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Preface

Immediately after I started working at the University of Stuttgart in late summer 2010, I revised the course "Fundamentals of Plastics Technology" with the help of my scientific staff. Since then, this important course has been held unchanged in Stuttgart for a long time. During the revision we not only updated figures and contents, but also gave the course a new structure, which I – inspired by didactic seminars of the German University Association – consider more contemporary. Numerous film sequences used in the lectures enable the students to understand the contents more quickly and deeply. I am convinced that the students in my course become well equipped with a comprehensive, fundamental knowledge of plastics and plastics technology for their upcoming professional life. If students want to deepen their knowledge of the subject, they can do so in the three main areas of "Materials Engineering", "Processing Technology", and "Product Engineering" in other courses later on.

This introductory and fundamental lecture series in Stuttgart is an elective course with four lessons per week for master students of process engineering, mechanical engineering (e. g. production engineering, automotive engineering), materials science, as well as of technology management. The course is actually aimed at technically educated students, but in the meantime non-technical students (economics, environmental issues) choose the course as well. While about 100 students had this subject examined after the 2010 winter semester, the number was growing year by year subsequently. The increasing interest of highly motivated and disciplined master's students led me to supplement the figures with continuous text and publish them in the form of a book the first time in 2014.

In winter 2012/13, students started asking me about the critical topics that are "heard in the media". I decided to get to the bottom of the topics "environmental pollution", "toxins in plastics", "bioplastics", and "life cycle analyses" right down to the original sources and to prepare this as a part of the course as well. These topics form the final chapter "plastics and the environment" of this book, and I have the impression that factual information is the best means of clarification. The reader may decide whether I have succeeded in dealing with the topics in a factual way.

I was a little surprised when, just one and a half years after the start of sales of the first German edition, the publisher asked me to prepare the second one. The many reviews that were sent to the publisher were all positive, contained valuable suggestions and encouraged me to continue this book the same way. Since 2016, more than 500 students chose the course underlying this book in structure and content and also encouraged me to continue teaching in this way. In the second German edition, I concentrated on individual additions, revisions, and updates, as well as the correction of several errors.

In the meantime, I am being asked by university professors from all over the world to give not only scientific presentations, but master's courses about plastics technology there as well. Since not everyone speaks German and I usually do not speak their native language, I often hold the course in English. To help the students with the rework, I have decided to translate the second edition of this book into the English language and made only minor changes.

I would like to thank the publisher for their trust and advice as well as for offering this book in color and hardcover. I would also like to thank my supporting staff members, who have carefully worked through and gave valuable hints on mistakes and the comprehensibility of the text of the first and second German editions. Technical staff members supported me with figures and photos from their daily work. The students Adriana Steinitz and Lisa Schleeh greatly helped me with translation of the text and the figures.

I am sure that with the knowledge of the book I will give every reader/student the opportunity to quickly gain a foothold in the plastics industry and to enable her or him to decide early on in which application plastics can do great things.

Stuttgart, September 2019

Univ.-Prof. Dr.-Ing. Christian Bonten

The Author:
Prof. Christian Bonten

University Professor Dr.-Ing. Christian Bonten heads the Institute for Plastics Technology (Institut für Kunststofftechnik; IKT) in Stuttgart, one of the leading German research institutes in the field of plastics technology. After studying mechanical engineering in Duisburg/Germany and plastics processing at the University in Aachen/Germany, Prof. Bonten received his doctorate in the field of welding plastics under supervision of Prof. Ernst Schmachtenberg. After several years of technical responsibility and later business responsibility at the chemical company BASF and the bioplastics manufacturer FKuR, he was appointed Director and Head of the IKT by the University of Stuttgart in 2010. The institute works in all areas of plastics technology: materials engineering, processing technology, and product engineering.

Contents

Figure 2.16 Dipole-dipole forces

Hydrogen Bonds

Hydrogen bonds are a special form of the dipole-dipole bond and are formed by a hydrogen atom covalently bonded to a much more electronegative atom (e.g. O, N, F) whose common electrons are shifted in the direction of this atom (Figure 2.17).
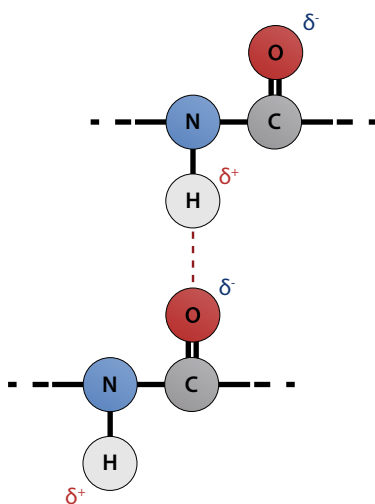
Figure 2.17
Hydrogen bonds

