TENSILE TESTING

Second Edition

ASM
INTERNATIONAL

Tensile Testing

Second Edition

Edited by
J.R. Davis
Davis & Associates

The Materials
Information Society
Materials Park, Ohio 44073-0002
www.asminternational.org

Preview for: *Tensile Testing* (Second Edition), edited by J.R. Davis, ASM International, 2004
Full digital book available at https://doi.org/10.31399/asm.tb.tt2.9781627083553

Copyright © 2004
by
ASM International®
All rights reserved

No part of this book may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the written permission of the copyright owner.

First printing, December 2004

Great care is taken in the compilation and production of this book, but it should be made clear that NO WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, ARE GIVEN IN CONNECTION WITH THIS PUBLICATION. Although this information is believed to be accurate by ASM, ASM cannot guarantee that favorable results will be obtained from the use of this publication alone. This publication is intended for use by persons having technical skill, at their sole discretion and risk. Since the conditions of product or material use are outside of ASM's control, ASM assumes no liability or obligation in connection with any use of this information. No claim of any kind, whether as to products or information in this publication, and whether or not based on negligence, shall be greater in amount than the purchase price of this product or publication in respect of which damages are claimed. THE REMEDY HEREBY PROVIDED SHALL BE THE EXCLUSIVE AND SOLE REMEDY OF BUYER, AND IN NO EVENT SHALL EITHER PARTY BE LIABLE FOR SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES WHETHER OR NOT CAUSED BY OR RESULTING FROM THE NEGLIGENCE OF SUCH PARTY. As with any material, evaluation of the material under end-use conditions prior to specification is essential. Therefore, specific testing under actual conditions is recommended.

Nothing contained in this book shall be construed as a grant of any right of manufacture, sale, use, or reproduction, in connection with any method, process, apparatus, product, composition, or system, whether or not covered by letters patent, copyright, or trademark, and nothing contained in this book shall be construed as a defense against any alleged infringement of letters patent, copyright, or trademark, or as a defense against liability for such infringement.

Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

Prepared under the direction of the ASM International Technical Book Committee (2004–2005), Yip-Wah Chung, Chair (FASM).

ASM International staff who worked on this project include Scott Henry, Senior Manager of Product and Service Development; Bonnie Sanders, Manager of Production; Carol Polakowski, Production Supervisor; and Pattie Pace, Production Coordinator.

Library of Congress Cataloging-in-Publication Data

Tensile testing / edited by J.R. Davis.—2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-87170-806-X
1. Materials—Testing. 2. Brittleness. 3. Tensiometers. I. Davis, J. R. (Joseph R.)
TA418.16.T46 2004
620.1′126—dc22 2004057353

ISBN: 0-87170-806-X
SAN: 204-7586

ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

Printed in the United States of America

Downloaded from http://dl.asminternational.org/technical-books/monograph/173/bookpreview-pdf/605712
by guest

Preview for: *Tensile Testing* (Second Edition), edited by J.R. Davis, ASM International, 2004
Full digital book available at https://doi.org/10.31399/asm.tb.tt2.9781627083553

Contents

Section 1 Tensile Testing: Understanding the Basics

Section 2 Tensile Testing of Engineered Materials and Components

Section 3 Tensile Testing at Extreme Temperatures or High-Strain Rates

Section 4 Reference Information

Preview for: *Tensile Testing* (Second Edition), edited by J.R. Davis, ASM International, 2004
Full digital book available at https://doi.org/10.31399/asm.tb.tt2.9781627083553

Preface

In the preface to the first edition of *Tensile Testing*, editor Patricia Han wrote "Our vision for this book was to provide a volume that could serve not only as an introduction for those who are just starting to perform tensile tests and use tensile data, but also as a source of more detailed information for those who are better acquainted with the subject. We have written this reference book to appeal to laboratory managers, technicians, students, designers, and materials engineers." This vision has been preserved in the current edition, with some very important new topics added.

As in the first edition, section one opens with an introduction that discusses the fundamentals and language of tensile testing. Subsequent chapters describe test methodology and equipment, the use of tensile testing for design, and the use of tensile testing for determining the formability of sheet metals.

The second section consists of five chapters that deal with tensile testing of the major classes of engineering materials—metals, plastics, elastomers, ceramics, and composites. New material on testing of adhesively bonded joints, welded joints, and threaded fasteners has been added.

The third section contains chapters that review testing at elevated and low temperatures and special tests carried out at very high strain rates. Although these subjects were introduced in the first edition, they have been substantially expanded in this book.

In the fourth and final section, a glossary of terms related to tensile testing and properties has been compiled. Comprehensive tables provide tensile yield strengths of various materials and compare the elastic modulus of engineering materials.

In summary, this edition retains much of the flavor of the first edition while introducing readers to a number of additional topics that will extend their knowledge and appreciation of the tensile test.

Joseph R. Davis
Davis & Associates
Chagrin Falls, Ohio

Preview for: *Tensile Testing* (Second Edition), edited by J.R. Davis, ASM International, 2004
Full digital book available at https://doi.org/10.31399/asm.tb.tt2.9781627083553

CHAPTER 1

Introduction to Tensile Testing

TENSILE TESTS are performed for several reasons. The results of tensile tests are used in selecting materials for engineering applications. Tensile properties frequently are included in material specifications to ensure quality. Tensile properties often are measured during development of new materials and processes, so that different materials and processes can be compared. Finally, tensile properties often are used to predict the behavior of a material under forms of loading other than uniaxial tension.

The strength of a material often is the primary concern. The strength of interest may be measured in terms of either the stress necessary to cause appreciable plastic deformation or the maximum stress that the material can withstand. These measures of strength are used, with appropriate caution (in the form of safety factors), in engineering design. Also of interest is the material's ductility, which is a measure of how much it can be deformed before it fractures. Rarely is ductility incorporated directly in design; rather, it is included in material specifications to ensure quality and toughness. Low ductility in a tensile test often is accompanied by low resistance to fracture under other forms of loading. Elastic properties also may be of interest, but special techniques must be used to measure these properties during tensile testing, and more accurate measurements can be made by ultrasonic techniques.

This chapter provides a brief overview of some of the more important topics associated with tensile testing. These include:

- Tensile specimens and test machines
- Stress-strain curves, including discussions of elastic versus plastic deformation, yield points, and ductility
- True stress and strain
- Test methodology and data analysis

It should be noted that subsequent chapters contain more detailed information on these topics. Most notably, the following chapters should be referred to:

- Chapter 2, "Mechanical Behavior of Materials Under Tensile Loads"
- Chapter 3, "Uniaxial Tensile Testing"
- Chapter 4, "Tensile Testing Equipment and Strain Sensors"

Tensile Specimens and Testing Machines

Tensile Specimens. Consider the typical tensile specimen shown in Fig. 1. It has enlarged ends or shoulders for gripping. The important part of the specimen is the gage section. The cross-sectional area of the gage section is reduced relative to that of the remainder of the specimen so that deformation and failure will be

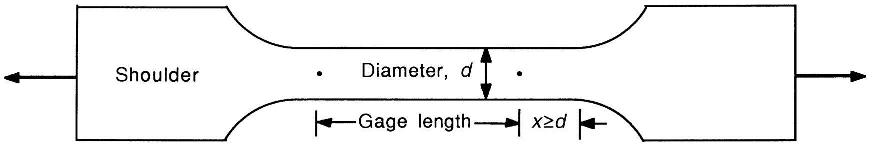


Fig. 1 Typical tensile specimen, showing a reduced gage section and enlarged shoulders. To avoid end effects from the shoulders, the length of the transition region should be at least as great as the diameter, and the total length of the reduced section should be at least four times the diameter.

localized in this region. The gage length is the region over which measurements are made and is centered within the reduced section. The distances between the ends of the gage section and the shoulders should be great enough so that the larger ends do not constrain deformation within the gage section, and the gage length should be great relative to its diameter. Otherwise, the stress state will be more complex than simple tension. Detailed descriptions of standard specimen shapes are given in Chapter 3 and in subsequent chapters on tensile testing of specific materials.

There are various ways of gripping the specimen, some of which are illustrated in Fig. 2. The end may be screwed into a threaded grip, or it may be pinned; butt ends may be used, or the grip section may be held between wedges. There are still other methods (see, for example, Fig. 24 in Chapter 3). The most important concern in the selection of a gripping method is to ensure that the specimen can be held at the maximum load without slippage or failure in the grip section. Bending should be minimized.

Testing Machines. The most common testing machines are universal testers, which test materials in tension, compression, or bending. Their primary function is to create the stress-strain curve described in the following section in this chapter.

Testing machines are either electromechanical or hydraulic. The principal difference is the method by which the load is applied.

Electromechanical machines are based on a variable-speed electric motor; a gear reduction system; and one, two, or four screws that move the crosshead up or down. This motion loads the specimen in tension or compression. Crosshead speeds can be changed by changing the speed of the motor. A microprocessor-based closed-loop servo system can be implemented to accurately control the speed of the crosshead.

Hydraulic testing machines (Fig. 3) are based on either a single or dual-acting piston that moves the crosshead up or down. However, most static hydraulic testing machines have a single acting piston or ram. In a manually operated machine, the operator adjusts the orifice of a pressure-compensated needle valve to control the rate of loading. In a closed-loop hydraulic servo system, the needle valve is replaced by an electrically operated servo valve for precise control.

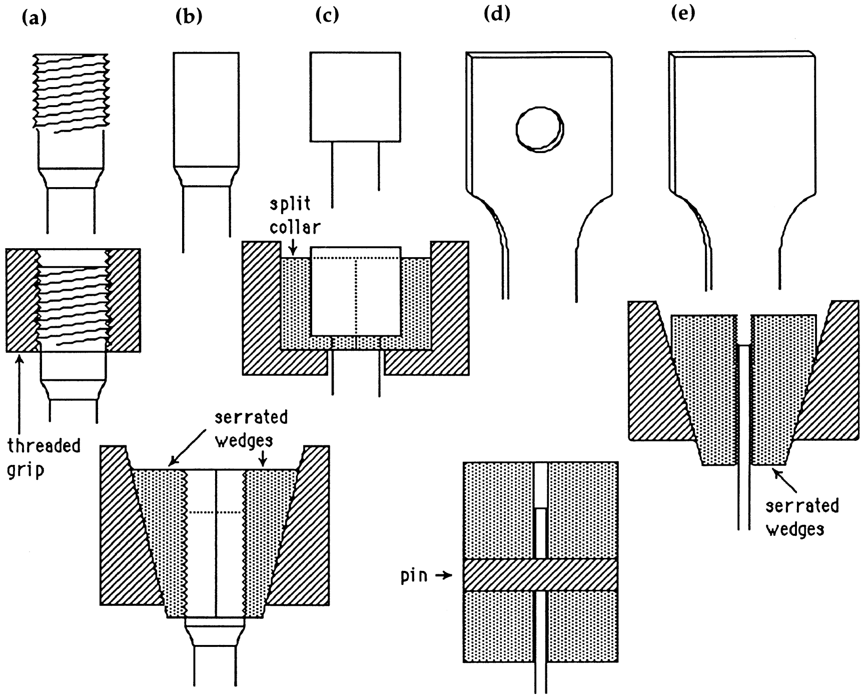


Fig. 2 Systems for gripping tensile specimens. For round specimens, these include threaded grips (a), serrated wedges (b), and, for butt end specimens, split collars constrained by a solid collar (c). Sheet specimens may be gripped with pins (d) or serrated wedges (e).

