators, accelerators, inhibitors). During *polymerization* the monomers connect through a chain reaction by either splitting of multiple bonds or by ring opening to form *polymers*. Here, *polycondensation* reactions are step reactions during which monomers are polymerized by the elimination of reaction products (*e.g.*, water). In *polyaddition* reactions, intermolecular migration of hydrogen atoms without the elimination of any reaction products creates *polyadducts*. An example of this reaction is the urethane reaction. There are a number of other polymerization reactions; however, they will not be discussed in detail. It is not possible to unambiguously relate

polymers to specific reaction types, because polymer synthesis may occur in a number of different ways. Polyacetal (POM), for example, can be synthesized by each of the above mentioned reaction mechanisms. Other polymers, such as polyamide (PA), are synthesized in several steps using different reaction mechanisms, such as condensation and addition polymerization.

From a technical point of view, polymerization reactions can be categorized with respect to the reaction medium into bulk-, suspension-, emulsion-, and solution polymerizations. When the type of polymerization reaction is relevant for the material properties of the polymer, an appropriate designation will be added to the polymer acronym.

Appropriate reaction control (*e.g.,* stereo-catalysis; metallocene catalysts) allows tailoring of the structure of engineering polymers, which explains why it is possible for plastic materials with identical elemental compositions to exhibit a wide range of properties. For example, the soft, rubber-like, amorphous, atactic (random) PP-R is of very little practical interest, while the harder, semi-crystalline, isotactic PP-I has found wide-spread applications. The so-called impact-modified polypropylenes are a blend of these two structures.

The technical synthesis of 100% PP-I is not achievable. The atactic content can be determined as a heptane-soluble phase and is declared in form of the "isotacticity index" as a material characteristic.

2.3.1.4 Major Plastic Material Groups

In this section we will introduce the major groups of plastic materials currently in use. In Chapter 5 many of these materials are covered in more detail regarding their properties and processing options.

Linear homopolymers should also be mentioned here; they are either polymerized directly from unsaturated monomers or created by polymer-analogue conversions. The latter are represented by polyvinyl alcohol and by polyvinyl acetals, which are chemically derived from polyvinyl acetate. The many possible combinations of monomers result in the respective variety of copolymers.

Often, these plastic materials are categorized by different attributes. For example, all plastic materials based on olefinic precursors are categorized as polyolefins (PO): PE, PP, PB, PMB, and PIB.

Polyacetals and polyether result when heteroatoms, such as oxygen, are part of the backbone. When additional "bulky" aromatic units are incorporated (polyaryl ether, polyaryl ether ketone), the stiffer macromolecules cause a significant increase in heat distortion temperature of these plastic materials.

In the early days of plastic material development, natural products, such as cellulose, were subjected to conversion reactions that resulted in plastic materials suit-

able for technical applications, some of which are still (or again) in use today. The stiff cellulose molecule impedes thermoplastic processing so that these materials are blended with plasticizers or other polymers. The high polarity of these blends results in high levels of water absorption, and in some cases even in water solubility, such as in carboxy methyl(ated) cellulose (CMC) used as wallpaper paste.

Polyamides are linear polycondensation products that are widely used as structural materials, fibers, and films, among other applications. Some of these polymers are highly heat resistant because of their hydrogen bridges and aromatic groups; however, they are also hydrophilic and exhibit relatively high water absorption rates. Varying the non-polar methylene groups [–CH_2–] allows the creation of almost all transitional phases between polyolefins and polyamides with high levels of amide group concentration [–NHCO–]. As a result, a variety of copolyamides makes up the wide property palette.

Linear polyesters are also polycondensation products; however, they have gained technical importance only in the form of aromatic polyaryl esters. Specific copolyesters contain extremely stiff molecular segments (mesogens) that render them anisotropic even in the molten state; they represent liquid crystalline, self-reinforced polymers (LCP).

The chemical structure of polyimides provides the highest level of molecular stiffness. Some of these materials, such as PPI, PBI, PBMI, can no longer be processed like thermoplastic materials. They exhibit very high heat aging and heat distortion resistance and are typically used as conductive or semi-conductive polymers.

Polyaryl ether sulfones and polyaryl sulfides represent a group of technically important thermoplastic materials. Their well-balanced properties are based on their chemical structure, in particular the combination of aromatic and sulfuric chain units, which makes them uniquely suitable for structural applications.

All plastic materials described so far are linear polymers that can be processed in their molten state by molding or shaping methods; if they are infusible, they are processed as solutions, dispersions, or powders by coating or sintering technologies. Polymers with double bonds in their macromolecules can be chemically crosslinked to form elastomers (*e.g.*, by sulfur vulcanization), representing typical rubbers. Recently, polycyclic olefins have gained importance as particularly heat resistant thermoplastic materials.

The production of crosslinked plastics (thermosets) or elastomers (rubbers) requires soluble or melt-processable molding materials that are composed of largely linear or partially crosslinked macromolecules or of low-molecular compounds. The actual molding compound is generated only during the crosslinking reaction *(curing, vulcanization)*. The starting materials must contain tri- or higher functional molecules in order to facilitate the crosslinking reaction. Here, the plastics manufacturer needs to control not only the molding operation, but also the chemi-

cal synthesis. If it is not possible to initiate the reaction with low molecular, reactive compounds, the use of "prefabricated" macromolecules *(prepolymers)* is an option. These are typically oligomers in terms of their molecular mass. Potential crosslinking reactions include all types of polymerization reactions discussed so far. The most important crosslinked plastics are phenolic plastics (PF), aminoplastics (UF, MF), unsaturated polyester resins (UP), epoxy resins (EP), polyurethane thermosets and -elastomers (PUR), and silicone resins and -elastomers. With appropriate chemical modifications each represents a wide variety of types. A more detailed description of crosslinked plastics can be found in Chapter 5.