The hydrogen atom, which is partially positively charged by the electron shift, is more strongly bound to another electronegative atom of a second macromolecule and thus acts as a "hydrogen bridge" between the two molecule chains. With ~ 20 kJ/mol, this strongest type of intermolecular force reaches the order of weak main valence bonds. Figure 2.18 shows hydrogen bonds in polyurethane (PUR) and polyamide (PA).
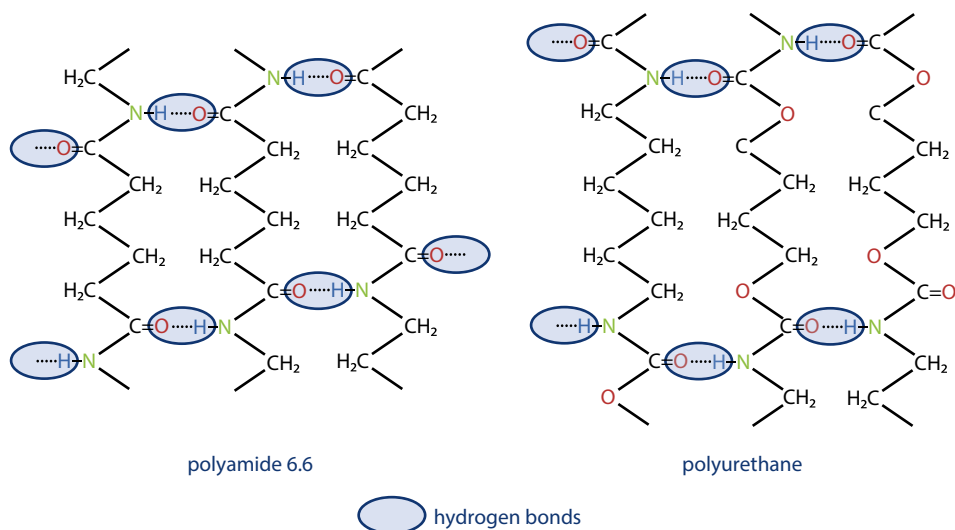
Figure 2.18 PA66 and PUR as examples for formation of hydrogen bonds

Induction Forces

Induction forces are very weak secondary valence bonds. Molecules with permanent dipoles can cause electron shifts in adjacent nonpolar molecules and thus induce dipole moments. The binding energy is only 1/500 to 1/2000 of a main valence bond.

In summary, the following applies to the secondary valence forces already listed: a prerequisite for the occurrence of dipole-dipole forces and/or induction forces is the presence of permanent dipoles.

Dispersion Forces

With binding energies of 1/500 to 1/1000 of a main valence bond, dispersion forces (also Van der Waals forces, London dispersion forces) are also very weak. By random movement of the electrons and the resulting deformations of the electron cloud, momentary dipoles are formed even in non-polar molecules. These rapidly varying dipoles, which compensate each other to zero on a time average, also induce dipoles in the neighboring molecules in the rhythm of their own frequencies, but they are not permanent.

To illustrate this, Figure 2.19 shows spheres strung together as atoms which are connected to each other by main valence bonds and form polymer chains. Between the polymer chains there are secondary valence forces of different kinds, depending on the atoms of the polymer chain.

The mechanical stress of solids and fluids can basically be described by normal stresses (tension/compression) and shear stresses (Figure 2.40). If tensile stresses occur, the body responds with "elongation". If compressive stresses occur, the result is called "compression". If shear stresses occur, the result is "shear deformation".

tensile stress inside
(response: elongation)

compressive stress inside
(response: compression)

shear stress inside
(response: deformation)
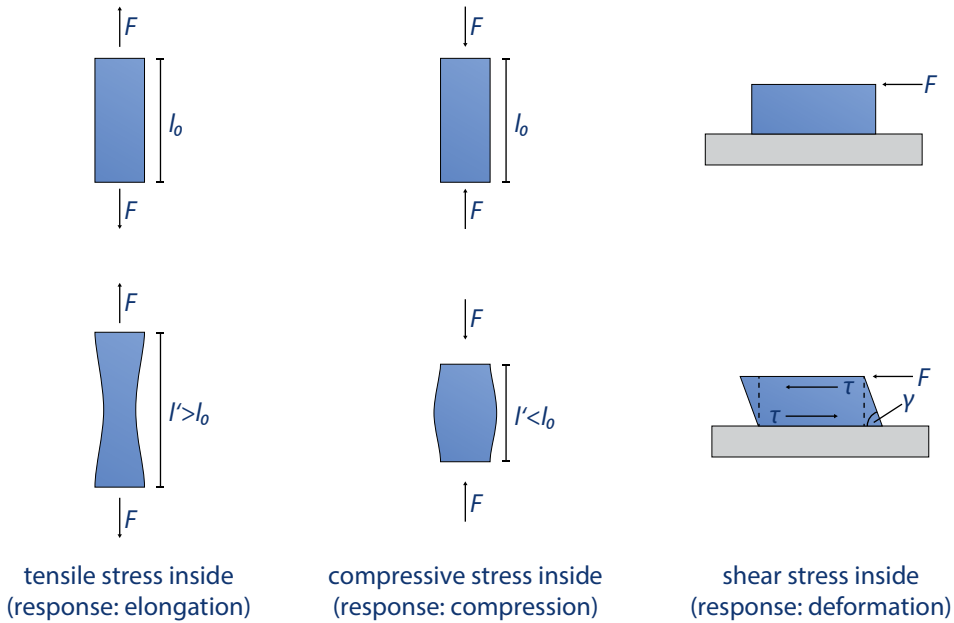
Figure 2.40 Typical stresses and their responses