In general, electromechanical machines are capable of a wider range of test speeds and longer crosshead displacements, whereas hydraulic machines are more cost-effective for generating higher forces.

Stress-Strain Curves

A tensile test involves mounting the specimen in a machine, such as those described in the previous section, and subjecting it to tension. The tensile force is recorded as a function of the increase in gage length. Figure 4(a) shows a typical curve for a ductile material. Such plots of tensile force versus tensile elongation would be of little value if they were not normalized with respect to specimen dimensions.

Engineering stress, or nominal stress, s, is defined as

$$s = F/A_0 \qquad \text{(Eq 1)}$$

where F is the tensile force and A_0 is the initial cross-sectional area of the gage section.

Engineering strain, or nominal strain, e, is defined as

$$e = \Delta L/L_0 \qquad \text{(Eq 2)}$$

where L_0 is the initial gage length and ΔL is the change in gage length ($L - L_0$).

When force-elongation data are converted to engineering stress and strain, a stress-strain curve (Fig. 4b) that is identical in shape to the force-elongation curve can be plotted. The advantage of dealing with stress versus strain rather than load versus elongation is that the stress-strain curve is virtually independent of specimen dimensions.

Elastic versus Plastic Deformation. When a solid material is subjected to small stresses, the bonds between the atoms are stretched. When the stress is removed, the bonds relax and the material returns to its original shape. This re-

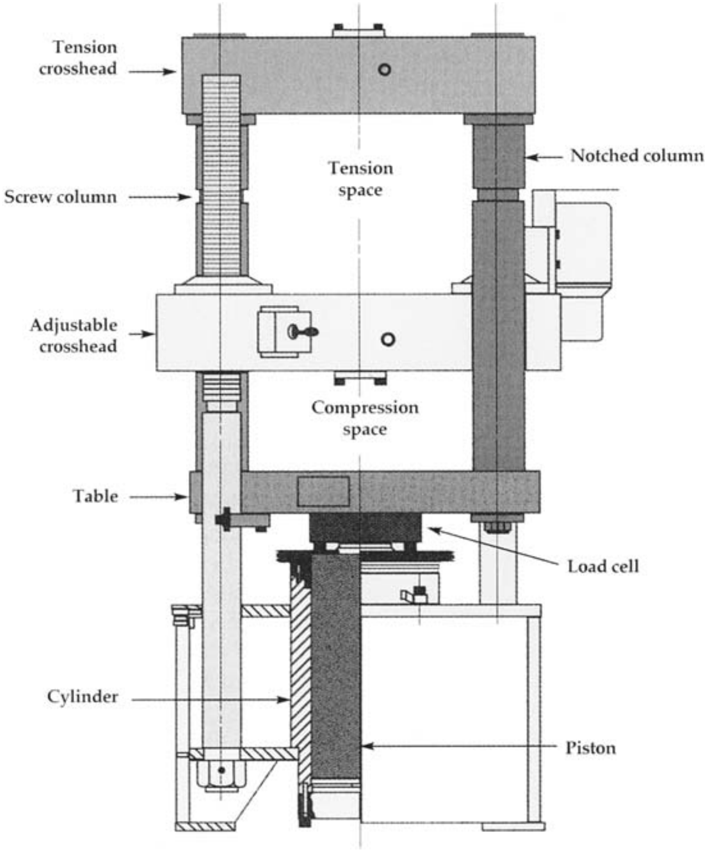
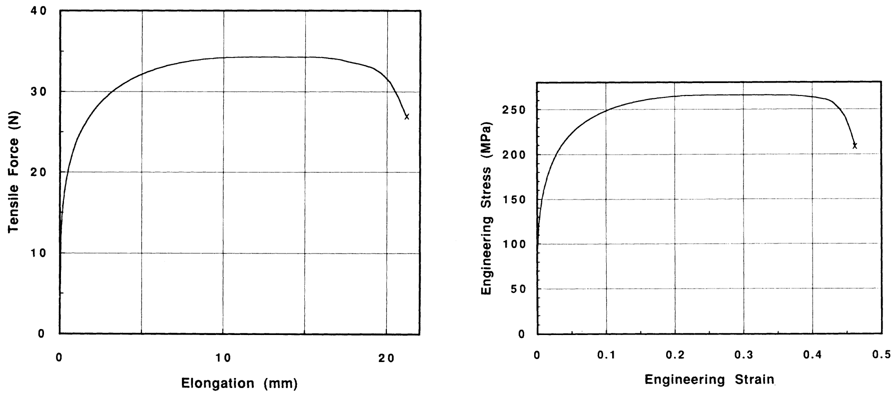


Fig. 3 Components of a hydraulic universal testing machine



(a) (b)

Fig. 4 (a) Load-elongation curve from a tensile test and (b) corresponding engineering stress-strain curve. Specimen diameter, 12.5 mm; gage length, 50 mm.

versible deformation is called *elastic deformation.* (The deformation of a rubber band is entirely elastic). At higher stresses, planes of atoms slide over one another. This deformation, which is not recovered when the stress is removed, is termed *plastic deformation.* Note that the term "plastic deformation" does not mean that the deformed material is a plastic (a polymeric material). Bending of a wire (such as paper-clip wire) with the fingers (Fig. 5) illustrates the difference. If the wire is bent a little bit, it will snap back when released (top). With larger bends, it will unbend elastically to some extent on release, but there will be a permanent bend because of the plastic deformation (bottom).

For most materials, the initial portion of the curve is linear. The slope of this linear region is called the *elastic modulus* or *Young's modulus:*

$$E = s/e \qquad \text{(Eq 3)}$$

In the elastic range, the ratio, υ, of the magnitude of the lateral contraction strain to the axial strain is called *Poisson's ratio:*

$$\upsilon = -e_y/e_x \text{ (in an } x\text{-direction tensile test)} \qquad \text{(Eq 4)}$$

Because elastic strains are usually very small, reasonably accurate measurement of Young's modulus and Poisson's ratio in a tensile test requires that strain be measured with a very sensitive extensometer. (Strain gages should be used for lateral strains.) Accurate results can also be obtained by velocity-of-sound measurements (unless the modulus is very low or the damping is high, as with polymers).

When the stress rises high enough, the stress-strain behavior will cease to be linear and the strain will not disappear completely on unloading. The strain that remains is called plastic strain. The first plastic strain usually corresponds to the first deviation from linearity. (For some materials, the elastic deformation may be nonlinear, and so there is not always this correspondence). Once plastic deformation has begun, there will be both elastic and plastic contributions to the total strain, e_T. This can be expressed as $e_T = e_e + e_p$, where e_p is the plas-

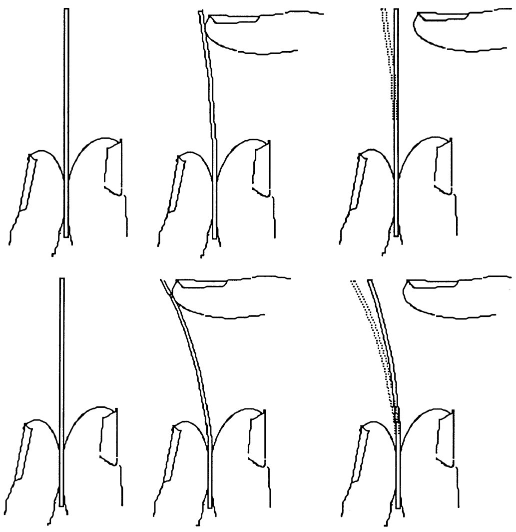


Fig. 5 Elastic and plastic deformation of a wire with the fingers. With small forces (top), all of the bending is elastic and disappears when the force is released. With greater forces (below), some of the bending is recoverable (elastic), but most of the bending is not recovered (is plastic) when the force is removed.

tic contribution and e_e is the elastic contribution (and still related to the stress by Eq 3).

It is tempting to define an *elastic limit* as the stress at which plastic deformation first occurs and a *proportional limit* as the stress at which the stress-strain curve first deviates from linearity. However, neither definition is very useful, because measurement of the stress at which plastic deformation first occurs or the first deviation from linearity is observed depends on how accurately strain can be measured. The smaller the plastic strains that can be sensed and the smaller the deviations from linearity can be detected, the smaller the elastic and proportional limits.

To avoid this problem, the onset of the plasticity is usually described by an offset *yield strength,* which can be measured with greater reproducibility. It can be found by constructing a straight line parallel to the initial linear portion of the stress-strain curve, but offset by $e = 0.002$ or 0.2%. The yield strength is the stress at which this line intersects the stress-strain curve (Fig. 6). The rationale is that if the material had been loaded to this stress and then unloaded, the unloading path would have been along this offset line and would have resulted in a plastic strain of $e = 0.2\%$. Other offset strains are sometimes used. The advantage of defining yield strength in this way is that such a parameter is easily reproduced and does not depend heavily on the sensitivity of measurement.

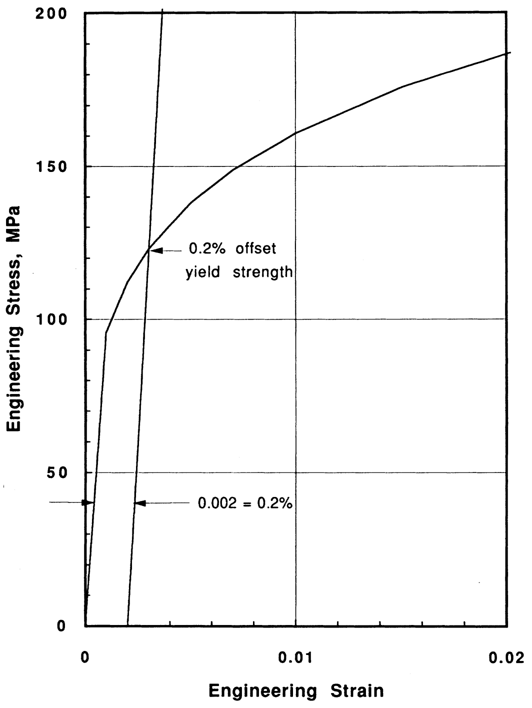


Fig. 6 The low-strain region of the stress-strain curve for a ductile material

Sometimes, for convenience, yielding in metals is defined by the stress required to achieve a specified total strain (e.g., $e_T = 0.005$ or 0.5% elongation) instead of a specified offset strain. In any case, the criterion should be made clear to the user of the data.

Yield Points. For some materials (e.g., low-carbon steels and many linear polymers), the stress-strain curves have initial maxima followed by lower stresses, as shown in Fig. 7(a) and (b). After the initial maximum, all the deformation at any instant is occurring within a relatively small region of the specimen. Continued elongation of the specimen occurs by propagation of the deforming region (Lüders band in the case of steels) along the gage section rather than by increased strain within the deforming region. Only after the entire gage section has been traversed by the band does the stress rise again. In the case of linear polymers, a yield strength is often defined as the initial maximum stress. For steels, the subsequent *lower* yield strength is used to describe yielding. This is because measurements of the initial maximum or *upper* yield strength are extremely sensitive to how axially the load is applied during the tensile test. Some laboratories cite the minimum, whereas others cite a mean stress during this discontinuous yielding.