2.3.2 Morphological Structure (Conformation and Aggregation of Macromolecules)

Now that we have covered chemical composition and molecular architecture of macromolecules, we will investigate the state of motion and order in macromolecules under varying external conditions, *e.g.,* changes in temperature or deformation under load.

Amorphous structures lack a continuous, long-range order of their molecules. The molecules assume the lowest state of energy in a statistical intertwined coil. Therefore, a certain short-range order is only detectable in a range of approx. 1 nm, and it depends on intermolecular forces and the shape of the molecule. If the intermolecular forces are weakened, *e.g.,* by increasing temperatures or through adsorption of solvent molecules (solvation), micro-Brownian motion is released and all polymers assume this amorphous intertwined state, independently of their specific structure in the solid state.

The amorphous solid state resembles the state of solidified glass and is therefore often referred to as "*glassy state*". Because of their random structure, the characteristic size of the largest ordered region of amorphous materials is on the order of a carbon-carbon bond. This dimension is much smaller than the wavelength of visible light, and thus amorphous thermoplastics are generally transparent. Figure 2.11 shows the shear modulus G' (a measure for the linear elastic deformation of a plastic material) of polystyrene as a function of temperature. Polystyrene is one of the most commonly used amorphous plastic materials. We distinguish two major regions: for low temperatures or in the glassy state the modulus is relatively constant; with increasing temperatures the modulus decreases significantly. At high temperatures, the modulus is negligible – the material is soft enough to flow. Although amorphous materials do not exhibit a sharp transition between the "solid" and the "fluid" state, we identify the temperature range separating these two states as the *glass transition range or glass transition temperature* T_g. For the polystyrene in Figure 2.11 the glass transition temperature is approx. 110 °C. At

temperatures below T_g the material behaves like a viscoelastic solid, identified as the *energyelastic zone* in the figure. Once the material is heated above its T_g, it enters the *entropy-elastic zone*, where it can be readily molded, *e.g.*, utilizing thermoforming processes. However, in order for the material to flow, the temperature has to be increased beyond the *softening temperature* T_s. Then the material behaves like a viscoelastic fluid. The softening temperature is also characterized as the point at which the viscous parts of the deformation (the loss modulus) outweigh the elastic parts of the deformation (the storage modulus). For amorphous materials, this zone is typically 50 K above the glass transition temperature. The exact determination of *glass transition* and *softening temperatures* relies on the testing method and also depends on the type and duration of the load during testing. There is a delay between the "load" exerted by the test method and the "molecular response". Therefore, dynamic-mechanical tests with high load cycle frequencies result in significantly higher glass transition temperatures (dynamic glass transition temperature $T_{g\ dyn}$) than calorimetric or dilatometric (elongation) tests with slow temperature changes (static glass transition temperature $T_{g\ stat}$). Depending on type of plastic and level of glass transition temperature, differences of up to 50 K are to be expected. A descriptive way to explain this phenomenon is the statement that plastic materials are the more rigid or stiff the faster the load cycle during testing.

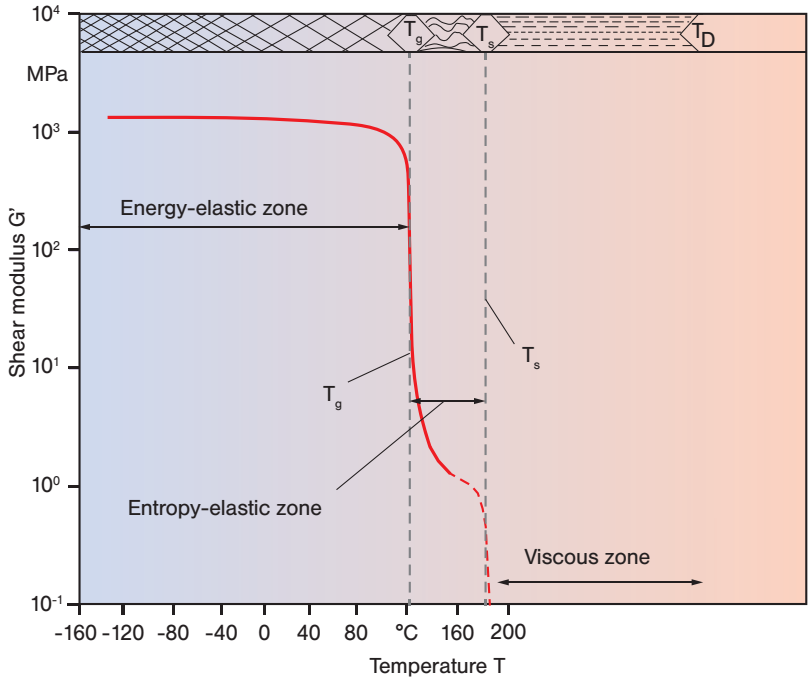

Figure 2.11 Shear modulus of PS as a function of temperature

When plastic materials are exposed to loads or deformations, we observe a time-dependent increase in strain at constant stress *(creep, retardation)* and a time-dependent decrease in stress after being deformed *(relaxation)*. This behavior, also called *viscoelasticity*, is determined by the simultaneous effect of three deformation mechanisms:

- Energy-elastic (also spontaneous-elastic) deformation,
- Entropy-elastic (also rubber-elastic) deformation, and
- Plastic (also viscous) deformation.