Figure 2.41 lists some frequently occurring superimpositions of stresses: "peeling" is only possible with flexible (soft) components. The crack propagation front is always the main force application point, which is why the peeling stress is considered to be very challenging. A bending load, e.g. in the bar shown here, generates a compressive load (with resulting compression) on the underside and a tensile load (with resulting elongation) on the top. The virtual "neutral fiber" is neither stretched nor compressed. Torsional stress generates shear, tensile, and compressive stresses with their respective responses of shear deformation, elongation, and compression in the torsioned component. Here, as well, there is no stress in the neutral fiber, which is identical to the torsion axis in the picture.

peel stress   bending stress   torsional stress
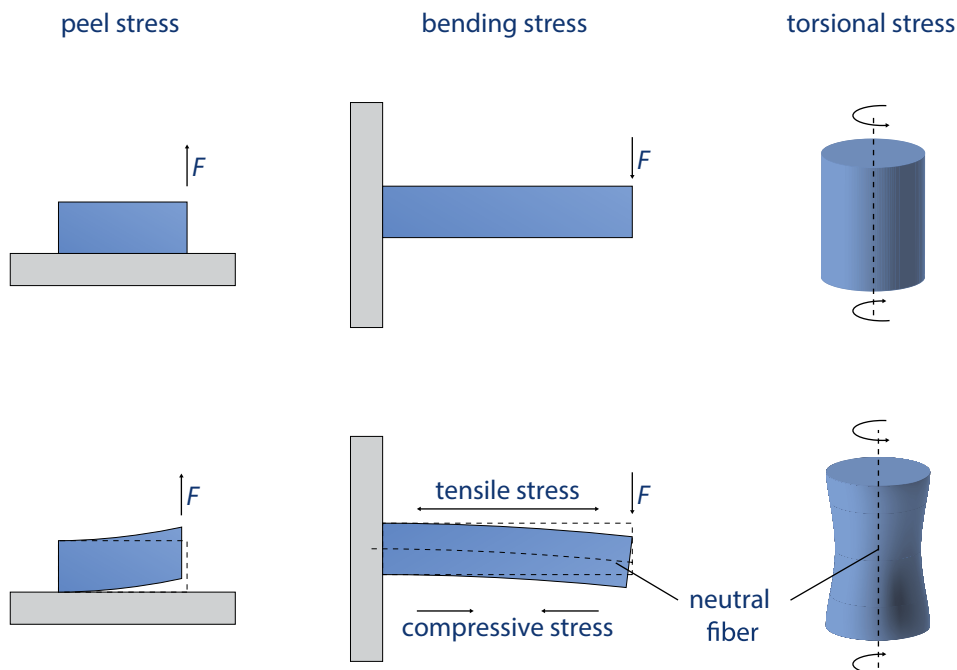

Figure 2.41 Superimposed stresses

2.2.2 State Ranges of Plastics

For the mechanical behavior of plastics under temperature changes, we remember that the molecular motion of the long polymer chains also correlates with the absolute temperature. They "oscillate" more strongly at higher temperatures, resulting in an increase in their mean oscillation distance. A larger oscillation distance on average over time also means lower secondary valence forces and thus the possibility that the molecule chains slide against each other with less force and the material expands.

2.2.2.1 Glass Transition Temperature T_g

Glass transition is the softening of the amorphous molecular structures due to increasing Brownian molecular motion during heating. The thermoplastic changes from a brittle-stiff to an elastically flexible ("thermoelastic") state (Figure 2.42). Amorphous thermoplastics undergo continuous change to the plastic ("thermoplastic") state as the temperature continues to rise.

Plastics manufactured from amorphous polymers are generally used below their glass transition temperature, as they only have sufficient strength for use there. However, primary forming (see Chapter 4 "Processing") takes place far above this softening temperature, at which the amorphous polymer flows with as little resistance as possible.

The **Couette rheometer** (Figure 3.33) is made of two concentrically arranged cylinders in which the sample is subjected to a shear flow by rotation of a cylinder. The large shear areas on the cylinder walls allow large torques even with low flow resistance, so that even low-viscosity substances such as monomer solutions can be measured. A disadvantage, however, is that highly viscous thermoplastic melts cannot be measured. There are also error influences due to the flow in the bottom area and on the concentric circular ring surface.
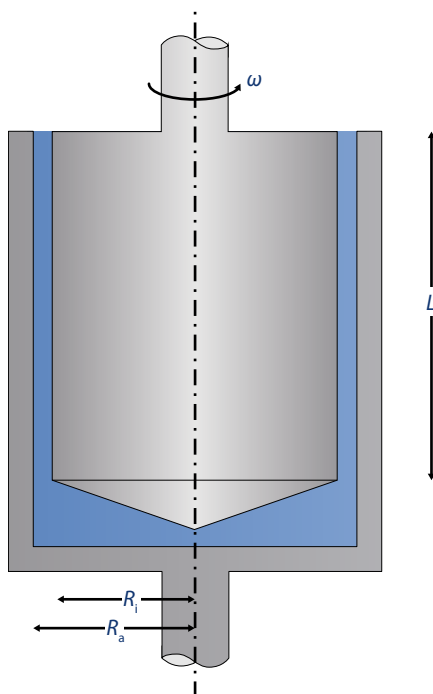

Figure 3.33
The Couette rheometer

Experiments with Rotational Rheometers

With rotational rheometers, different types of tests can be performed on melts (Figure 3.34). With a constant speed and thus a constant shear rate, the resulting shear stress can be determined by means of the torque setting. In this so-called **clamping test**, the viscosity function for small and medium shear rates can be determined by varying the speed and thus the shear rate.