The tensile strength (ultimate strength) is defined as the highest value of engineering stress* (Fig. 8). Up to the maximum load, the deformation should be uniform along the gage section. With ductile materials, the tensile strength corresponds to the point at which the deformation starts to localize, forming a neck (Fig. 8a). Less ductile materials fracture before they neck (Fig. 8b). In this case, the fracture strength is the tensile strength. Indeed, very brittle materials (e.g., glass at room temperature) do not yield before fracture (Fig. 8c). Such materials have tensile strengths but not yield strengths.

Ductility. There are two common measures used to describe the ductility of a material. One

---

*Sometimes the upper yield strength of low-carbon steel is higher than the subsequent maximum. In such cases, some prefer to define the tensile strength as the subsequent maximum instead of the initial maximum, which is higher. In such cases, the definition of tensile strength should be made clear to the user.

is the percent elongation, which is defined simply as

$$\%\text{El} = [(L_f - L_0)/L_0] \times 100 \qquad \text{(Eq 5)}$$

where L_0 is the initial gage length and L_f is the length of the gage section at fracture. Measurements may be made on the broken pieces or under load. For most materials, the amount of elastic elongation is so small that the two are equivalent. When this is not so (as with brittle metals or rubber), the results should state whether or not the elongation includes an elastic contribution. The other common measure of ductility is percent reduction of area, which is defined as

$$\%\text{RA} = [(A_0 - A_f)/A_0] \times 100 \qquad \text{(Eq 6)}$$

where A_0 and A_f are the initial cross-sectional area and the cross-sectional area at fracture, respectively. If failure occurs without necking, one can be calculated from the other:

$$\%\text{El} = \%\text{RA}/(100 - \%\text{RA}) \qquad \text{(Eq 7)}$$

After a neck has developed, the two are no longer related. Percent elongation, as a measure of ductility, has the disadvantage that it is really composed of two parts: the uniform elongation that occurs before necking, and the localized elongation that occurs during necking. The second part is sensitive to the specimen shape. When a gage section that is very long (relative to its diameter), the necking elongation converted to percent is very small. In contrast, with a gage section that is short (relative to its di-

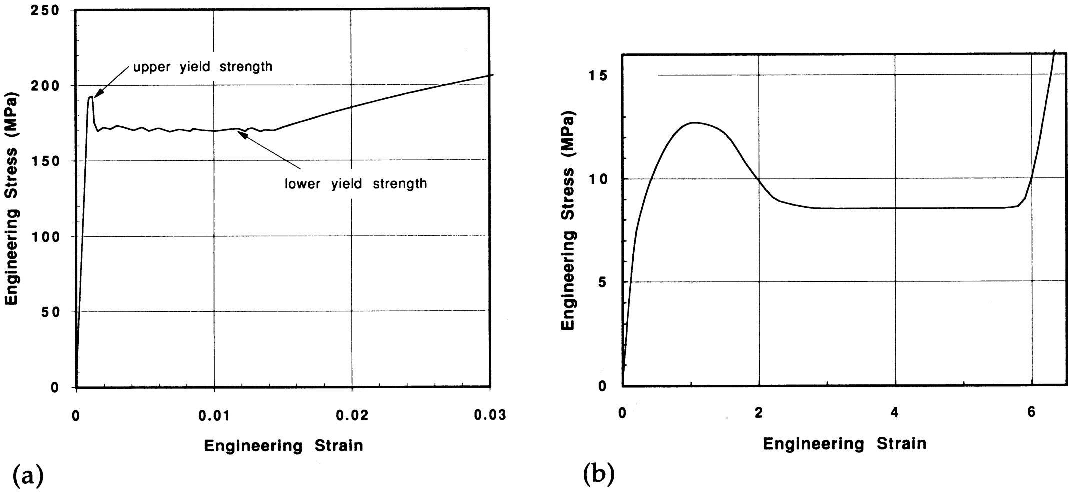


Fig. 7 Inhomogeneous yielding of a low-carbon steel (a) and a linear polymer (b). After the initial stress maxima, the deformation occurs within a narrow band, which propagates along the entire length of the gage section before the stress rises again.

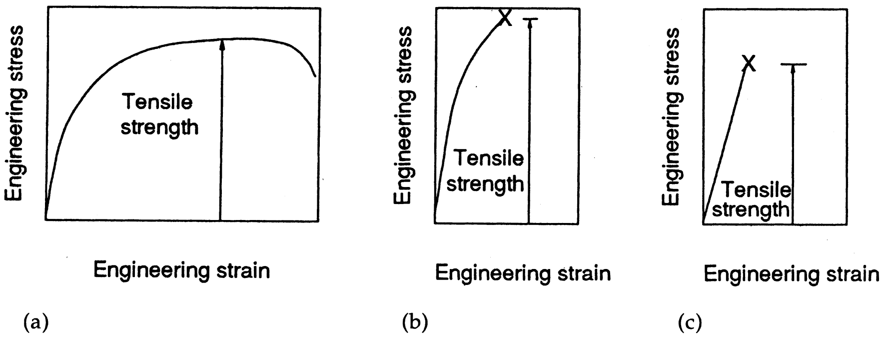


Fig. 8 Stress-strain curves showing that the tensile strength is the maximum engineering stress regardless of whether the specimen necks (a) or fractures before necking (b and c).

ameter), the necking elongation can account for most of the total elongation.

For round bars, this problem has been remedied by standardizing the ratio of gage length to diameter to 4:1. Within a series of bars, all with the same gage-length-to-diameter ratio, the necking elongation will be the same fraction of the total elongation. However, there is no simple way to make meaningful comparisons of percent elongation from such standardized bars with that measured on sheet tensile specimens or wire. With sheet tensile specimens, a portion of the elongation occurs during diffuse necking, and this could be standardized by maintaining the same ratio of width to gage length. However, a portion of the elongation also occurs during what is called localized necking, and this depends on the sheet thickness. For tensile testing of wire, it is impractical to have a reduced section, and so the ratio of gage length to diameter is necessarily very large. Necking elongation contributes very little to the total elongation.

Percent reduction of area, as a measure of ductility, has the disadvantage that with very ductile materials it is often difficult to measure the final cross-sectional area at fracture. This is particularly true of sheet specimens.

True Stress and Strain

If the results of tensile testing are to be used to predict how a metal will behave under other forms of loading, it is desirable to plot the data in terms of true stress and true strain. True stress, σ, is defined as

$$\sigma = F/A \qquad \text{(Eq 8)}$$

where A is the cross-sectional area at the time that the applied force is F. Up to the point at which necking starts, true strain, ε, is defined as

$$\varepsilon = \ln(L/L_0) \qquad \text{(Eq 9)}$$

This definition arises from taking an increment of true strain, $d\varepsilon$, as the incremental change in length, dL, divided by the length, L, at the time, $d\varepsilon = dL/L$, and integrating. As long as the deformation is uniform along the gage section, the true stress and strain can be calculated from the engineering quantities. With constant volume and uniform deformation, $LA = L_0A_0$:

$$A_0/A = L/L_0 \qquad \text{(Eq 10)}$$

Thus, according to Eq 2, $A_0/A = 1 + e$. Equation 8 can be rewritten as

$$\sigma = (F/A_0)(A_0/A)$$

and, with substitution for A_0/A and F/A_0, as

$$\sigma = s(1 + e) \qquad \text{(Eq 11)}$$

Substitution of $L/L_0 = 1 + e$ into the expression for true strain (Eq 9) gives

$$\varepsilon = \ln(1 + e) \qquad \text{(Eq 12)}$$

At very low strains, the differences between true and engineering stress and strain are very small. It does not really matter whether Young's modulus is defined in terms of engineering or true stress strain.

It must be emphasized that these expressions are valid only as long as the deformation is uniform. Once necking starts, Eq 8 for true stress is still valid, but the cross-sectional area at the base of the neck must be measured directly rather than being inferred from the length measurements. Because the true stress, thus calculated, is the true stress at the base of the neck, the corresponding true strain should also be at the base of the neck. Equation 9 could still be used if the L and L_0 values were known for an extremely short gage section centered on the middle of the neck (one so short that variations of area along it would be negligible). Of course, there will be no such gage section, but if there were, Eq 10 would be valid. Thus the true strain can be calculated as

$$\varepsilon = \ln(A_0/A) \qquad \text{(Eq 13)}$$

Figure 9 shows a comparison of engineering and true stress-strain curves for the same material.

Other Factors Influencing the Stress-Strain Curve

There are a number of factors not previously discussed in this chapter that have an effect on the shape of the stress-strain curve. These include strain rate, temperature, and anisotropy. For information on these subjects, the reader should refer to Chapters 2 and 3 listed in the introduction to this chapter as well as Chapter 12, "Hot Tensile Testing" and Chapter 15, "High Strain Rate Tensile Testing."

Test Methodology and Data Analysis

This section reviews some of the more important considerations involved in tensile testing. These include:

- Sample selection
- Sample preparation
- Test set-up
- Test procedure
- Data recording and analysis
- Reporting

Sample Selection. When a material is tested, the objective usually is to determine whether or not the material is suitable for its intended use.

The sample to be tested must fairly represent the body of material in question. In other words, it must be from the same source and have undergone the same processing steps.

It is often difficult to match exactly the test samples to the structure made from the material. A common practice for testing of large castings, forgings, and composite layups is to add extra material to the part for use as "built-in" test samples. This material is cut from the completed part after processing and is made into test specimens that have been subjected to the same processing steps as the bulk of the part.

In practice, these specimens may not exactly match the bulk of the part in certain important details, such as the grain patterns in critical areas of a forging. One or more complete parts may be sacrificed to obtain test samples from the most critical areas for comparison with the "built-in" samples. Thus, it may be determined how closely the "built-in" samples represent the material in question.

There is a special case in which the object of the test is to evaluate not the material, but the test itself. Here, the test specimens must be as nearly identical as possible so the differences in the test results represent, as far as possible, only the variability in the testing process.

Sample Preparation. It should be remembered that a "sample" is a quantity of material that represents a larger lot. The sample usually is made into multiple "specimens" for testing. Test samples must be prepared properly to achieve accurate results. The following rules are suggested for general guidance.

First, as each sample is obtained, it should be identified as to material description, source, location and orientation with respect to the body of material, processing status at the time of sampling, and the data and time of day that the sample was obtained.

Second, test specimens must be made carefully, with attention to several details. The specimen axis must be properly aligned with the material rolling direction, forging grain pattern, or composite layup. Cold working of the test section must be minimized. The dimensions of the specimen must be held within the allowable tolerances established by the test procedure. The attachment areas at each end of the specimen must be aligned with the axis of the bar (see Fig. 10). Each specimen must be identified as belonging to the original sample. If total elongation is to be measured after the specimen breaks, the gage length must be marked on the reduced section of the bar prior to testing.

The test set-up requires that equipment be properly matched to the test at hand. There are

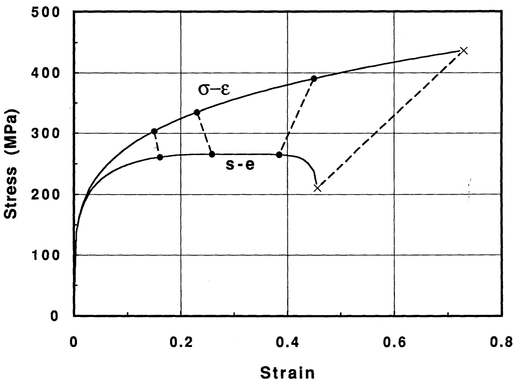


Fig. 9 Comparison of engineering and true stress-strain curves. Prior to necking, a point on the σ-ε curve can be constructed from a point on the *s-e* curve using Eq 11 and 12. Subsequently, the cross section must be measured to find true stress and strain.