The difference in behavior between plastic materials and rubbers is determined only by the gradually different deformation mechanisms in the respective thermal state. The different mechanisms of molecular motion allow for widely different deformations, ranging from approx. 0.1% for energy-elastic deformations, to almost 100% for rubber-elastic deformations, to deformations of up to 10^4% for plastic melts. The *non-Newtonian flow* behavior (*e.g.*, shear thinning) of plastic melts and solutions is also attributed to these deformation mechanics, see Chapter 3.

The amorphous coil structure is a well-suited example to explain the main structure-property relationships encountered in plastic materials. In very uniformly structured macromolecules in which configuration and intermolecular forces allow for a denser packing of the molecules, we observe the formation of *crystallites*, because the increase in order creates, at least partially, a larger energy gain than the entropy increase.

Because structure formation during the crystallization of organic polymers is such a complex phenomenon, we will provide only a very simplified description. Similar to lower molecular weight materials, crystallization is determined by two distinct stages: nucleation and crystal growth. The variety of conformations together with the macromolecules' tendency towards increase in entropy (coiling of molecules) do not allow for complete crystallization during manufacturing and processing. As a result, plastic materials are typically *semi-crystalline*. Their morphological structure is characterized by a mix of amorphous and crystalline phases whose boundaries on the molecular level cannot be determined easily. Specific sections of the same macromolecule may be part of either an amorphous or a crystalline phase.

In general, the lamellar or micellar crystallites aggregate to form *crystalline superlattices* (Fig. 2.12), such as *spherulites*, one of their most common representatives. The degree of crystallization is a quantitative measure of the crystalline part in a macromolecule. In plastic materials that crystallize particularly easily this degree can reach 60 to 80%. Under laboratory conditions higher values are possible, even reaching *polymeric mono-crystals*.

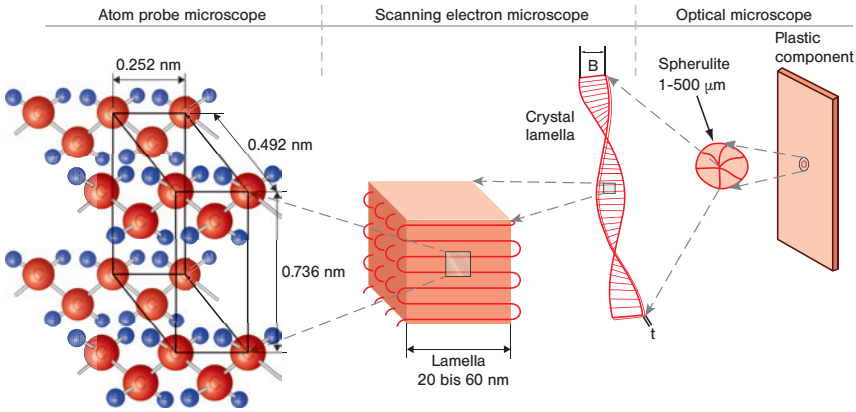

Figure 2.12 Morphology of a semi-crystalline thermoplastic material

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.

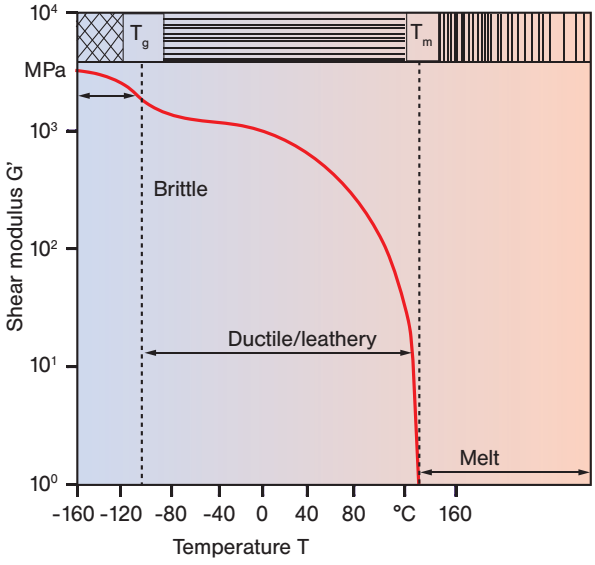

Figure 2.13
Shear modulus of PE-HD as a function of temperature

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.

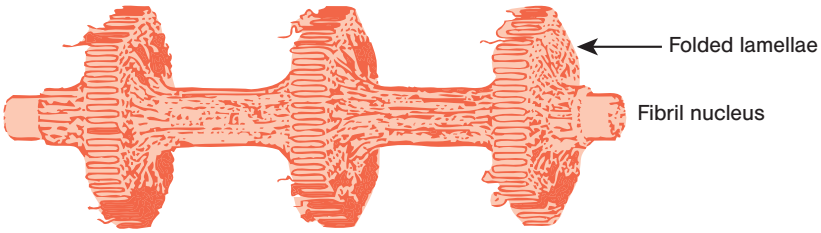

Figure 2.14 Shish-kebab structure

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

temperature interval rather than at a specific melting point. Melting requires additional latent thermal energy in the form of *melting heat*. During rapid solidification, crystallization sets in at temperatures that may be up to 20 to 40 K below the melt temperature range. The use of nucleating agents may decrease this difference. Crystalline regions increase hardness, stiffness, and wear resistance in plastic materials. They also decrease permeation, diffusion, solubility, and swelling. In many respects, the effects of crystallization on the properties of plastic materials are similar to those seen after chemical crosslinking. Therefore, crystalline structures can be described as thermally reversible *physical cross-linking points*.

