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Plastics Handbook

The Resource for Plastics Engineers

5th Edition

Hanser Publishers, Munich

HANSER

Hanser Publications, Cincinnati

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Distributed in the Americas by:

Hanser Publications

6915 Valley Avenue, Cincinnati, Ohio 45244-3029, USA

Fax: (513) 527-8801

Phone: (513) 527-8977

www.hanserpublications.com

Distributed in all other countries by:

Carl Hanser Verlag

Postfach 86 04 20, 81631 Munich, Germany

Fax: +49 (89) 98 48 09

www.hanser-fachbuch.de

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Cataloging-in-Publication Data is on file with the Library of Congress

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© Carl Hanser Verlag, Munich 2019

Editor: Dr. Mark Smith

Translation: Dr. Christine Strohm, Engineering and Science Editors

Production Management: Jörg Strohbach

Coverconcept: Marc Müller-Bremer, www.rebranding.de, Munich

Coverdesign: Stephan Rönigk

Typesetting: Kösel Media GmbH, Krugzell

Printed and bound by Druckerei Hubert & Co GmbH und Co KG BuchPartner, Göttingen

Printed in Germany

ISBN: 978-1-56990-559-3

E-Book ISBN: 978-1-56990-560-9

Preface

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

Winter 2018

Erwin Baur, Tim A. Osswald, and Natalie Rudolph

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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 time-liness 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.



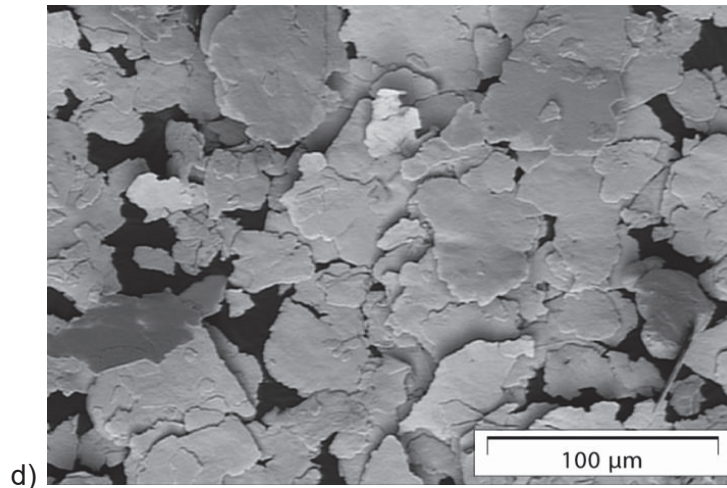


Figure 3.14 Change in filler orientation caused by variation in specimen thickness d for PA 6 + 30 vol.-% Cu compound; dimensions: 50 x 50 x d [mm³]; flow direction from left to right [2]
 a) Micrograph of outer layer
 b) Micrograph of specimen center
 c) Sketch of the positions of extracted polished sections
 d) REM micrograph of the Cu filler

■ 3.3 Mechanical Properties

The mechanical behavior of plastic materials depends on a variety of factors:

- Rate of deformation,
- Duration and frequency of load,
- Specimen geometry,
- Processing parameters during specimen manufacture, and
- Ambient conditions, in particular temperature.

The tensile test is a suitable means to exemplify the effects of these factors on the behavior of plastic materials.

3.3.1 Short-Term Behavior

3.3.1.1 Accelerated Tensile Test

The mechanical behavior of plastics, *i. e.*, the correlation between stress σ and the resulting strain ϵ or between the load F acting on a component and the resulting deformation ΔL , is best characterized using tensile testing. During short-term tensile tests, tensile bars (dog-bone shaped specimens, see Fig. 3.15, top) are elon-

gated at a constant rate while the load F and the change in length ΔL of the measured length L_0 is recorded. The stress σ (in N/mm^2) can be calculated by dividing the load by the original cross sectional area A_0 of the specimen, while the strain ϵ (in %) is derived from the change in length divided by the original specimen L_0 . In general, the slope of the load/deformation curve is used to calculate the modulus of elasticity E as the ratio between stress and strain.