A rotational rheometer can also be used to apply a constant shear stress and record the increasing shear. This is called a **creep test**. Conversely, a constant deformation and thus shear can be induced in the **relaxation test** and the spontaneous shear stress can be measured with its decay over time.

In the so-called **oscillation test**, oscillating shear is induced and the resulting torque/shear stress is measured. The vibration test mainly provides information about the viscoelastic behavior of the melt. A phase shift between 0° (purely elas-

tic behavior) and 90° (purely viscous behavior) occurs between the shear angle and the shear stress response, which can be used to characterize the viscoelastic properties of the plastic melt. The storage and loss modulus (G', G'') as well as the loss factor tan δ can be determined.
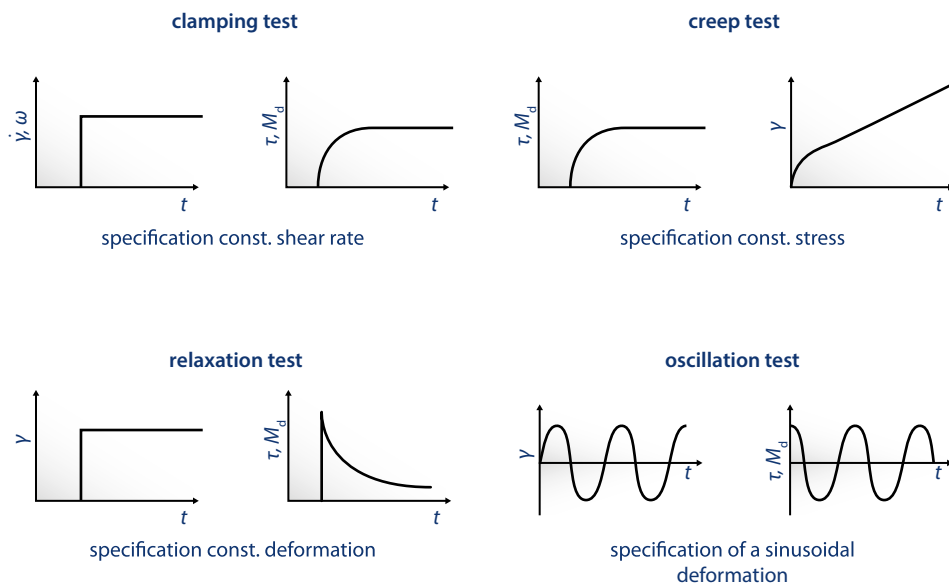

Figure 3.34 Different types of experiments with rotational rheometers

The qualitative viscosity curve shown in Figure 3.35 shows the shear rate range in which the various rheometers operate. The high-pressure capillary rheometer cannot achieve very low shear rates, but it can map the entire shear rate range relevant for plastics processing: from the very slow flow processes in thermoforming, through extrusion, to injection molding at very high shear rates.
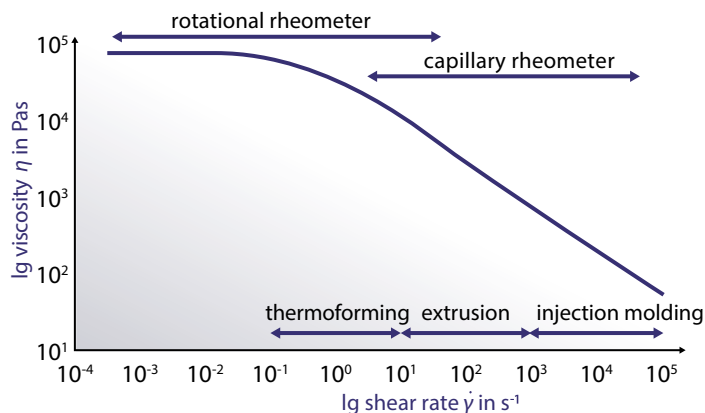
Figure 3.35
Application range of capillary and rotational rheometers
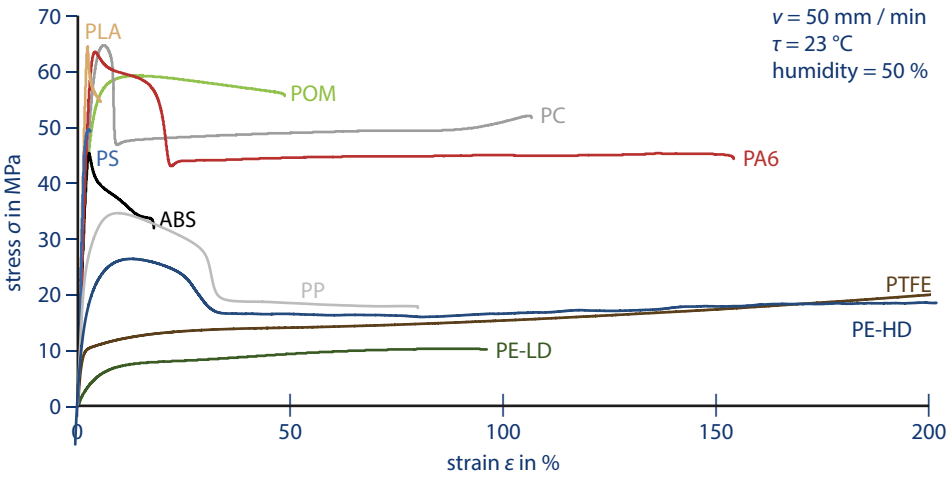
Figure 3.40 Comparison of different thermoplastics