Extremely stiff macromolecules, *e.g.,* ladder polymers (double-strand polymers with a ladder-like structure), are neither able to form an amorphous coil structure, nor can they be arranged in crystal lattices. The molecules can be compared to rather inflexible rods *(mesogens)* with limited micro-Brownian mobility. If macro-Brownian motion is possible, they form anisotropic parallel structures (model: tree trunks in a river) that are called *mesophases*. Although there are intermolecular forces between the mesogens, their strength is far smaller than those in crystal lattice structures. In other words, this is a quasi-crystal degree of order with a low energy level. In a liquid-like state, the mesophase structure is typically retained, and polymers exhibiting such structures are called *liquid crystal polymers (LCP)*. Because even minimal macro-Brownian molecular motion will cause a unidirectional orientation of the mesogens in the direction of stretching or flow, the result are anisotropic structures with excellent mechanical properties, also called *self-reinforcing polymers*. The mesophase structure is considered an intermediate between amorphous and crystalline structure and such materials are called *mesomorphous*.

Continuous ladder polymers (*e.g.,* aramids) cannot be plasticized by heating; a liquid-like state can only be achieved in solution *(lyotropic LCP)*. In order to obtain *thermotropic* LCPs, the ladder structures have to be combined with flexible molecular segments, so-called *spacers*. In these polymers the mesophase structure is limited to the mesogens. The mesogens in the solid phase are arranged differently than in the melt, which leads to a variety of mesophase structures (*e.g.,* nematic, smectic) that exhibit different orientation and packing symmetries. Mesophase transitions occur at certain temperatures without general changes in the mesomorphous (anisotropic) structure of the LCPs. Above a certain temperature (as long as there is no thermal degradation), the mesophase structure is transformed to an un-ordered, isotropic structure. All these transitions require only low levels of heat of transformation. The spacer segments in the macromolecules may exhibit any kind of polymeric morphology (amorphous, crystalline).

2.3.2.1 Different Classes of Plastic Materials

Figure 2.4 explained the classification of plastic materials in thermoplastic, thermosetting, elastomeric, and thermoplastic elastomeric materials based on a qualitative differentiation of their molecular mobility at room temperature (RT). Here, the identification as a thermoplastic material indicates only the potential, not the imperative for a thermoplastic state. Figure 2.15 relates the classes of plastic materials introduced in Figure 2.4 to their respective macro- and micro-Brownian molecular mobility.

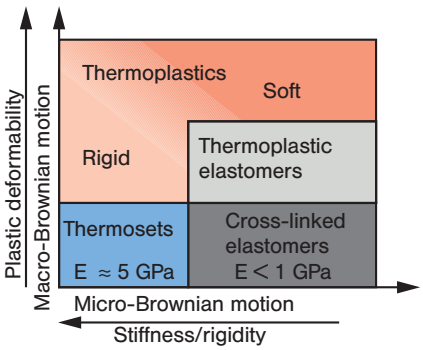

Figure 2.15
Classification of plastics according to their molecular mobility at room temperature (RT)

The materials classified here are end product materials, not resins or precursors. Compared to thermoplastics and thermoplastic elastomers, thermosets and crosslinking elastomers exhibit lower macro-Brownian mobility (free mobility of complete molecular chains: sliding of chains past each other, formation and releasing of entanglements) because of their covalent (chemical) crosslinks. Therefore, plastic deformation of thermosets and rubbers is typically not observed; only incomplete crosslinking allows for a limited degree of plastic deformation.

The differentiation between thermosets and rubbers is a question of convention and typically refers to differences in hardness and stiffness. This approach to a classification is directly related to micro-Brownian molecular mobility (rotational and translational movement around the bond axis of atoms or small chain segments) of the material. Materials covered by this include rigid rubber, flexible EP-, UP-, PUR-X-, SI-X-resins, and others.

Following this categorization, thermosets and thermoplastic elastomers are identified as non-crosslinked plastic materials, *i.e.*, they consist of either linear or branched macromolecules. Only this type of structure allows for a thermoplastic state with highest macro-Brownian molecular mobility. Plastic materials that combine rubber-like properties with the ability to be processed like thermoplastics have gained increasing importance since approx. 1990. This class of materials is identified by the term *thermoplastic elastomers*. The current efforts regarding the nomenclature of these plastic materials are yet another example of the long strug-

gle with classification systems in the plastics technology community. It also sheds light on the fact that the physical composition of thermoplastic elastomers represents a complex problem. In essence, these materials are supposed to be ideal rubber materials that can be processed like thermoplastics. This demand means that the highest possible micro-Brownian molecular mobility has to be combined with sufficient rubber-elastic (entropy-elastic) deformability and low macro-Brownian mobility (little plastic deformation). This requires a loosely crosslinked plastic material with low intermolecular forces and thermally reversible crosslinks. Such *physical crosslinks* can be realized in a number of different ways.

The entanglements of the molecules in thermoplastic materials represent a certain "rubber potential". In fact, soft polyvinyl chloride (PVC-P, PVC plasticized), polyisobutene (PIB), and other soft-elastic thermoplastic materials have been widely used as rubber-like substitutes in a range of applications until they were substituted by modern thermoplastic elastomers.

However, Figure 2.15 also shows that the ideal rubber material is reached only when the physical crosslinks attain the bond strength of covalent crosslinks. Perfecting the ionic structures may offer a promising approach.