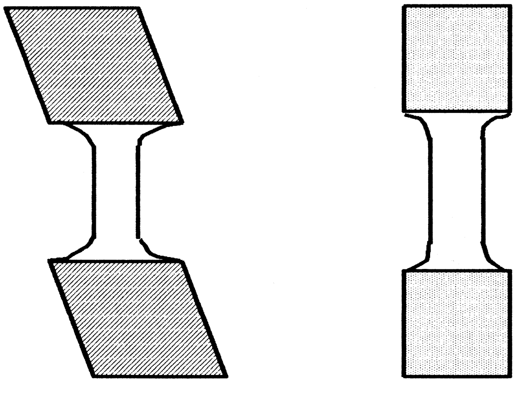


Fig. 10 Improper (left) and proper (right) alignment of specimen attachment areas with axis of specimen

three requirements of the testing machine: force capacity sufficient to break the specimens to be tested; control of test speed (or strain rate or load rate), as required by the test specification; and precision and accuracy sufficient to obtain and record properly the load and extension information generated by the test. This precision and accuracy should be ensured by current calibration certification.

For grips, of which many types are in common use in tensile testing, only two rules apply: the grips must properly fit the specimens (or vice versa), and they must have sufficient force capacity so that they are not damaged during testing.

As described earlier in the section "Tensile Specimens and Testing Machines," there are several techniques for installing the specimen in the grips. With wedge grips, placement of the specimen in the grips is critical to proper alignment (see Fig. 11). Ideally, the grip faces should be of the same width as the tab ends of the test bar; otherwise, lateral alignment is dependent only on the skill of the technician. The wedge grip inserts should be contained within the grip body or crosshead, and the specimen tabs should be fully engaged by the grips (see Fig. 12).

Other types of grips have perhaps fewer traps for the inexperienced technician, but an obvious one is that, with threaded grips, a length of threads on the specimen equal to at least one diameter should be engaged in the threaded grips.

There are several potential problems that must be watched for during the test set-up, including specimen misalignment and worn grips. The physical alignment of the two points of attachment of the specimen is important, because any off-center loading will exert bending loads on the specimen. This is critical in testing of brittle materials, and may cause problems even for ductile materials. Alignment will be affected by the testing-machine loadframe, any grips and fixtures used, and the specimen itself. Misalignment may also induce load-measurement errors due to the passage of bending forces through the load-measuring apparatus. Such errors may be reduced by the use of spherical seats or "U-joints" in the set-up.

Worn grips may contribute to off-center loading. Uneven tooth marks across the width of the specimen tab are an indication of trouble in wedge grips. Split-collar grips may also cause off-center loading. Uneven wear of grips and mismatching of split-shell insert pairs are potential problem areas.

Strain measurements are required for many tests. They are commonly made with extensometers, but strain gages are frequently used—especially on small specimens or where Pois-

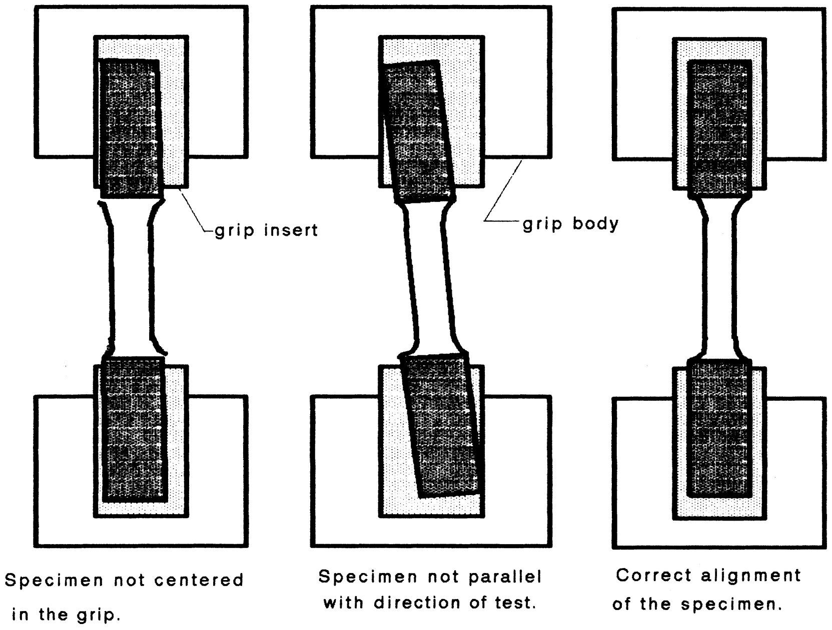


Fig. 11 Improper (left, center) and proper (right) alignment of specimen in wedge grips

son’s ratio is to be measured. If strain measurements are required, appropriate strain-measuring instruments must be properly installed. The technician should pay particular attention to setting of the extensometer gage length (mechanical zero). The zero of the strain readout should repeat consistently if the mechanical zero is set properly. In other words, once the extensometer has been installed and zeroed, subsequent installations should require minimal readjustment of the zero.

Test Procedure. The following general rules for test procedure may be applied to almost every tensile test.

Load and strain ranges should be selected so that the test will fit the range. The maximum values to be recorded should be as close to the top of the selected scale as convenient without running the risk of going past full scale. Ranges may be selected using past experience for a particular test, or specification data for the material (if available). Note that many computer-based testing systems have automatic range selection and will capture data even if the range initially selected is too small.

The identity of each specimen should be verified, and pertinent identification should be accurately recorded for the test records and report.

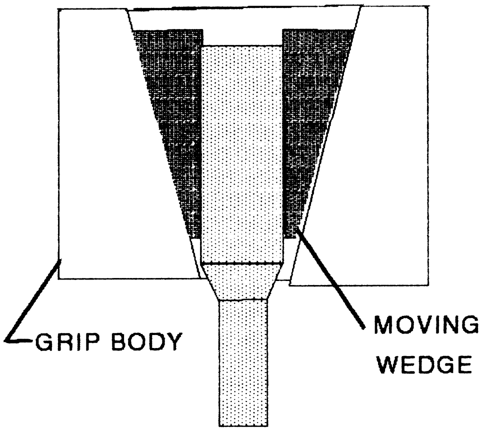
The dimensions needed to calculate the cross-sectional area of the reduced section should be measured and recorded. These measurements should be repeated for every specimen; it should not be assumed that sample preparation is perfectly consistent.

The load-indicator zero and the plot-load-axis zero, if applicable, should be set before the specimen is placed in the grips. Zeroes should never be reset after the specimen is in place.

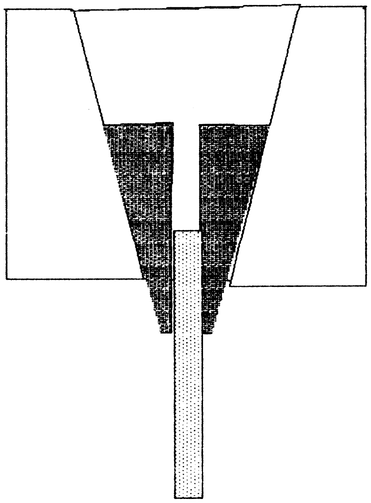
The specimen is placed in the grips and is secured by closing the grips. If preload is to be removed before the test is started, it should be physically unloaded by moving the loading mechanism. The zero adjustment should never be used for this purpose. Note that, in some cases, preload may be desirable and may be deliberately introduced. For materials for which the initial portion of the curve is linear, the strain zero may be corrected for preload by extending the initial straight portion of the stress-strain curve to zero load and measuring strain from that point. The strain valve at the zero-load intercept is commonly called the “foot correction” and is subtracted from readings taken from strain scale (see Fig. 10 in Chapter 3, “Uniaxial Tensile Testing”).

When the extensometer, if applicable, is installed, the technician should be sure to set the mechanical zero correctly. The strain-readout zero should be set after the extensometer is in place on the specimen.

The test procedure should be in conformance with the published test specification and should



PROPER ENGAGEMENT OF A SPECIMEN IN WEDGE GRIPS.



POOR ENGAGEMENT. THIS SMALL "BITE" IS LIKELY TO CAUSE DAMAGE TO THE GRIPS, AND RISK OF INJURY TO ANYONE NEAR THE MACHINE.

Fig. 12 Proper and improper engagement of a specimen in wedge grips be repeated consistently for every test. It is important that the test specification be followed for speed of testing. Some materials are sensitive to test speed, and different speeds will give different results. Also, many testing machine load- and strain-measuring instruments are not capable of responding fast enough for accurate recording of test results if an excessive test speed is used.

The technician should monitor the test closely and be alert for problems. One common sign of trouble is a load-versus-strain plot in which the initial portion of the curve is not straight. This may indicate off-center loading of the specimen, improper installation of the extensometer, or the specimen was not straight to begin with.

Another potential trouble sign is a sharp drop in indicated load during the test. Such a drop may be characteristic of the material, but it also can indicate problems such as slippage between the specimen and the grips or stick-slip movement of the wedge grip inserts in the grip body. Slippage may be caused by worn inserts with dull teeth, particularly for hard, smooth specimens.

The stick-slip action in wedge grips is more common in testing of resilient materials, but it also can occur in testing of metals. Specimens cut from the wall of a pipe or tube may have curved tab ends that flatten with increasing force, allowing the inserts to move relative to the grip body. Short tab ends on round specimens also may be crushed by the wedge grips, with the same result. If the sliding faces are not lubricated, they may move in unpredictable steps accompanied by drops in the load reading. Dry-film molybdenum disulfide lubricants are effective in solving stick-slip problems in wedge grips, particularly when testing is done at elevated temperature.

When wedge grips are used, the specimen must be installed so that the clamping force is contained within the grip body. Placing the specimen too near the open end of the grip body results in excessive stress on the grip body and inserts and is a common cause of grip failure. WARNING: Grip failures are dangerous and may cause injury to personnel and damage to equipment.

Data generally may be grouped into "raw data," meaning the observed readings of the measuring instruments, and "calculated data," meaning the test results obtained after the first step of analysis.

In the most simple tensile test, the raw data comprise a single measurement of peak force and the dimensional measurements taken to determine the cross-sectional area of the test specimen. The first analysis step is to calculate the "tensile strength," defined as the force per unit area required to fracture the specimen. More complicated tests will require more information, which typically takes the form of a graph of force versus extension. Computer-based testing machines can display the graph without paper, and can save the measurements associated with the graph by electronic means.

A permanent record of the raw test data is important, because it allows additional analyses to be performed later, if desired, and because it allows errors in analysis to be found and corrected by reference to the original data.

Data Recording. Test records may be needed by many departments within an organization, including metallurgy, engineering, commercial, and legal departments.

Engineering and metallurgy departments typically are most interested in material properties, but may use raw data for error checking or additional analyses. The metallurgy department wants to know how variations in raw materials or processing change the properties of the product being produced and tested, and the engineering department wants to know the properties of the material for design purposes.

Shipping, receiving, and accounting departments need to know whether or not the material meets the specifications for shipping, acceptance, and payment. The sales department needs information for advertising and for advising prospective customers.

If a product incorporating the tested material later fails—particularly if persons are injured—the legal department may need test data as evidence in legal proceedings. In this case, a record of the raw data will be important for support of the original analysis and test report.

Analysis of test data is done at several levels. First, the technician observes the test in progress, and may see that a grip is slipping or that the specimen fractures outside the gage section. These observations may be sufficient to determine that a test is invalid.