Figure 3.41 qualitatively shows a typical stress-strain curve of a semi-crystalline thermoplastic. Close to the origin, i. e. in the range of small strains, plastics, including thermoplastics, behave in a linearly elastic manner. This means that after minor deformation they would spontaneously "reset" to their original state.
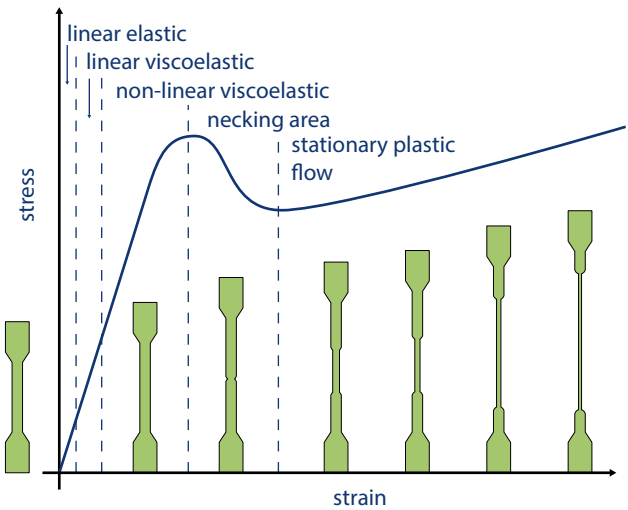
Figure 3.41
Deformation behavior under load; according to [3]

If one stretches a little further, a flow is superimposed, which can reset itself over time: here the material behaves linearly viscoelastically. In the further course of elongation, irreversible unloops, crazes, and microcracks, i. e. an irreversibly plastic deformation, are added. From now on, the material behaves as nonlinearly viscoelastic overall, because it still partially resets after relief.

Only after exceeding the yield point do the viscous behavior and the plastic deformation dominate, also recognizable by the constriction of the test specimen with a cross-sectional change. The elastic recovery is very low here.

3.2.1.2 The High Speed Tensile Test

Special testing machines allow for tensile tests at very high speeds. Figure 3.42 shows the high speed tensile testing machine of the IKT with test speeds of up to 20 m/s (!). In the background you can see the temperature chamber retracted here, very similar to that of the quasi-static tensile test (see above), so the temperature influence can also be recorded. An upper carrier grips a transverse yoke, which is attached to the upper part of a tensile specimen. The lower clamping is operated hydraulically.

moving traverse
upper carrier
broken specimen
clamping
load cell
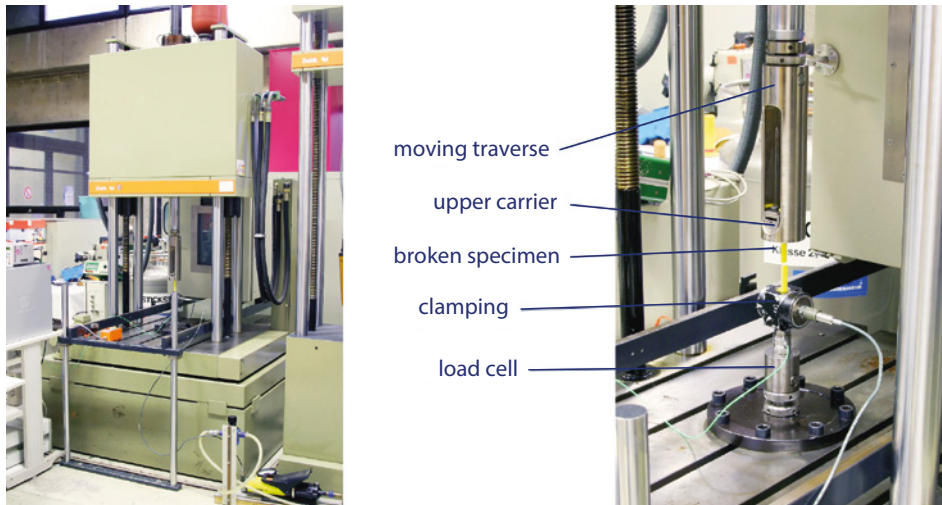
Figure 3.42 High speed tensile testing machine of the IKT

Characteristic for this test arrangement is the uniaxial tensile stress with determination of a stress-strain curve as in the quasi-static tensile test, but at very high speeds. Compared to the impact tensile test with a pendulum impact tester (see below), very high loading speeds can be applied and set at different heights. The specimen is also deformed at a constant speed, while an impact pendulum slows down when it hits the ground (see below). Stresses and strains can be measured fully instrumentally. A disadvantage is certainly the far greater equipment effort compared to an impact pendulum.

Figure 3.43 shows the behavior of polyoxymethylene (POM) at room temperature under load with very different strain rates. Lower strain rates result in greater strain at lower strength, while very high loading rates show less strain at higher strength.

This is changing right now. In 2009, BMW and carbon fiber specialist SGL Carbon (formerly Hoechst AG) founded the joint venture SGL Automotive Carbon Fibers. This ensures that BMW and its subsidiaries have an exclusive supply of carbon fiber-based materials and technologies. At the IAA 2013, BMW launched the i3, the world's first mass-produced vehicle with a passenger cell made of carbon fiber-reinforced plastics (CFRP). The chassis is still made of aluminum, and the electric motor has 125 kW (170 hp).