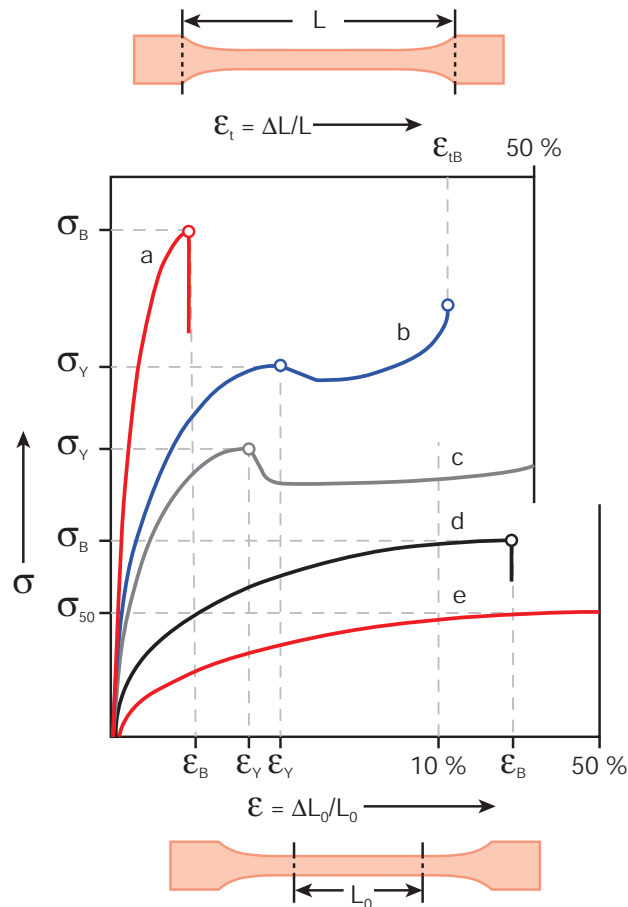


Figure 3.15 Schematic σ/ϵ -diagrams based on CAMPUS data for tensile tests;
a: brittle plastic, b: ductile plastic, c: stretched plastic, d and e: plasticized plastic
 σ_B = stress at break ϵ_B = strain at break
 σ_Y = yield stress ϵ_Y = yield strain
 σ_{50} = stress at 50% strain ϵ_{tB} = nominal strain at break

Figure 3.15 uses the stress-strain diagram to show the characteristic data (according to CAMPUS) typically used to evaluate plastic materials. For plastics exhibiting yield stress or major deformation prior to break, nominal strain at break (in %) is determined using the change in gripping distance and the original clamping distance.

It is used as a comparative value, describing a plastic's elasticity under tensile load.

Figure 3.16 shows real stress-strain diagrams for several plastic classes. Note that the y-axis in the left part of the figure (strain up to 20%) is depicted at a 5 times larger scale than that of the y-axis on the right part of the figure to allow for a clearer depiction.