In the context of these structural considerations, we will provide a characterization of the most important classes of plastic materials (except LCPs):

- *Amorphous Thermoplastics.* Linear and branched macromolecules with amorphous structure. Thermo-plastically softening (*e.g.,* PMMA molding compounds) or for extremely high molecular mass materials only thermo-elastically softening (*e.g.,* PMMA cast semi-finished products). Generally soluble in suitable solvents. T_g < RT for low intermolecular forces (*e.g.,* non-polar PIB) or when intermolecular forces are decreased by solvation (*e.g.,* addition of plasticizers, PVC-P) and flexible macromolecules. These plastic materials are soft-elastic at RT and increasingly rubber-like with higher molecular mass. Stronger intermolecular forces and stiffer molecules result in T_g > RT, *i.e.,* at RT they are rigid-elastic plastic materials. In extreme cases (*e.g.,* ladder polymers) thermal degradation will set in prior to softening.
- *Semi-crystalline Thermoplastics.* General characteristics of the molecules are similar to those of amorphous plastics. In addition, semi-crystallinity causes higher hardness and lower solubility. When T_g < RT, the crystalline phase results in horn-like, ductile-rigid behavior at RT. A thermoplastic state is attainable only above T_m. If T_m is much higher than T_g, materials reach a thermoplastic state immediately after the crystallites melt (*e.g.,* polyamides). When this is not the case or for materials with very high molecular mass (*e.g.,* high-molecular polyamides), the material reaches a thermo-elastic state. Extreme reduction of molecular mobility may prevent both thermo-elastic softening (*e.g.,* anhydrous cellulose with T_g = 225 °C) and a thermoplastic state (*e.g.,* PE-UHMW, ultra-high

molecular weight PE) prior to degradation. The solubility at RT of such materials may be severely limited, and for some there is no currently known solvent (*e.g.*, polytetrafluoroethylene, PTFE).

- *Thermoplastic Elastomers.* Thermally reversible crosslinked macromolecules with low crosslinking density created by amorphous and semi-crystalline rigid segments (domains) or by ion clusters. Also blends of thermoplastic materials with high contents of crosslinked and non-crosslinked elastomer phases. Thermo-plastically softening and soluble, elastomer-like plastic materials.
- *Crosslinked Elastomers (Rubber).* Thermally irreversibly (covalently) crosslinked macromolecules with predominantly amorphous structure and typically low crosslinking density (low hardness). Thermo-plastic softening not possible. Generally not soluble, but suitable media cause high levels of swelling. Pronounced rubber-elasticity (entropy elasticity) without plastic deformation in service temperature range. Stretching-induced crystallization relatively common.
- *Thermosets.* Thermally irreversibly (covalently) crosslinked macromolecules with amorphous structure and high crosslinking density. Thermo-elastic softening more or less pronounced depending on the strength of the intermolecular forces and crosslinking density. For very high crosslinking densities of no practical interest. Generally not soluble, but depending on the degree of crosslinking more or less swelling in suitable media.

2.4 Effects of Processing on Material Properties

The properties of a plastic material in a manufactured component are determined by the processing and its many variable parameters together with component geometry, material properties, and other factors (Fig. 2.16). Because of these typically complex interdependencies, it has become common practice in plastics technology to define “intrinsic characteristics”. These characteristics are attributes describing the state of a plastic material, which include:

- Morphology,
- Orientation,
- Residual stresses,
- Crystallization (crystallization parameter),
- Molecular composition (average molecular weight, molecular weight distribution),
- Change in additives/reinforcements (*e.g.*, stabilizer content, fiber length).

The intrinsic characteristics describe the change in properties during use and allow the determination of processing conditions on component properties.

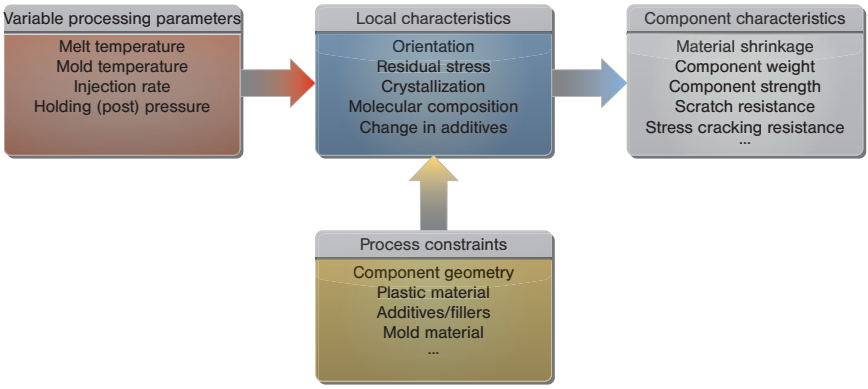

Figure 2.16 Factors influencing intrinsic properties

2.4.1 Residual Stress

Residual stresses are the direct result of pressure and temperature control during the solidification process (Fig. 2.17). Internal stress will increase with:

- a heterogeneous temperature distribution in the component,
- high cooling rates,
- high coefficients of thermal expansion, and
- high Young's modulus of the material.

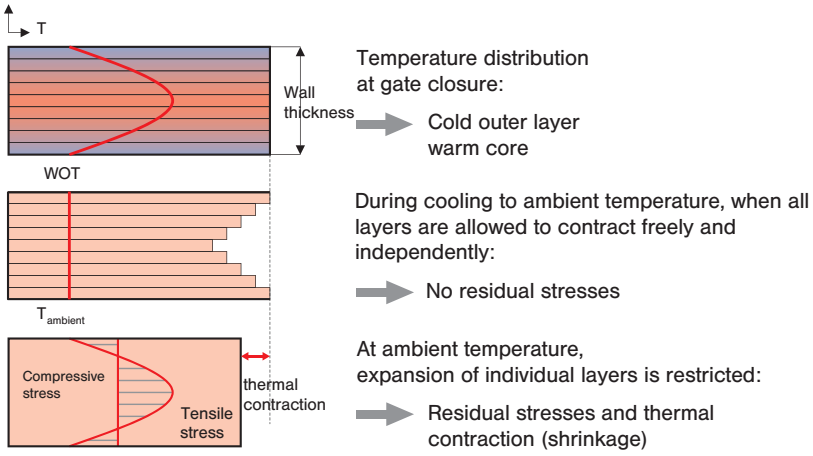

Figure 2.17 Layer model: formation of residual stresses during cooling

Residual stresses represent mechanical loads that act on the component just like external stresses and need to be considered during strength analysis (in a first approximation by reducing the strength parameter).