Figure 3.97
Leisure applications made of fiber-reinforced plastic composites
[Image source: IKT, IFB, Löhmann]

Fiber-reinforced plastic composites are also used in leisure applications. Figure 3.97 shows a boat hull made of glass fiber reinforced plastic (GFRP) (top), a bicycle frame made of carbon fiber reinforced plastic (CFRP) (middle), and the electric aircraft "e-Genius" (bottom), which is made entirely of carbon fiber reinforced plastic and manufactured by the Institute of Aircraft Construction (IFB) of the University of Stuttgart. These components, including the bicycle frame, are manufactured in small series.

3.3.1.1 Fibers and the Principle of Reinforcement

A small insight into textile technology is helpful: mostly glass fibers, carbon fibers (inorganic), or aramid and natural fibers (organic) are used. The individual threads are called filaments and have a diameter d of 5 to 50 µm. The fiber bundles used can be divided into the following groups depending on their length:

0.1 to 1 mm (short fibers)	$l/d > 10$
1 to 50 mm (long fibers)	$l/d > 1000$
> 50 mm (continuous fibers)	$l/d = \infty$

Figure 3.98 schematically illustrates how the stiffness, strength, and impact strength of plastics can be influenced as a function of fiber length. While the stiffness of even short fibers is strongly influenced, only long fibers and continuous fibers show a sharp increase in strength and impact strength.
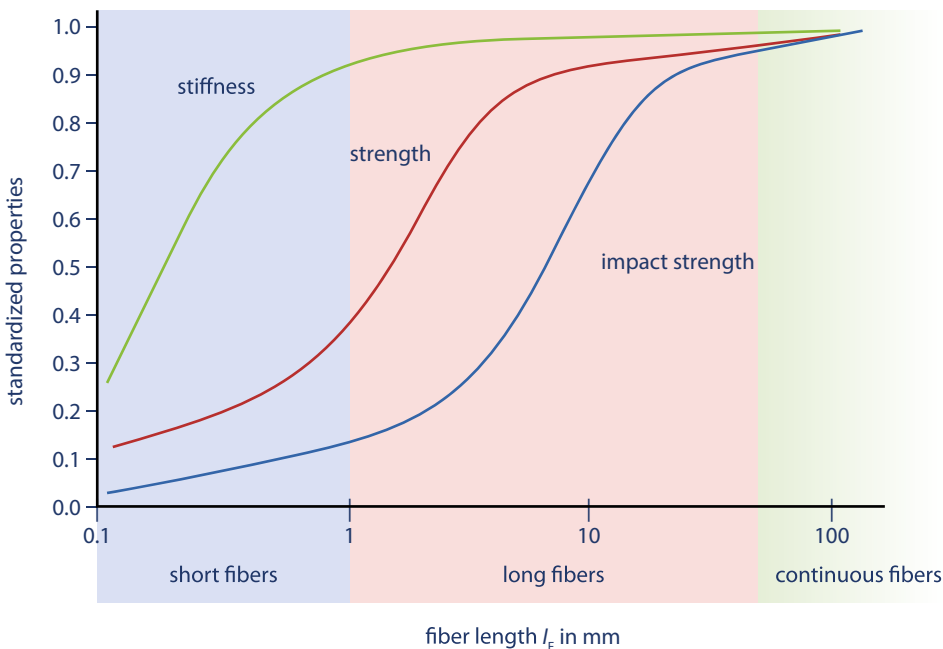
Figure 3.98 Fiber lengths influencing the mechanical properties of fiber–reinforced plastic composites [5]]

Abbreviation	Name	Section
High-performance thermoplastics		
PTFE	polytetrafluoroethylene	3.23
PEEK	polyether ether ketone	3.24
PES, PSU	polyethersulfone, polysulfone	3.25
PPS	polyphenylene sulfide	3.26
Thermoplastic biopolymers and bioplastics		
CA, CAB, CP	cellulose derivatives	3.27
PHA	polyhydroxyalkanoates	3.28
PLA	polylactide	3.29
Thermoplastic elastomers and other elastomers		
TPE-U/TPU	thermoplastic polyurethane	3.30
PUR	polyurethane	3.31
EPDM	ethylene-propylene-(diene) copolymer	3.10
Thermosets		
EP	epoxy resin	3.32
MF	melamine formaldehyde resin	3.33
PF	phenol-formaldehyde/phenol resin	3.34
UF	urea-formaldehyde resin	3.35
UP	unsaturated polyester resin	3.36

■ 3.8 Polyethylene (PE)

Semi-crystalline standard thermoplastic

Brief Description

Polyethylene can be produced in various polymerization processes that lead to a less or more branched chain structure.

$$- - - \left[\begin{array}{cc} \overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}} & \overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}} \end{array} \right]_{n} - - -$$
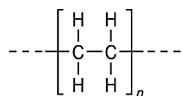
Processing

Polyethylenes can be converted in all processing methods usual for thermoplastics. All welding processes, except high-frequency welding, can also be used. Due to the non-polar structure, gluing and coating are only applicable after pre-treatment of the surfaces.