Immediately after the test, a first-level analysis is performed according to the calculation requirements of the test procedure. ASTM test specifications typically show the necessary equations with an explanation and perhaps an example. This analysis may be as simple as dividing peak force by cross-sectional area, or it may require more complex calculations. The outputs of this first level of analysis are the mechanical properties of the material being tested.

Upon completion of the group of tests performed on the sample, a statistical analysis may be made. The statistical analysis produces average (mean or median) values for representation of the sample in the subsequent database and also provides information about the uniformity of the material and the repeatability of the test.

The results of tests on each sample of material may be stored in a database for future use. The database allows a wide range of analyses to be performed using statistical methods to correlate the mechanical-properties data with other information about the material. For example, it may allow determination of whether or not there is a significant difference between the material tested and similar material obtained from a different supplier or through a different production path.

Reporting. The test report usually contains the results of tests performed on one sample composed of several specimens.

When ASTM specifications are used for testing, the requirements for reporting are defined by the specification. The needs of a particular user probably will determine the form for identification of the material, but the reported results will most likely be as given in the ASTM test specification.

The information contained in the test report generally should include identification of the testing equipment, the material tested, and the test procedure; the raw and calculated data for each specimen; and a brief statistical summary for the sample.

Each piece of test equipment used for the test should be identified, including serial numbers, capacity or range used, and date of certification or date due for certification.

Identification of the material tested should include the type of material (alloy, part number, etc.); the specific batch, lot, order, heat, or coil from which the sample was taken; the point in the processing sequence (condition, temper, etc.) at which the sample was taken; and any test or pretest conditions (test temperature, aging, etc.).

Identification of the test procedure usually will be reported by reference to a standard test procedure such as those published by ASTM or perhaps to a proprietary specification originating within the testing organization.

The raw data for each specimen are recorded, or a reference to the raw data is included so that the data can be obtained from a file if and when they are needed. Frequently, only a portion of the raw data—dimensions, for example—is recorded, and information on the force-versus-extension graph is referenced.

A tabulation of the properties calculated for each specimen is recorded. The calculations at this stage are the first level of data analysis. The calculations required usually are defined in the test procedure or specification.

A brief statistical summary for the sample is a feature that is becoming more common with the proliferation of computerized testing systems, because the computations required can be done automatically without added operator workload. The statistical summary may include the average (mean) value, median value, standard deviation, highest value, lowest value, range, etc. The average or median value would be used to represent this sample at the next level of analysis, which is the material database.

Examination of this initial statistical information can tell a great deal about the test as well as the material. A low standard deviation or range indicates that the material in the sample has uniform properties (each of several specimens has nearly the same values for the measured properties) and that the test is producing consistent results. Conversely, a high standard deviation or range indicates that a problem of inconsistent material or testing exists and needs to be investigated.

A continuing record of the average properties and the associated standard deviation and range information is the basis for statistical process control, which systematically interprets this information so as to provide the maximum information about both the material and the test process.

ACKNOWLEDGMENTS

This chapter was adapted from:

- W.F. Hosford, Overview of Tensile Testing, *Tensile Testing,* P. Han, Ed., ASM International, 1992, p 1–24
- P.M. Mumford, Test Methodology and Data Analysis, *Tensile Testing,* P. Han, Ed., ASM International, 1992, p 49–60
- R. Gedney, Guide To Testing Metals Under Tension, *Advanced Materials & Processes,* February, 2002, p 29–31

Chapter 2: Mechanical Behavior of Materials under Tensile Loads

References

1. G.E. Dieter, Introduction to Ductility, in *Ductility*, American Society for Metals, 1968

2. P.G. Nelson and J. Winlock, *ASTM Bull.*, Vol 156, Jan 1949, p 53

3. D.J. Mack, *Trans. AIME*, Vol 166, 1946, p 68–85

4. P.E. Armstrong, Measurement of Elastic Constants, in *Techniques of Metals Research*, Vol V, R.F. Brunshaw, Ed., Interscience, New York, 1971

5. H.E. Davis, G.E. Troxell, and G.F.W. Hauck, *The Testing of Engineering Materials*, McGraw-Hill, New York, 1964, p 33

6. J.R. Low and F. Garofalo, *Proc. Soc. Exp. Stress Anal.*, Vol 4 (No. 2), 1947, p 16–25

7. J.R. Low, *Properties of Metals in Materials Engineering*, American Society for Metals, 1949

8. J. Datsko, *Material Properties and Manufacturing Processes*, John Wiley & Sons, New York, 1966, p 18–20

9. W.B. Morrison, *Trans. ASM*, Vol 59, 1966, p 824 doi: 10.1177/003591576605900909

10. D.C. Ludwigson, *Metall. Trans.*, Vol 2, 1971, p 2825–2828

11. H.J. Kleemola and M.A. Nieminen, *Metall. Trans.*, Vol 5, 1974, p 1863–1866 doi: 10.1007/BF02644152

12. C. Adams and J.G. Beese, *Trans. ASME*, Series H, Vol 96, 1974, p 123–126 doi: 10.1115/1.3443193

13. J.H. Keeler, *Trans. ASM*, Vol 47, 1955, p 157–192

14. A. Considére, *Ann. Ponts Chaussées*, Vol 9, 1885, p 574–775

15. G.W. Geil and N.L. Carwile, *J. Res. Natl. Bur. Stand.*, Vol 45, 1950, p 129 doi: 10.6028/jres.045.012

16. P.W. Bridgman, *Trans. ASM*, Vol 32, 1944, p 553 doi: 10.1109/JRPROC.1944.233371

17. J. Aronofsky, *J. Appl. Mech.*, Vol 18, 1951, p 75–84 doi: 10.1115/1.4010223

18. T.A. Trozera, *Trans. ASM*, Vol 56, 1963, p 280–282 doi: 10.2307/4345168

19. E.R. Marshall and M.C. Shaw, *Trans. ASM*, Vol 44, 1952, p 716 doi: 10.1002/j.1551-8833.1952.tb20110.x

20. W.J. McG. Tegart, *Elements of Mechanical Metallurgy*, Macmillan, New York, 1966, p 22

21. N.E. Dowling, *Mechanical Behavior of Materials*, Prentice-Hall, Englewood Cliffs, NJ, 1993, p 165

22. M.J. Barba, *Mem. Soc. Ing. Civils*, Part I, 1880, p 682

23. E.G. Kula and N.N. Fahey, *Mater. Res. Stand.*, Vol 1, 1961, p 631

24. W.F. Hosford, Overview of Tensile Testing, *Tensile Testing*, P. Han, Ed., ASM International, 1992, p 2–24

25. W.T. Becker, Special Applications of Tension and Compression Testing, Course 12, Lesson 5, *Mechanical Testing of Metals*, American Society for Metals, 1983, p 19

26. G.B. Espey, M.H. Jones, and W.F. Brown Jr., *ASTM Proc.*, Vol 59, 1959, p 837

27. J.D. Lubahn, *Trans. ASME*, Vol 79, 1957, p 111–115 doi: 10.3406/bulmo.1957.3805

28. Ductile and Brittle Fractures, *Failure Analysis and Prevention*, Vol 11, *Metals Handbook*, 9th ed., American Society for Metals, 1986, p 82–101

Chapter 3: Uniaxial Tensile Testing

References

1. D. Lewis, Tensile Testing of Ceramics and Ceramic-Matrix Composites, *Tensile Testing*, P. Han, Ed., ASM International, 1992, p 147–182

2. R.J. Del Vecchio, Tensile Testing of Elastomers, *Tensile Testing*, P. Han, Ed., ASM International, 1992, p 135–146

3. N.E. Dowling, *Mechanical Behavior of Materials—Engineering Methods for Deformation, Fracture, and Fatigue*, 2nd ed., Prentice Hall, 1999, p 123

4. R.L. Brockenbough and B.G. Johnson, "Steel Design Manual," United States Steel Corporation, ADUSS 27 3400 03, 1974, p 2–3

5. P.M. Mumford, Test Methodology and Data Analysis, *Tensile Testing*, P. Han, Ed., ASM International, 1992, p 55

6. "Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus," E 111, ASTM

7. *Making, Shaping, and Treating of Steel*, 10th ed., U.S. Steel, 1985, Fig. 50-12 and 50-13

8. "Standard Test Methods and Definitions for Mechanical Testing of Steel Products," A 370, Annex 6, *Annual Book of ASTM Standards*, ASTM, Vol 1.03

9. "Conversion of Elongation Values, Part 1: Carbon and Low-Alloy Steels," 2566/1, International Organization for Standardization, revised 1984

10. W.P. Goepfert, Statistical Aspects of Mechanical Property Assurance, *Reproducibility and Accuracy of Mechanical Tests*, STP 626, ASTM, 1977, p 136–144

11. F.B. Seely and J.O. Smith, *Resistance of Materials*, 4th ed., John Wiley & Sons, p 45

12. N.R.N. Rao *et al*., "Effect of Strain Rate on the Yield Stress of Structural Steel," Fritz Engineering Laboratory Report 249.23, 1964

13. R.L. Klueh and R.E. Oakes Jr., High Strain-Rate Tensile Properties of 2¼ Cr-1 Mo Steel, *J. Eng. Mater. Technol.*, Oct 1976, p 361–367 doi: 10.1115/1.3443390

14. M.J. Manjoine, Influence of Rate of Strain and Temperature on Yield Stresses of Mild Steel, *J. Appl. Mech.*, Vol 2, 1944, p A-211 to A-218 doi: 10.1115/1.4009394

15. A.H. Jones, C.J. Maiden, S.J. Green, and H. Chin, Prediction of Elastic-Plastic Wave Profiles in Aluminum 1060-O under Uniaxial Strain Loading, *Mechanical Behavior of Materials under Dynamic Loads*, U.S. Lindholm, Ed., Springer-Verlag, 1968, p 254–269 doi: 10.1007/978-3-642-87445-1_12

Selected References

- “Standard Method of Sharp-Notch Tension Testing of High-Strength Sheet Materials,” E 338, ASTM

- “Standard Method of Sharp-Notch Tension Testing with Cylindrical Specimens,” E 602, ASTM

- “Standard Methods and Definitions for Mechanical Testing of Steel Products,” A 370, ASTM

- “Standard Methods of Tension Testing of Metallic Foil,” E 345, ASTM

- “Standard Test Methods for Poisson’s Ratio at Room Temperature,” E 132, ASTM

- “Standard Test Methods for Static Determination of Young’s Modulus of Metals at Low and Elevated Temperatures,” E 231, ASTM

- “Standard Test Methods for Young’s Modulus, Tangent Modulus, and Chord Modulus,” E 111, ASTM

- “Standard Methods of Tension Testing of Metallic Materials,” E 8, ASTM

- “Standard Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products,” B 557, ASTM

- “Standard Recommended Practice for Elevated Temperature Tension Tests of Metallic Materials,” E 21, ASTM

- “Standard Recommended Practice for Verification of Specimen Alignment Under Tensile Loading,” E 1012, ASTM

Chapter 4: Tensile Testing Equipment and Strain Sensors

References

1. R.C. Anderson, *Inspection of Metals: Destructive Testing*, ASM International, 1988, p 83–119

2. H.E. Davis, G.E. Troxell, and G.F.W. Hauck, *The Testing of Engineering Materials*, 4th ed., McGraw-Hill, 1982, p 80–124