Differences in coefficients of thermal expansion in composite materials may also cause residual stresses subject to the temperature interval experienced (bi-metal effect). Tempering (heating over a long period of time) to just below the melting temperature and subsequent slow cooling allow for a release of these stresses. In components made from materials that are prone to stress cracking, even small external loads or exposure to crack-inducing media may cause crack formation.

The effects of processing, and in particular those of residual stresses, on the component properties are most pronounced in characteristics such as shrinkage and warpage. They will be covered in more detail in Sections 3.2.2.2 and 3.2.2.3.

2.4.2 Molecular Orientation

In a stationary plastic melt, the molecular chains are in an unordered, coiled state (LCPs are the only exception), while in a moving melt stream the molecules align in a preferred direction, an effect that is also called molecular orientation. Figure 2.18 schematically shows how a circular melt element turns into an oriented element during flow. Molecular orientation is based on two distinct phenomena:

- Local stretching of a melt element, *e.g.*, in a narrowing flow channel or when a melt front expands similar to a balloon being inflated; this effect is also seen during blow molding and thermoforming.
- Shearing of adjacent melt layers in flows with velocity gradients, *e.g.*, during injection molding or extrusion when the melt adheres to the channel walls.

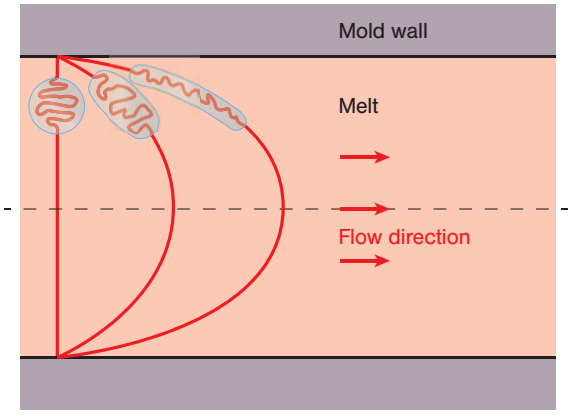

Figure 2.18 Formation of molecular orientation

Determining the level of orientation may be difficult, and in particular for complex components it takes a certain level of experience and the help of simulation programs. Stretching of the flow front and its sudden solidification on contact with the mold wall typically result in a thin, highly bi-axially oriented layer at the component surface. During filling, the high shear differential below the surface results in a layer that is primarily oriented in flow direction. The center of the component wall experiences low shear differentials and thus little orientation.

Because of molecular Brownian motion, orientations in the melt quickly decrease, the molecules relax. Under the conditions prevalent during injection molding, relaxation takes only a few seconds; however, because the mold also cools very fast, orientation is partially frozen in the plastic component. The degree to which orientation is frozen-in depends on the melt temperature, the level of stretching and shear flow, the solidification behavior of the melt, the temperature at the mold wall, and the thickness of the component wall. Although high injection rates during injection molding will cause high levels of orientation, they also result in longer residence times at higher temperatures, which in turn allow for higher levels of relaxation. In consequence, the level of frozen-in orientation may be lower than at slower injection rates. Low melt temperatures, cool molds, and thinner component walls result in higher levels of orientation.

Once at room temperature, the frozen-in orientations will no longer relax. However, if the component experiences elevated service temperatures for longer periods, these orientations may relax, causing shrinkage or warpage, unless this deformation is prevented by suitable constraints, similar to the mold constraint during injection molding, see Sections 3.2.2.2 and 3.2.2.3.

Orientation always results in anisotropic properties: parallel to the direction of orientation strength, stiffness, thermal expansion, and mold shrinkage will increase.

Orientations in transparent materials can be qualitatively evaluated by optical polarization methods, because oriented regions are birefringent, see Section 3.6. X-ray diffraction analysis is particularly suited for a quantitative evaluation of semi-crystalline plastic materials. Measuring shrinkage is another quantitative approach. Here, complete components, sections, or microtome cuts are stored at elevated temperatures so that orientations can relax and cause deformations. The degree of deformation is a measure for the frozen-in orientation.

2.4.3 Crystallization Behavior

The intrinsic properties of semi-crystalline thermoplastic materials are also determined by the level of crystallinity. The degree of crystallinity together with general structural properties (*e.g.*, the diameter of the spherulites) are crystallinity characteristics.

- The higher the degree of crystallinity, the stiffer, stronger, but also the more brittle the component. The density of the plastic material is directly correlated to its degree of crystallinity. Low degrees of crystallinity or very fine crystal structures result in opaque to transparent parts. The degree of crystallinity is determined by the chemical structure of the plastic material, the type of nucleation, the processing technique, and also potential heat treatment (tempering). Lower tool temperatures and high rates of cooling result in low degrees of crystallinity and fine crystalline structures. A typical example is bottles made from PET. They are cooled so rapidly that the normally white material solidifies into transparent bottles. The same effect is seen for components with thin walls and on the surfaces of components. Long melt residence times at high temperatures result in high degrees of crystallization and coarser crystalline structures, which will occur in particular in the interior of thick-walled components. In injection molded parts, heat is conducted through the component surface to the tool. The low thermal conductivity of plastic materials causes a temperature gradient in the component, which in turn results in a layer-specific degree of crystallinity, Fig. 2.19.
- Post-crystallization is observed with extended use of molded components, in particular at elevated temperatures. It causes a decrease in volume that may cause warpage or clearance problems. Tempering or annealing, *i.e.*, exposure to elevated temperatures for a certain period, may preempt post shrinkage. During processing, the spherulites can be aligned by shearing – similar to the macromolecules – and subsequently cause anisotropic behavior of the component. The higher the degree of order of the macromolecules in the melt (orientation), the easier they are able to crystallize (shear-induced crystallization).