Properties during Use

Polyethylene crystallizes to different degrees due to the different types of production. The mechanical properties increase with crystallinity. Low density polyethylene (PE-LD) is not very stiff and very ductile. Therefore, it is rarely used as a construction material, mostly as a film.

High density polyethylene (PE-HD) can be used as a construction material despite the still low level of mechanical properties versus engineering plastics. It is quite strong, stiff, and very tough, shows low creep, and is moderately heat resistant. Its sliding wear and electrical properties are good, and its water absorption is low. Its chemical properties are excellent: it is resistant to salt solutions, acids, alkalis, alcohols, and gasoline (petrol). Below 60 °C it is insoluble in all organic solvents, but swells in aliphatic and aromatic hydrocarbons. Strong oxidizing agents such as fuming sulfuric acid, concentrated nitric acid, and chromium sulfuric acid attack polyethylene. Polyethylene is unstabilized, not UV-resistant, and burns like wax.

Fields of Application (Selection)

Structural components: toys, medical applications, gas and gasoline tanks, chemical containers (welded from semi-finished products), canisters, garbage cans, suitcases, simple garden seating, household cans, and bottle crates.

Other components: packaging, closures, piping.

Trade Names (Selection)

Alathon, Dowlex, Eltex, Eraclene, Escorene, Finathene, Fortiflex, Formolene, Hostalen, Lacqtene, Lupolen, marlex, Microthene, NeoZex, Novapol, Perothene, Polisul, Rigidex, Sclair, Sholex, Samylan, Samylex, Sumikathene, Unipol, Vestolen

Good Advice

Polyethylene is inexpensive and versatile. If the requirements for mechanical properties, especially those at higher temperatures, are not too high (low stiffness!), polyethylene can also be used for complex shaped parts.

Properties of Polyethylene

See Table 3.9.

annular melt is divided several times by the spider legs. This can lead to flow marks and mechanically weak points on this pipe.

In terms of flow dynamics, the spider legs should offer as little flow resistance as possible, i. e. be slim. However, it must be ensured that they keep the mandrel holder and the mandrel rigid in the tool. A solution is offered by somewhat more expensive double mandrel holders (Figure 4.18). They divide the melt several times, slightly offset, and lead to lower flow markings and better mechanical properties of the pipes.

Figure 4.18
Double mandrel holder

Figure 4.19 shows other common profile types that are manufactured in a very similar way. A distinction is made between the full profile and the pipe profile, the hollow profile, the open profile, and the chamber profile. Figure 4.20 shows typical examples of chamber profiles with window profiles.

pipe profile   hollow profile   open profile   chamber profile   solid profile
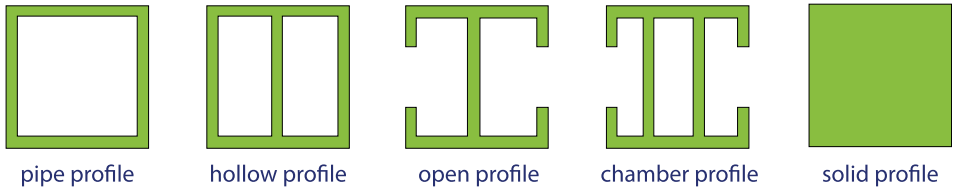
Figure 4.19 Profile cross-sections

QR-Code 4-4

The video shows the extrusion of a PVC window profile: die exit, calibration, cooling, pull-off unit and assembly (Aluplast GmbH, Karlsruhe).

http://www.ikt.uni-stuttgart.de/links/Videolinks/Profilextrusion
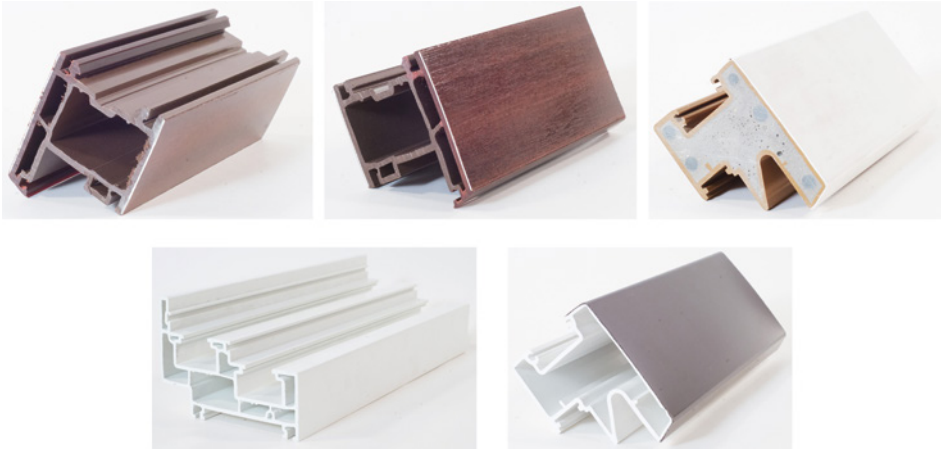
Figure 4.20 Window profiles

The die exit usually does not have exactly the same shape and dimensions as the later profile (Figure 4.21). The shape and dimensions of the extrudate strand are influenced by several factors after leaving the die:

- the pull-off force,
- the die swell (see Section 3.1.6),
- the relaxation processes in the melt, and
- the cooling rate.
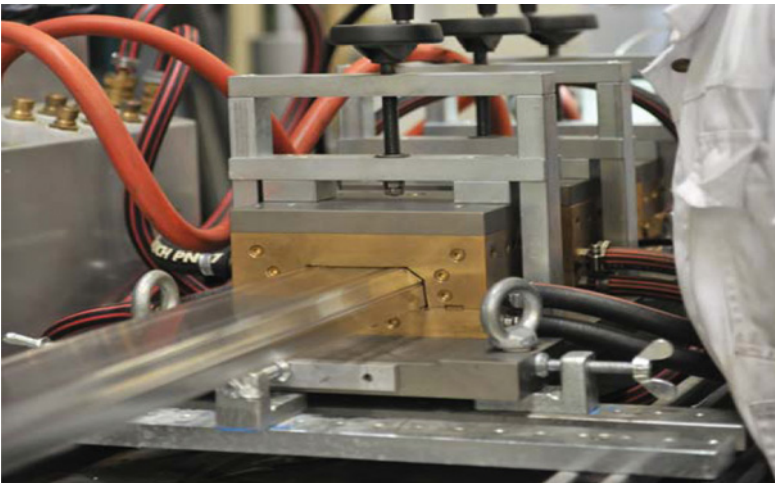
Figure 4.21 Profile extrusion [Image source: Technoform Kunststoffprofile GmbH]

Further remedial measures against component warpage are listed here:

- Mold temperature as uniform as possible
- Cooling time as long as possible
  (possibly expensive)   } Process engineer
- Annealing under form constraint
  (additional step: expensive)

- Selection of a stiff material
- Insertion of stiffening elements
  (ribs, stepped zones, …)   } Product developer/designer
- uniform wall thicknesses

Figure 5.33
Broken door handle with void and brittle fracture

If an insert is to be overmolded, the mass accumulations associated with this can also be reduced by rethinking the shape. The designer's creativity is required here (Figure 5.34)!

insert

mass accumulation

avoid mass accumulation through other shape
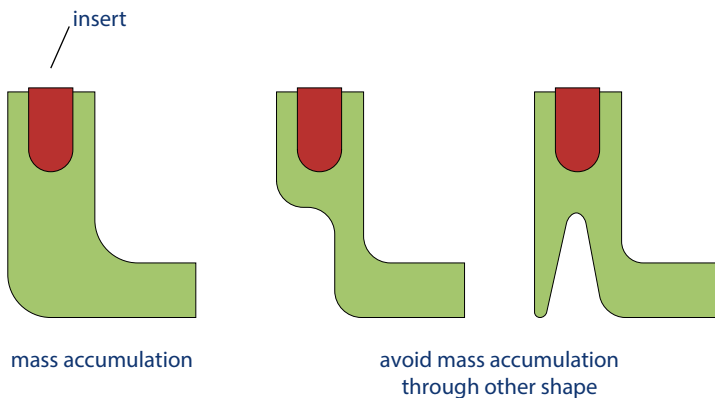
Figure 5.34 Avoidance of mass accumulations

Figure 5.35 gives suggestions for avoiding mass accumulations in the corner areas of a component.

mass accumulation
in corner areas

avoid mass accumulation
through other shape
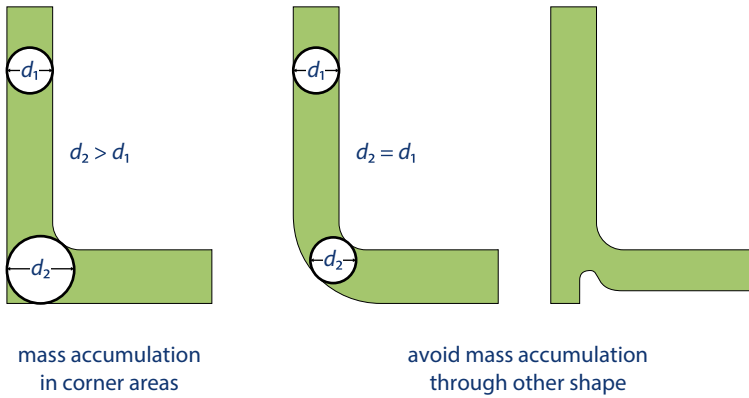
Figure 5.35 Avoidance of mass accumulations in the corner area [12]

Ribs should also be relatively thin-walled in order to enable rapid heat dissipation and thereby keep the cooling time to a minimum. If component stiffness is not achieved, the number of ribs should be increased rather than their thickness. Figure 5.36 shows empirically determined design recommendations.
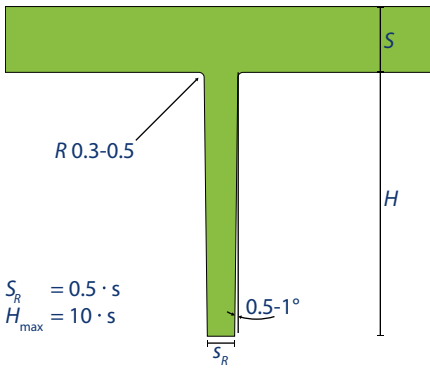
Figure 5.36
Dimensioning recommendation – empirically determined

As a reference value for the rib thickness S_R and the rib height H is valid:

$$S_R \approx 0.5 \cdot S \tag{5.3}$$

$$H_{max} \leq 10 \cdot S \tag{5.4}$$

Index

Symbols