3. P. Han, Ed., *Tensile Testing*, ASM International, 1992, p 28

4. G.E. Dieter, *Mechanical Metallurgy*, McGraw-Hill, 2nd ed., 1976, p 349

5. D.J. Shippy, P.P. Gillis, and K.G. Hoge, Computer Simulation of a High Speed Tension Test, *J. Appl. Polym. Sci.*, Applied Polymer Symposia (No. 5), 1967, p 311– 325 doi: 10.2172/4497403

6. P.P. Gillis and D.J. Shippy, Vibration Analysis of a High Speed Tension Test, *J. Appl. Polym. Sci.*, Applied Polymer Symposia (No. 12), 1969, p 165–179

7. M.A. Hamstad and P.P. Gillis, Effective Strain Rates in Low-Speed Uniaxial Tension Tests, *Mater. Res. Stand.*, Vol 6 (No. 11), 1966, p 569–573

8. P. Gillis and J.J. Gilman, Dynamical Dislocation Theories of Crystal Plasticity, *J. Appl. Phys.*, Vol 36, 1965, p 3375– 3386 doi: 10.1063/1.1702999

9. J.E. Hockett and P.P. Gillis, Mechanical Testing Machine Stiffness, Parts I and II, *Int. J. Mech. Sci.*, Vol 13, 1971, p 251–275 doi: 10.1016/0020-7403(71)90007-5

10. W.G. Johnston, Yield Points and Delay Times in Single Crystals, *J. Appl. Phys.*, Vol 33, 1962, p 2716 doi: 10.1063/1.1702538

11. H.G. Baron, Stress-Strain Curves of Some Metals and Alloys at Low Temperatures and High Rates of Strain, *J. Iron Steel Inst. (Brit.)*, Vol 182, 1956, p 354

12. J. Miklowitz, The Initiation and Propagation of the Plastic Zone in a Tension Bar of Mild Steel as Influenced by the Speed of Stretching and Rigidity of the Testing Machine, *J. Appl. Mech. (Trans. ASME)*, Vol 14, 1947, p A-31 doi: 10.1115/1.4009624

13. M.A. Hamstead, “The Effect of Strain Rate and Specimen Dimensions on the Yield Point of Mild Steel,” Lawrence Radiation Laboratory Report UCRL-14619, April 1966

Chapter 5: Tensile Testing for Design

References

1. Cambridge Engineering Selector, Granta Design Ltd., Cambridge, UK, 1998

2. G.E. Dieter, *Engineering Design: A Materials and Processing Approach*, McGraw Hill, 1991, p 1–51, 231–271

3. *Metals Handbook*, American Society for Metals, 1948

4. F.B. Seely, *Resistance of Materials*, John Wiley & Sons, 1947

5. *Properties and Selection of Metals*, Vol 1, *Metals Handbook*, 8th ed., American Society for Metals, 1961, p 503

6. *Modern Plastics Encyclopedia*, McGraw Hill, 2000

7. M.F. Ashby, *Materials Selection for Mechanical Design*, 2nd ed., Butterworth-Heinemann, 1999

8. H. Davis, G. Troxell, and G. Hauck, *The Testing of Engineering Materials*, 4th ed., McGraw Hill, 1982, p 314

9. G. Carter, *Principles of Physical and Chemical Metallurgy*, American Society for Metals, 1979, p 87

10. M.A. Meyers and K.K. Chawla, *Mechanical Metallurgy*, Prentice-Hall, Edgewood Cliffs, NJ, 1984, p 626–627

11. George Vander Voort, *Metallography: Principles and Practices*, ASM International, 1999, p 383–385, 391–393

12. R.T. Shield, On the Plastic Flow of Metals under Conditions of Axial Symmetry, *Proc. R. Soc.*, Vol A233, 1955, p 267 doi: 10.1098/rspa.1955.0262

13. A. Fee, Selection and Industrial Applications of Hardness Tests, *Mechanical Testing and Evaluation*, Vol 8, *ASM Handbook*, ASM International, 2000, p 260–277 doi: 10.31399/asm.hb.v08.a0003276

14. J. Datsko, L. Hartwig, and B. McClory, On the Tensile Strength and Hardness Relation for Metals, *Journal of Materials Engineering and Performance*, Vol 10 (6), Dec 2001, p 718–722 doi: 10.1361/105994901770344601

15. W.J. Taylor, The Hardness Test as a Means of Estimating the Tensile Strength of Metals, *J.R. Aeronaut. Soc.*, Vol 46 (No. 380), 1942, p 198–202 doi: 10.1017/S0001924000100636

Selected References

- M. Ashby, *Materials Selection for Mechanical Design*, 2nd ed., Butterworth-Heinemann, 1999

- N. Dowling, *Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue*, Prentice Hall, 1999

- R.C. Juvinall and K.M. Marshek, *Fundamentals of Machine Component Design*, 2nd ed., John Wiley & Sons, 1991 doi: 10.1115/1.2899687

- J.E. Shigley and L.D. Mitchell, *Mechanical Engineering Design*, 4th ed., McGraw-Hill, 1983

Chapter 6: Tensile Testing for Determining Sheet Formability

References

1. J.H. Holloman, Tensile Deformation, *Trans. AIME*, Vol 162, 1945, p 268–290

2. W.A. Backofen, Massachusetts Institute of Technology Industrial Liaison Symposium, Chicago, March 1974

3. A.K. Ghosh, The Influence of Strain Hardening and Strain-Rate Sensitivity on Sheet Metal Forming, *Trans. ASME*, Vol 99, July 1977, p 264–274 doi: 10.1115/1.3443530

4. I.S. Brammar and D.A. Harris, Production and Properties of Sheet Steel and Aluminum Alloys for Forming Applications, *J. Austral. Inst. Met.*, Vol 20 (No. 2), 1975, p 85–100

5. S.P. Keeler and W.A. Backofen, Plastic Instability and Fracture in Sheets Stretched Over Rigid Punches, *Trans. ASM*, Vol 56 (No. 1), 1963, p 25–48

6. G.M. Goodwin, "Application of Strain Analysis to Sheet Metal Forming Problems in the Press Shop," Paper 680093, Society of Automotive Engineers, 1968 doi: 10.4271/680093

7. S.P. Keeler, Determination of Forming Limits in Automotive Stampings, *Sheet Met. Ind.*, Vol 42, Sept 1965, p 683–691 doi: 10.4271/650535

8. S.P. Keeler and W.G. Brazier, Relationship Between Laboratory Material Characterization and Press-Shop Formability, in *Microalloying 75 Proceedings*, Union Carbide Corporation, 1977, p 517–530

9. H. Naziri and R. Pearce, The Effect of Plastic Anisotropy on Flange-Wrinkling Behavior During Sheet Metal Forming, *Int. J. Mech. Sci.*, Vol 10, 1968, p 681–694 doi: 10.1016/0020-7403(68)90083-0

10. K. Yoshida and K. Miyauchi, Experimental Studies of Material Behavior as Related to Sheet Metal Forming, in *Mechanics of Sheet Metal Forming*, Plenum Press, 1978, p 19–49 doi: 10.1007/978-1-4613-2880-3_2

11. W.F. Hosford and R.M. Caddell in *Metal Forming, Mechanics and Metallurgy*, Prentice-Hall, 1983, p 273, 309

12. J. Havranek, The Effect of Mechanical Properties of Sheet Steels on the Wrinkling Behavior During Deep Drawing of Conical Shells, in *Sheet Metal Forming and Energy Conservation*,

Proceedings of the 9th Biennial Congress of the International Deep Drawing Research Group, Ann Arbor, MI, American Society for Metals, 1976, p 245–263

13. J.S.H. Lake, The Yoshida Test—A Critical Evaluation and Correlation with Low-Strain Tensile Parameters, in *Efficiency in Sheet Metal Forming*, Proceedings of the 13th Biennial Congress, Melbourne, Australia, International Deep Drawing Research Group, Feb 1984, p 555–564

14. J.L. Duncan R. Sowerby and M.P. Sklad, "Failure Modes in Aluminum Sheet in Deep Drawing Square Cups," Paper presented at the Conference on Sheet Forming, University of Aston, Birmingham, England, Sept 1981

15. G. Glover J.L. Duncan and J.D. Embury, Failure Maps for Sheet Metal, *Met. Technol.*, March 1977, p 153–159 doi: 10.1179/030716977803292006

16. J.D. Embury and J.L. Duncan, Formability Maps, *Ann. Rev. Mat. Sci.*, Vol 11, 1981, p 505–521 doi: 10.1146/annurev.ms.11.080181.002445

17. J. Datsko, *Materials in Design and Manufacturing*, J. Datsko Consultants, 1977, p 7–16

18. N. Kuhn, On the Springback Behavior of Low-Carbon Steel Sheet After Stretch Bending, *J. Austral. Inst. Met.*, Vol 12 (No. 1), Feb 1967, p 71–76

19. G.V. Smith, Elevated Temperature Static Properties of Wrought Carbon Steel, in *Special Technical Publication on Temperature Effects*, STP 503, American Society for Testing and Materials, 1972

20. F.N. Rhines and P.J. Wray, Investigation of the Intermediate Temperature Ductility Minimum in Metals, *Trans. ASM*, Vol 54, 1961, p 117–128

21. B. Taylor R.A. Heimbuch and S.G. Babcock, Warm Forming of Aluminum, in *Proceedings of the Second International Conference on Mechanical Behavior of Materials*, American Society for Metals, 1976, p 2004–2008

22. W.G. Granzow, The Influence of Tooling Temperature on the Formability of Stainless Sheet Steel, in *Formability of Metallic Materials—2000 A.D.*, STP 753, J.R. Newby and B.A. Niemeier Ed., American Society for Testing and Materials, 1981, p 137–146

23. B. Taylor, Formability Testing of Sheet Metals, *Forming and Forging*, Vol 14, *Metals Handbook*, 9th ed., ASM International, 1988, p 877–899

24. H.C. Wu and D.R. Rummler, Analysis of Misalignment in the Tension Test, *Trans. ASME*, Vol 101, Jan 1979, p 68–74 doi: 10.1115/1.3443653

25. G.E. Dieter, *Mechanical Metallurgy*, 2nd ed., McGraw-Hill, 1976, p 347, 349, 681

26. R.L. Whitely, *Correlation of Deep Drawing Press Performance With Tensile Properties*, STP 390, American Society for Testing and Materials, 1965

27. S.J. Green J.J. Langan J.D. Leasia and W.H. Yang, Material Properties, Including Strain-Rate Effects, as Related to Sheet Metal Forming, *Met. Trans. A*, Vol 2A, 1971, p 1813–1820

28. G. Rai and N.J. Grant, On the Measurements of Superplasticity in an Al-Cu Alloy, *Met. Trans A.*, Vol 6A, 1975, p 385–390 doi: 10.1007/BF02667294

29. W.J. McGregor Tegart in *Elements of Mechanical Metallurgy*, Macmillan, 1966, p 29–38

30. M.L. Devenpeck and O. Richmond, Limiting Strain Tests for In-Plane Sheet Stretching, in *Novel Techniques in Metal Deformation Testing*, The Metallurgical Society, 1983, p 79–88

31. R.H. Wagoner and N.M. Wang, An Experimental and Analytical Investigation of In-Plane Deformation of 2036-T4 Aluminum, *Int. J. Mech. Sci.*, Vol 21, 1979, p 255–264 doi: 10.1016/0020-7403(79)90001-8