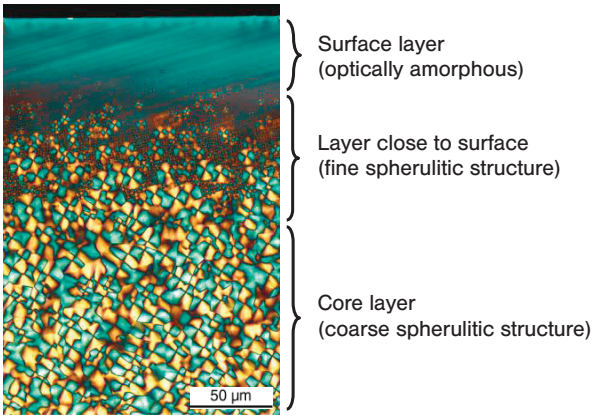

Figure 2.19 Structure of an injection molded component made of PA 66 [1)]

[1)] C. M. Dallner, M. O. Kobes, R. W. Feulner, E. Schmachtenberg: Influence of the morphology on the tribological behaviour of assembly injection moulded Microdrives, PPS-23, May 27–31, 2007, Salvador, Brazil (2007)

The crystalline portion in a given polymeric material can be identified by X-ray diffraction, differential scanning calorimetry (DSC), or by nuclear resonance spectroscopy. When a calibration curve is available, the direct relationship between density and the degree of crystallinity allows the inference of crystallinity from density.

2.5 Modifications of Plastic Materials

In the context covered here, material modifications will include blending of homopolymers and the addition of fillers and other additives for a variety of specific functions. This field is rather complex and we will give only a general overview here. More detailed information is provided in the following chapters.

2.5.1 Copolymers and Polymer Blends

Copolymers are plastic materials containing two or more types of monomers within their chain. A copolymer consisting of two different monomers is also called a *bi-polymer*. Copolymers consisting of three different monomer units are called *ter-polymers*. Depending on the arrangement of the different monomer units within the chain, we distinguish between four different types of copolymers: *statistical*, alternating, *block-* and *graft-copolymers*. Ethylene-propylene is a typical example of a copolymer. Although both monomers are semi-crystalline thermoplastics, blends with ratios between 35/65 und 65/35 do not exhibit a melting temperature: the material is an elastomer. These so-called EDM-materials (ethylene propylene-diene rubbers) are increasingly utilized for industrial applications because of their good weather resistance. In contrast, all ethylene-propylene block copolymers exhibit a melting temperature, independent of their blend ratios.

Plastic mixtures, blends, and alloys are created by mixing or blending two or more plastic materials. The goal is to create a material with improved properties compared to those of its components. The most common polymer blends include PP-PC (polycarbonate), PVC-ABS (acrylonitrile butadiene styrene), and PE-PTFE. The miscibility of polymers is generally rather limited (disadvantageous energy states), and on a molecular level homogeneous mixtures (blends) are an exception.

The formation of a morphological multi-phase system may be advantageous, because many useful properties of the initial components can be retained. A prerequisite for high-value blends is a stable blend morphology. Dispersed phase and matrix must be uniformly distributed and exhibit good phase adhesion. With current state-of-the-art mixing and compounding technology “phase droplets” below

the wavelength of visible light can be achieved (transparent blends). A variety of methods and technologies is used to improve miscibility and adhesion:

- Matching of initial compatibility,
- Matching of quantitative composition and compounding temperature control,
- Chemical modification by ionic bonds, dynamic crosslinking of dispersed phases, partial graft copolymerization and others. Here, the reactions may take place during blending,
- Addition of compatibilizers, and
- Formation of interpenetrating networks (IPN) for crosslinked polymer structures, which result in particularly good mechanical properties.

Originally, blending was used to improve processability and achieve impact modification, in particular for thermoforming applications, typically using rubbers as blend components (elastomer modified plastics). Today, polymer blends are used to improve any given property, including increasing the heat distortion temperature, decreasing stress crack formation, improving coated and plated surfaces, and reducing flammability. Utilizing blend technologies for thermoplastic elastomers should be particularly noted. The increasing trend for material recycling has proven to be an additional incentive for blend technology.

2.5.2 Plastic Composites

Plastic composites represent a form of property and/or material modification that can be classified by the type of bonding:

- Multi-layer composites and
- Reinforced composites.

Multi-layer composites consist of geometrically distinct layers of different materials. They include *multi-layer films, sheets, pipes, hoses, and sandwich designs* consisting of light plastic, honey comb, or homogenous cores with relatively thin-walled surface layers, *multi-component parts* manufactured by multi-component and/or multicolor injection molding, back-injection molding, and by *insert- and outsert methods*. Multi-layer structures allow the development of composite films with clearly defined permeation behavior and of light yet very rigid sandwich designs for aeronautical and automotive applications. They also facilitate a variety of other property combinations with regard to strength, stiffness, gas permeability, flammability, decorative appearance, thermal insulation, ease of assembly, among others. Multilayer composites can be formed by the combination of different plastic materials as well as by combinations with other materials (metals, wood, etc.). A technological focus of this material modification is to achieve sufficient adhesion between the layers using chemical and/or mechanical bonding principles.