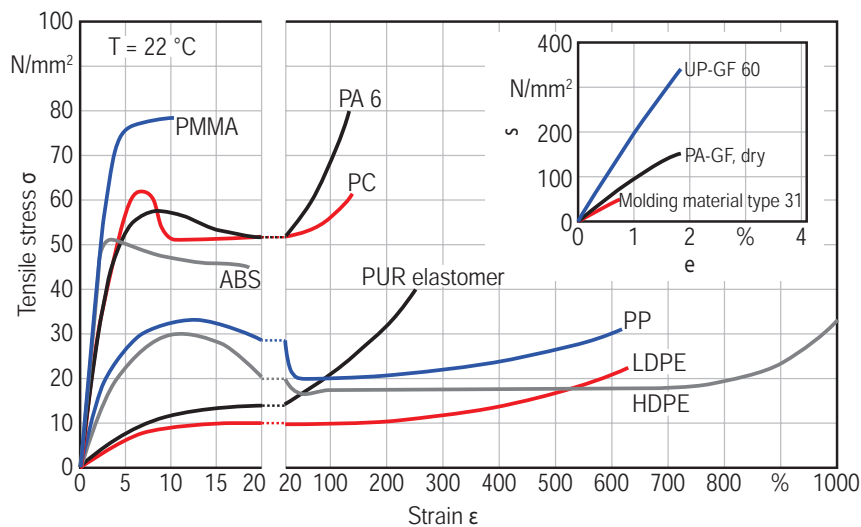


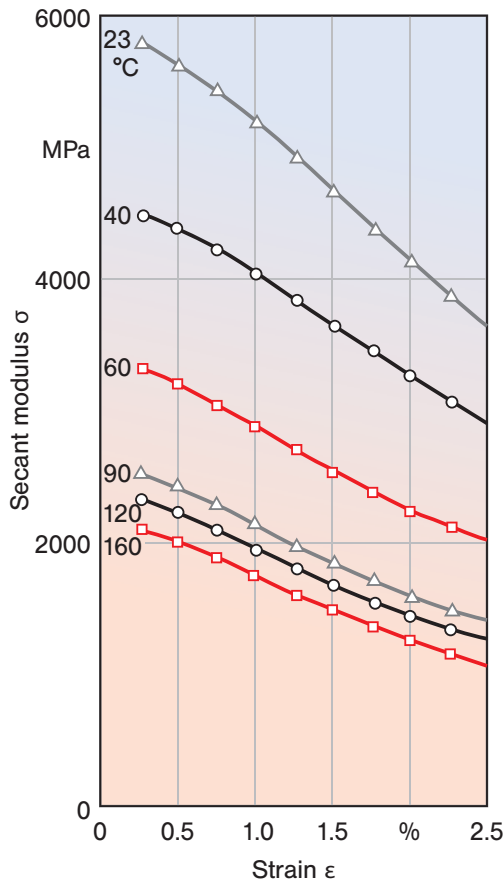
Figure 3.16 Examples of stress-strain diagrams derived from tensile tests

With the help of these diagrams the characteristic values defined in Figure 3.15 can be determined. The diagrams can also be used to compare plastic materials with decidedly different levels of flexibility.

Most plastics do not exhibit a linear section in their stress-strain diagrams, and therefore it is not permissible here to use the slope of load/deformation curve to calculate the modulus of elasticity. Figure 3.17 demonstrates this fact clearly: plotted is the slope of the straight line from the origin of the stress-strain curve to the strain value considered (also called secant modulus). The modulus exhibits strong strain dependence. In order to determine the “modulus of elasticity”, the slope of stress-strain curve between 0.05% and 0.25% strain is used alternatively.

It is important to note that the characteristics determined for any given molded component may not reflect the data measured for a standardized testing specimen.

A special tensile test is used with notched film specimens to determine both edge tear and tear propagation resistance (force required to propagate tearing in proportion to specimen thickness) according to Graves.

**Figure 3.17**

Secant modulus for glass fiber reinforced PA 6

3.3.1.2 Short-Term Bend Test

In short-term bend tests, the ends of a beam-like specimen (80 mm × 10 mm × 4 mm) are placed on two supports and then a load is applied to the middle of the specimen using a bending punch. The measured loads and bending deflections are used to calculate the characteristics defined in Figure 3.18:

$$\text{Flexural stress } \sigma_b = \frac{3 \cdot F \cdot l_v}{2 \cdot b \cdot h^2} \quad \text{in N/mm}^2 \quad (3.6)$$

$$\text{Outer fiber strain } \varepsilon_b = \frac{600 \cdot h \cdot f}{l_v^2} \quad \text{in \%} \quad (3.7)$$

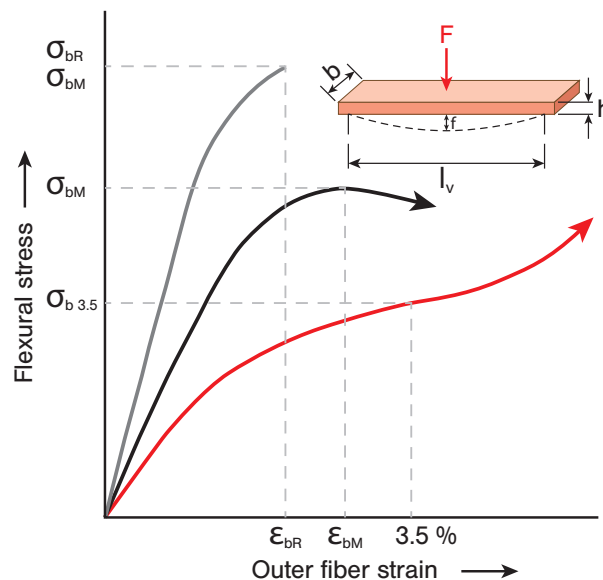


Figure 3.18 Schematic σ/ϵ diagrams for bending tests

σ_{bM} = Bending strength ϵ_{bM} = Outer fiber strain at maximum stress
 $\sigma_{b3.5}$ = 3.5% bending stress
 σ_{bR} = Bending stress at break ϵ_{bR} = Outer fiber strain at break

There are a number of reasons why the tensile test is preferred compared to the bending test. For one, tensile tests can be performed even with flexible plastics such as elastomers. In addition, the bending test often leads to exaggerated strength characteristics. Unfortunately, the bending test is still commonly used because it is less expensive, even though the characteristic data it provides are not relevant in practice. When a beam is bent, the outer fibers are either strained or compressed while the neutral fibers are not deformed. The strain increases in direct proportion with the distance to the neutral fiber. If the correlation between stress and strain is linear (as determined in the stress-strain diagram), the stress distribution through the beam thickness is also linear. However, plastics may also be under load outside the linear range (in particular under short-term loads) and then the stress profile through the beam cross section is no longer linear. In this case, the equation representing the elastic line that is employed to calculate the bending stress is no longer valid and the calculated stress values are too high. The further the stress-strain lines (determined with the help of the stress-strain diagram) deviate from linearity, the higher is the difference between the calculated bending strength values and the tensile strength and/or yield stress values that were determined by tensile testing. Then bending strength is only a notional stress that actually does not reflect the component, because failure will occur as soon as the tensile strength is exceeded. For these reasons alone, bending tests should be performed only with long fiber reinforced plastics to determine strength characteristics, *e.g.*, interlaminar shear strength.