32. R.H. Wagoner, Measurement and Analysis of Plane-Strain Work Hardening, *Met. Trans. A*, Vol 11A, Jan 1980, p 165–175 doi: 10.1007/BF02700453

33. R.H. Wagoner, Plane-Strain and Tensile Hardening Behavior of Three Automotive Sheet Alloys, in *Experimental Verification of Process Models*, Symposium proceedings, Cincinnati, OH, Sept 1981, American Society for Metals, 1983, p 236

34. E.J. Appleby M.L. Devenpeck L.M. O'Hara and O. Richmond, Finite Element Analysis and Experimental Examination of the Rectangular-Sheet Tension Test, in *Applications of Numerical Methods to Forming Processes*, Vol 28, Proceedings of the ASME Winter Annual Meeting, San Francisco, Applied Mechanics Division, American Society of Mechanical Engineers, Dec 1978, p 95–105

35. H. Sang and Y. Nishikawa, A Plane Strain Tensile Apparatus, *J. Met.*, Feb 1983, p 30–33 doi: 10.1007/BF03338202

Chapter 7: Tensile Testing of Metals and Alloys

Selected References

- C.R. Brooks, Plastic Deformation and Annealing, *Heat Treatment, Structure and Properties of Nonferrous Alloys*, American Society for Metals, 1982, p 1–73

- G.E. Dieter, *Mechanical Metallurgy*, 3rd ed., McGraw-Hill, New York, 1986

- T.M. Osman, Introduction to the Mechanical Behavior of Metals, *Mechanical Testing and Evaluation*, Vol 8, *ASM Handbook*, ASM International, 2000, p 3–12 doi: 10.31399/asm.hb.v08.a0003254

- T.H. Courtney, Fundamental Structure-Property Relationships in Engineering Materials, *Materials Selection and Design*, Vol 20, *ASM Handbook*, ASM International, 1997, p 336–356 doi: 10.31399/asm.hb.v20.a0002460

Chapter 8: Tensile Testing of Plastics

Reference

1. S. Turner, Mechanical Testing, *Engineering Plastics*, Vol 2, *Engineered Materials Handbook*, ASM International, 1988, p 544–558

Selected References

- A.-M.M. Baker and C.M.F. Barry, Effects of Composition, Processing, and Structure on Properties of Engineering Plastics, *Materials Selection and Design*, Vol 20, *ASM Handbook*, ASM International, 1997, p 434–456 doi: 10.31399/asm.hb.v20.a0002464

- J. Rietveld, Viscoelasticity, *Engineering Plastics*, Vol 2, *Engineered Materials Handbook*, ASM International, 1988, p 412–422

- M.L. Weaver and M.E. Stevenson, Introduction to the Mechanical Behavior of Nonmetallic Materials, *Mechanical Testing and Evaluation*, Vol 8, *ASM Handbook*, ASM International, 2000, p 13–25 doi: 10.31399/asm.hb.v08.a0003255

- Mechanical Testing of Polymers and Ceramics, *Mechanical Testing and Evaluation*, Vol 8, *ASM Handbook*, ASM International, 2000, p 26–48 doi: 10.31399/asm.hb.v08.a0003256

Chapter 9: Tensile Testing of Elastomers

References

1. R. Tuszynski, Elastomers, *Engineered Materials Handbook, Desk Edition*, ASM International, 1995, p 282–286 doi: 10.31399/asm.hb.emde.a0003011

2. ASTM D 412, "Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension," *Annual Book of ASTM Standards*, Vol 09.01, ASTM International

Selected References

- A.K. Bhowmick and H.L. Stephens, Ed., *Handbook of Elastomers*, 2nd ed., Marcel Dekker, 2000 doi: 10.1201/9781482270365

- A.K. Bhowmick, M.M. Hall, and H.A. Benarey, Ed., *Rubber Products Manufacturing Technology*, Marcel Dekker, 1994

- A.N. Gent, Ed., *Engineering with Rubber*, Hanser Publishers, 1992

- W.F. Harrington, Elastomeric Adhesives, *Engineered Materials Handbook*, Vol 3, *Adhesives and Sealants*, ASM International, 1990, p 143–150

- J.E. Mark, B. Erman, and F.R. Eirich, Ed., *Science and Technology of Rubber*, 2nd ed., Academic Press, 1994

- B.M. Walker and C.P. Rader, Ed., *Handbook of Thermoplastic Elastomers*, 2nd ed., Van Nostrand Reinhold, 1988

Preview for: *Tensile Testing* (Second Edition), edited by J.R. Davis, ASM International, 2004
Full digital book available at https://doi.org/10.31399/asm.tb.tt2.9781627083553

Chapter 10: Tensile Testing of Ceramics and Ceramic-Matrix Composites

References

1. J.R. Varner, Descriptive Fractography, *Ceramics and Glasses*, Vol 4, *Engineered Materials Handbook*, ASM International, 1991, p 635–644.

2. R.W. Rice, Ceramic Fracture Features, Observations, Mechanisms and Uses, *Fractography of Ceramic and Metal Failures*, STP 827, ASTM, 1984, p 5–103.

3. S.B. Batdorf, Fundamentals of the Statistical Theory of Failure, *Fracture Mechanics of Ceramics*, Vol 3, R.C. Bradt, D.P.H. Hasselman, A.G. Evans, and F.F. Lange, Ed., Plenum Press, 1978, p 1–29.

4. D. Lewis, Curve-Fitting Techniques and Ceramics, *Am. Ceram. Soc. Bull.*, Vol 57 (No. 4), 1978, p 434–437.

5. W. Weibull, A Statistical Distribution Function of Wide Applicability, *J. Appl. Mech.*, Vol 18, 1951, p 293–297. doi: 10.1115/1.4010337

6. D.F. Baxter Jr., Tensile Testing at Extreme Temperatures, *Adv. Mater. Proc.*, Vol 139 (No. 2), 1991, p 22–32.

7. J.C. Bittence, New Emphasis on Automation, *Adv. Mater. Proc.*, Vol 136 (No. 5), 1989, p 45–56.

8. K.C. Liu and C.R. Brinkman, Tensile Cyclic Fatigue of Structural Ceramics, *Proc. 23rd Automotive Technology Development Contractor's Coordination Meeting*, Vol 165, Society of Automotive Engineers, Oct 1985, p 279–284.

9. F.I. Baratta and W.T. Matthews, "Errors Associated with Flexure Testing of Brittle Materials," U.S. Army Materials Technology Laboratory Report MTL TR 87-35, 1987.

10. F.I. Baratta, Requirements for Flexure Testing of Brittle Materials, *Methods for Assessing the Structural Reliability of Brittle Materials*, STP 844, ASTM, 1984, p 194–222.

11. G. Quinn, "Flexural Strength of High Performance Ceramics at Ambient Temperature," Department of the Army, MIL-STD-1942(MR), 1984.

12. D.B. Marshall and A.G. Evans, Failure Mechanisms in Ceramic Fiber-Ceramic Matrix Composites, *J. Am. Ceram. Soc.*, Vol 68 (No. 5), 1985, p 225–231. doi: 10.1111/j.1151-2916.1985.tb15313.x

13. M.K. Ferber, V.J. Tennery, S. Waters, and J.C. Ogle, Fracture Strength Characterization of Tubular Ceramics Using a Simple C-Ring Geometry, *J. Mater. Sci.*, Vol 8, 1986, p 2628– 2632. doi: 10.1007/BF00551464

14. O.M. Jadaan, D.L. Shelleman, J.C. Conway Jr., J.J. Mecholsky, and R.E. Tressler, Prediction of the Strength of Ceramic Tubular Components: Part I—Analysis, *J. Test. Eval.*, Vol 19 (No. 3), 1991, p 181–191.

15. D.L. Shelleman, O.M. Jadaan, J.C. Conway Jr., and J.J. Mecholsky Jr., Prediction of the Strength of Ceramic Tubular Components: Part II—Experimental Verification, *J. Test. Eval.*, Vol 19 (No. 3), 1991, p 192–201.

16. G. de With and H.H.H. Wagemens, Ball-on-Ring Test Revisited, *J. Am. Ceram. Soc.*, Vol 72 (No. 8), 1989, p 1538– 1541. doi: 10.1111/j.1151-2916.1989.tb07702.x

17. H. Fessler and D.C. Fricker, A Theoretical Analysis of the Ring-on-Ring Loading Disk Test, *J. Am. Ceram. Soc.*, Vol 67 (No. 9), 1984, p 582–588. doi: 10.1111/j.1151-2916.1984.tb19598.x

18. D.K. Shetty, A.R. Rosenfield, and W.H. Duckworth, Statistical Analysis of Size and Stress State Effects on the Strength of An Alumina Ceramic, *Methods for Assessing the Structural Reliability of Brittle Materials*, STP 844, ASTM, 1984, p 57–80.

19. S.A. Bortz and T.B. Wade, Analysis and Review of Mechanical Testing Procedure for Brittle Materials, *Structural Ceramics and Testing of Brittle Materials*, S.J. Acquaviva and S.A. Bortz, Ed., Gordon and Breach, 1968, p 47–139.

20. Laser Gages Creep of Ceramics, *Adv. Mater. Proc.*, Vol 138 (No. 5), 1990, p 75–76.

Selected References

- J.E. Amaral and C.N. Pollock, Machine Design Requirements for Uniaxial Testing of Ceramics Materials, *Mechanical Testing of Engineering Ceramics at High Temperatures*, B.F. Dyson, R.D. Lohr, and R. Morrell, Ed., 1989, p 51–68.

- H.C. Cao, E. Bischoff, O. Sbaizero, M. Ruhle, A.G. Evans, D.B. Marshall, and J. Brennan, Effects of Interfaces on the Mechanical Properties of Fiber-Reinforced Brittle Materials, *J. Am. Ceram. Soc.*, Vol 73 (No. 6), 1990, p 1691– 1699. doi: 10.1111/j.1151-2916.1990.tb09814.x

- H. Cao and M.D. Thouless, Tensile Tests of Ceramic-Matrix Composites: Theory and Experiment, *J. Am. Ceram. Soc.*, Vol 73 (No. 7), 1990, p 2091– 2094. doi: 10.1111/j.1151-2916.1990.tb05273.x

- D.F. Carroll, S.M. Wiederhorn, and D.E. Roberts, Technique for Tensile Testing Ceramics, *J. Am. Ceram. Soc.*, Vol 72 (No. 9), 1989, p 1610– 1614. doi: 10.1111/j.1151-2916.1989.tb06291.x

- M.G. Jenkins, M.K. Ferber, R.L. Martin, V.T. Jenkins, and V.J. Tennery, "Study and Analysis of the Stress State in a Ceramic, Button-Head, Tensile Specimen," *ORNL/TM-11767*, Oak Ridge National Laboratory Technical Memorandum, Sept 1991. doi: 10.2172/5766576

- C.G. Larsen, *Ceramics Tensile Grip*, STP 1080, J.M. Kennedy, H.H. Moeller, and W.W. Johnson, Ed., ASTM, 1990, p 235–246.

- J.J. Mecholsky, Evaluation of Mechanical Property Testing Methods for Ceramic Matrix Composites, *Am. Ceram. Soc. Bull.*, Vol 65 (No. 2), 1986, p 315–322.