Reinforced composites consist of a polymer matrix into which fillers have been incorporated for reinforcement or to improve specific properties. The distribution of these fillers determines whether the composites exhibit isotropic or anisotropic behavior. Typical examples are *high-performance fiber composites* made from high-tensile and/or high-modulus fibers or textiles and a plastic matrix. In addition, this class of materials also includes plastic/concrete composites, laminated materials (fabric-, paper-, and glass mat based laminates), long-fiber reinforced thermoplastics, and the wide range of filled and reinforced thermosets and laminates. Chapter 5 will discuss these materials in more detail.

However, plastic components reflect the excellent mechanical properties of fiber-reinforced materials only if they contain high ratios of well-ordered fibers, which requires special, high-cost manufacturing methods (see Chapter 4).

The majority of plastic materials is shaped/molded using flow processes. To ensure the flowability of the plastic material, the reinforcing fibers must not exceed certain lengths. The type and ratio of reinforcing material determines the applicable manufacturing process (see Fig. 2.20). Plastic manufacturing processes suitable for large-scale production typically allow for fiber lengths of approx. 10 mm. It should be noted that fiber lengths typically decrease during manufacturing so that the fiber length in the component is always smaller than in the original molding compound.

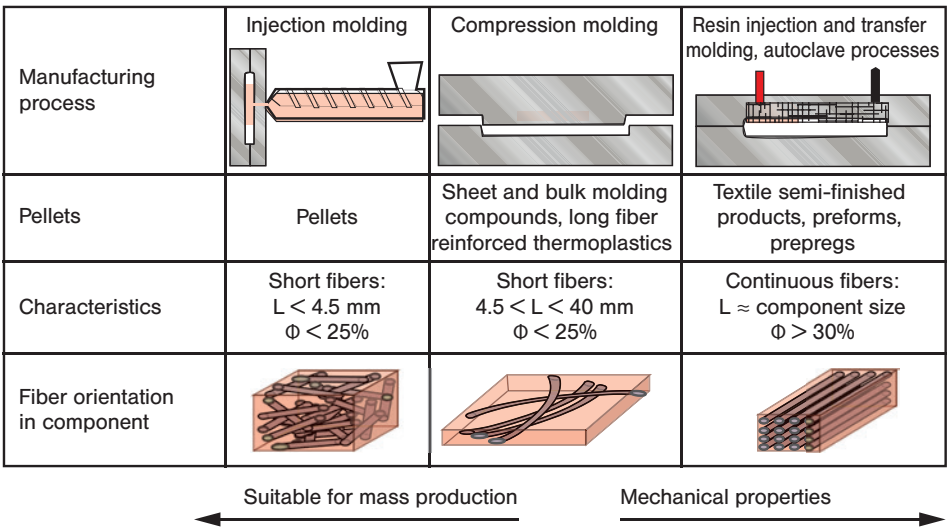

Figure 2.20 Correlation between manufacturing process and achievable fiber length

In general, a wide range of fillers can be incorporated into plastic materials in order to tailor the material's properties. Figure 2.21 shows matrix reinforcement (*i. e.,* the change in Young's modulus as a result of the filler) as a function of type, shape, and orientation of the filler particles at different filler contents.

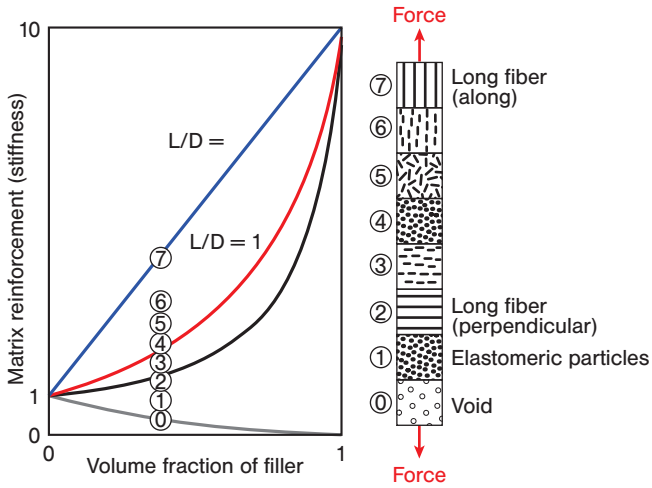

Figure 2.21 Relationship between stiffness and type, shape, and orientation of filler particles

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.

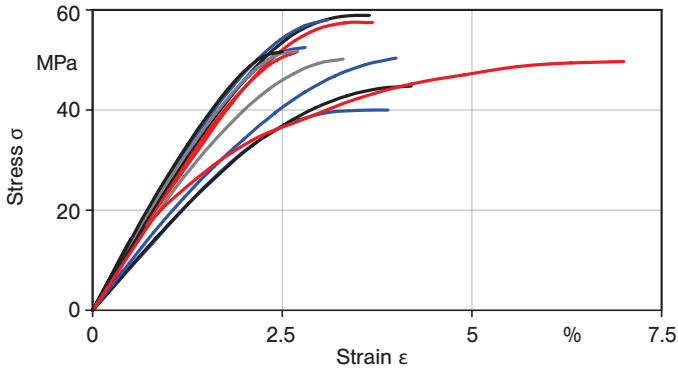

Figure 3.1 Range of stress-strain diagrams for PBT at 23 °C

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 ε = 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