3.3.1.3 Compression Test

Compression tests are used to determine material behavior under uniaxial compression load. However, in industrial practice it is relevant only for the evaluation of fiber reinforced and foamed plastics. Other than in high fiber reinforced plastics, compression stress does not cause failure. Therefore, compression testing is rarely used for the evaluation of plastics. Highly uniaxially reinforced plastics may delaminate under compression stress. These products are compression tested by laterally supporting a slim specimen, thus preventing buckling. Characteristics analogous to those derived from tensile tests are determined here.

3.3.1.4 Indentation Test, Hardness Measurements

Indentation tests determine the indentation resistance as well as the indentation depth of a defined body into a plastic surface. There is a certain correlation between hardness and modulus of elasticity when the elastic deformation predominates during testing; otherwise the characteristic values do not provide suitable comparative data for component design.

Plastics and elastomers can be evaluated with respect to their *Shore hardness*. The resistance against the penetration of a truncated cone (Shore A for flexible plastics and elastomers) or of a cone with rounded tip (Shore D for rigid elastomers and thermoplastics) is measured as the deformation of a spring 3 seconds (or 15 seconds for plastics with decidedly plastic behavior) after indentation of the tester into the surface of the specimen (Fig. 3.19).

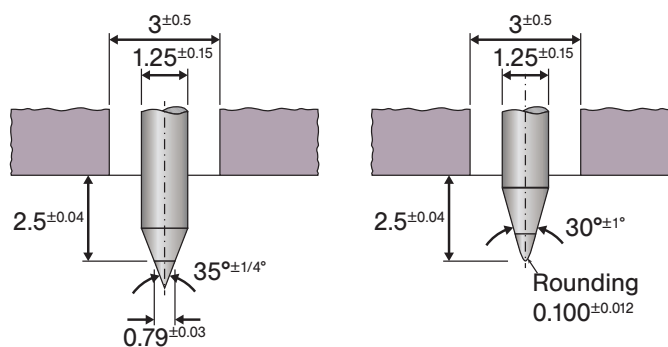


Figure 3.19 Indenter for the determination of Shore hardness

Table 3.3 provides an overview of the methods available for the determination of hardness, most of which were developed for metals and are of only limited suitability for applications in plastics technology.

Table 3.3 Comparison of Hardness Tests for Plastics

Test	Standard	Test			Application
		Indenter	Under load, depth of indentation	After load removal	
Shore A	ISO 868	Fig. 3.19	X		Soft elastomers and thermoplastics
Shore D	ISO 868	Fig. 3.19	X		Rigid elastomers and thermoplastics
Ball indentation hardness H	ISO 2039-1	Ball, Ø 5 mm	X		Thermoplastics and thermosets
Rockwell- α -hardness R α	ISO 2039-2	Ball, Ø depending on hardness scale R, L, M, E	X		Suitable for the determination of mechanical anisotropy effects
Rockwell HR	ISO 2039-2	Ball, Ø depending on hardness scale		X	
Vickers hardness HV	ISO 6507	Diamond pyramid with square base		X	Well suited for the determination of mechanical anisotropy effects
Knoop-hardness HKn	ASTM D1474	Pyramid with rhombic base		X	Excellent suited for the determination of mechanical anisotropy effects

Anisotropy effects: e. g., orientations and residual stresses, filler orientation, hardness profile in weld lines

3.3.2 Impact Behavior

3.3.2.1 Characteristics

The shear rate during short-term tensile tests is selected so that the characteristic strength values are reached within approx. 1 min. Plastics are viscoelastic materials and therefore their characteristics depend on the rate of the applied load. Figure 3.20 uses an ABS + PA 6 blend as an example to show that the yield stress increases with increasing shear rate while the strain at break decreases. The modulus of elasticity also increases with increasing loading rate. This indicates that data determined with the help of short-term tests have no relevance for processes taking place in extremely short time intervals, e. g., crash simulation in automotive engineering.