- L.C. Meija, High Temperature Tensile Testing of Advanced Ceramics, *Ceramic Engineering and Science Proceedings*, Vol 10 (No. 7-8), 1989, p 668–681. doi: 10.1002/9780470310557.ch14

- L.G. Mosiman, T.L. Wallenfelt, and C.G. Larsen, Tension/Compression Grips for Monolithic Ceramics and Ceramic Matrix Composites, *Ceramic Engineering and Science Proceedings*, Vol 12 (No. 7-8), 1991.

- T. Ohji, Towards Routine Tensile Testing, *Int. J. High. Technol. Ceram.*, Vol 4, 1988, p 211–225. doi: 10.1016/0267-3762(88)90046-X

- G.D. Quinn, Strength and Proof Testing, *Ceramics and Glasses*, Vol 4, *Engineered Materials Handbook*, ASM International, 1991, p 599–609

- S.G. Seshadri and K.-Y. Chia, Tensile Testing Ceramics, *J. Am. Ceram. Soc.*, Vol 70 (No. 10), 1987, p C242–C244. doi: 10.1111/j.1151-2916.1987.tb04887.x

Chapter 11: Tensile Testing of Fiber-Reinforced Composites

References

1. “Standard Test Method for Tensile Strength and Young’s Modulus for High-Modulus Single-Filament Materials,” D 3379, *Annual Book of ASTM Standards*, ASTM International

2. “Standard Test Methods for Properties of Continuous Filament Carbon and Graphite Fiber Tows,” D 4018, *Annual Book of ASTM Standards*, ASTM International Testing and Materials

3. *Composite Materials*, Vol 1, Chapter 6, MILHDBK-17-1E, Department of Defense Handbook

4. Use of Crossply Laminate Testing to Derive Lamina Strengths in the Fiber Direction, *Composite Materials*, Vol 1, Chapter 6, MILHDBK-17-1E, Department of Defense Handbook

5. J.M. Ogonowski, Analytical Study of Finite Geometry Plates with Stress Concentrations, *AIAA Paper 80-0778*, American Institute of Aeronautics and Astronautics, New York, 1980, p 694 doi: 10.2514/6.1980-778

6. J.M. Whitney and R.J. Nuismer, Stress Fracture Criteria for Laminated Composites Containing Stress Concentrations, *J. Compos. Mater.*, Vol 8, 1974, p 253 doi: 10.1177/002199837400800303

7. L.A. Carlsson and R.B. Pipes, *Experimental Characterization of Advanced Composite Materials*, 2nd ed., Technomic, Lancaster, 1987

8. R.B. Pipes, R.C. Wetherhold, and J.W. Gillespie Jr., Notched Strength of Composite Materials, *J. Compos. Mater.*, Vol 13, 1979, p 148 doi: 10.1177/002199837901300206

9. “Test Method for Tensile Properties of Fiber Reinforced Metal Matrix Composites,” D 3552, *Annual Book of ASTM Standards*, ASTM International

Chapter 12: Tensile Testing of Components

References

1. H.E. Fairman, Overview of Mechanical Properties for Component Design, *Mechanical Testing and Evaluation*, Vol 8, *ASM Handbook*, ASM International, 2000, p 789–797

2. R.S. Shoberg, Mechanical Testing of Threaded Fasteners and Bolted Joints, *Mechanical Testing and Evaluation*, Vol 8, *ASM Handbook*, ASM International, 2000, p 811–835 doi: 10.31399/asm.hb.v08.a0003323

3. "Standard Test Method for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, and Rivets (Metric)," ASTM F 606M, Annual Book of ASTM Standards, ASTM

4. K.L. Devries and P. Borgmeier, Testing of Adhesive Joints, *Mechanical Testing and Evaluation*, Vol 8, *ASM Handbook*, ASM International, 2000, p 836–844 doi: 10.31399/asm.hb.v08.a0003324

5. Adhesives, *Annual Book of ASTM Standards*, Vol 15.06, ASTM (updated annually)

6. G.P. Anderson and K.L. DeVries, Analysis of Standard Bond-Strength Tests, *Treatise on Adhesion and Adhesives*, Vol 6, R.L. Patrick, K.L. DeVries, and G.P. Andersen, Ed., Marcel Dekker, 1989

7. J.K. Strozier, K.J. Ninow, K.L. DeVries, and G.P. Anderson, *Adhes. Sci. Rev.*, Vol 1, 1987, p 121 doi: 10.1163/156856187X00229

8. G.P. Anderson, D.H. Brinton, K.J. Ninow, and K.L. DeVries, A Fracture Mechanics Approach to Predicting Bond Strength, *Advances in Adhesively Bonded Joints*, *Proceedings of a Conference at the Winter Annual Meeting of ASME*, 27 Nov–2 Dec 1988 (Chicago), S. Mall, K.M. Liechti, and J.K. Vinson, Eds., ASME, 1988, p 98–101

9. G.P. Anderson and K.L. DeVries, Predicting Strength of Adhesive Joints from Test Results, *Int. J. Fract.*, Vol 39, 1989, p 191–200 doi: 10.1007/978-94-009-0927-4_15

10. V.L. Hein and F. Erodogan, Stress Singularities in a Two-Material Wedge, *Int. J. Fract.*, Vol 7, 1971, p 317 doi: 10.1007/BF00184307

11. J.A. Marceau, Y. Moji, and J.C. McMillan, A Wedge Test for Evaluating Adhesive Bonded Surface Durability, *21st SAMPE Symposium*, Vol 21, 6- 8 April 1976

12. "Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus," E 111,, *Annual Book of ASTM Standards*, Vol 3.01, ASTM, 1999

13. “Standard Methods of Tension Testing of Metallic Materials,” E 8, *Annual Book of ASTM Standards*, Vol 3.01, ASTM, 1999

14. “Standard Methods of Tension Testing Wrought and Cast Aluminum, and Magnesium Alloy Products,” B 557, *Annual Book of ASTM Standards*, Vol 3.01, ASTM, 1999

Chapter 13: Hot Tensile Testing

References

1. *Met. Ind.*, Vol 11, 1963, p 247–249 doi: 10.1109/TCOM.1963.1088746

2. M.G. Cockroft and D.J. Latham, Ductility and the Workability of Metals, *J. Inst. Met.*, Vol 96, 1968, p 33–39

3. *J. Inst. Met.*, Vol 92, 1964, p 254–256 doi: 10.1042/bj0920254

4. G. Cusminsky and F. Ellis, An Investigation into the Influence of Edge Shape on Cracking During Rolling, *J. Inst. Met.*, Vol 95 (No. 2), Feb 1967, p 33–37

5. E.F. Nippes, W.F. Savage, B.J. Bastian, and R.M. Curran, An Investigation of the Hot Ductility of High-Temperature Alloys, *Weld. J.*, Vol 34, April 1955, p 183s–196s

6. D.F. Smith, R.L. Bieber, and B.L. Lake, "A New Technique for Determining the Hot Workability of Ni-Base Superalloys," presented at IMD-TMS-AIME meeting, 22 Oct 1974

7. S.I. Oh, S.L. Semiatin, and J.J. Jonas, An Analysis of the Isothermal Hot Compression Test, *Metall. Trans. A*, Vol 23A (No. 3), March 1992, p 963–975 doi: 10.1007/BF02675571

8. W.C. Unwin, *Proc. Inst. Civil Eng.*, Vol 155, 1903, p 170–185

9. P.A. Friedman and A.K. Ghosh, Microstructural Evolution and Superplastic Deformation Behavior of Fine Grain 5083Al, *Metall. Mater. Trans. A*, Vol 27A (No. 12), Dec 1996, p 3827–3839 doi: 10.1007/BF02595632

10. P.D. Nicolaou and S.L. Semiatin, High-Temperature Deformation and Failure of an Orthorhombic Titanium Aluminide Sheet Material, *Metall. Mater. Trans. A.*, Vol 27A (No. 11), Nov 1996, p 3675– 3681 doi: 10.1007/BF02595459

11. R. Pilkington, C.W. Willoughby, and J. Barford, The High-Temperature Ductility of Some Low-Alloy Ferritic Steels, *Metal Sci. J.*, Vol 5, Jan 1971, p 1 doi: 10.1179/030634571790439720

12. D.J. Latham, *J. Iron Steel Inst.*, Vol 92, 1963– 1964, p 255

13. R.E. Bailey, *Met. Eng. Quart.*, 1975, p 43–50 doi: 10.1097/00000542-197512000-00027

14. R.E. Bailey, R.R. Shiring, and R.J. Anderson, *Superalloys Metallurgy and Manufacture*, Proc. of the Third International Conference, Claitor's Publishing, Sept 1976, p 109–118

15. P.D. Nicolaou and S.L. Semiatin, An Investigation of the Effect of Texture on the High-Temperature Flow Behavior of an Orthorhombic Titanium Aluminide Alloy, *Metall. Mater. Trans. A.*, Vol 28A (No. 3A), March 1997, p 885–893 doi: 10.1007/s11661-997-0076-8

16. J. Pilling and N. Ridley, *Superplasticity in Crystalline Solids*, The Institute of Metals, London, UK, 1989

17. R.M. Imayev and V.M. Imayev, Mechanical Behaviour of TiAl Submicrocrystalline Intermetallic Compound at Elevated Temperatures, *Scr. Met. Mater.*, Vol 25 (No. 9), Sept 1991, p 2041– 2046 doi: 10.1016/0956-716X(91)90271-2

18. D.A. Woodford, Strain-Rate Sensitivity as a Measure of Ductility, *Trans. ASM*, vol 62 (No. 1), March 1969, p 291–293

19. A.K. Ghosh and R.A. Ayres, On Reported Anomalies in Relating Strain-Rate Sensitivity (*m*) to Ductility, *Metall. Trans. A*, Vol 7A, 1976, p 1589– 1591 doi: 10.1007/BF02656404

20. J.W. Hutchinson and K.W. Neale, Influence of Strain-Rate Sensitivity on Necking Under Uniaxial Tension, *Acta Metall.*, Vol 25 (No. 8), Aug 1977, p 839–846 doi: 10.1016/0001-6160(77)90168-7

21. F.A. Nichols, Plastic Instabilities and Uniaxial Tensile Ductilities, *Acta Mater.*, Vol 28 (No. 6), June 1980, p 663–673 doi: 10.1016/0001-6160(80)90144-3

22. M.A. Meyers and K.K. Chawla, *Mechanical Metallurgy Principles and Applications*, Prentice Hall, 1984.

23. N.E. Paton and C.H. Hamilton, Microstructural Influences on Superplasticity in Ti-6Al-4V, *Metall. Trans. A*, Vol 10A, 1979, p 241–250 doi: 10.1007/BF02817634

24. G.E. Dieter, *Mechanical Metallurgy*, 3rd ed., McGraw-Hill, 1986

25. A.K. Ghosh and C.H. Hamilton, Mechanical Behavior and Hardening Characteristics of a Superplastic Ti-6Al-4V Alloy, *Metall. Trans. A*, Vol 10A, 1979, p 699–706 doi: 10.1007/BF02658391

26. R. Verma, P.A. Friedman, A.K. Ghosh, S. Kim, and C. Kim, Characterization of Superplastic Deformation Behavior of a Fine Grain 5083 Al Alloy Sheet, *Metall. Mater. Trans. A*, Vol 27A (No. 7), July 1996, p 1889– 1898 doi: 10.1007/BF02651938

27. P.W. Bridgman, *Studies in Large Plastic Flow and Fracture*, McGraw-Hill, 1952

28. A.S. Argon, J. Im, and A. Needleman, Distribution of Plastic Strain and Negative Pressure in Necked Steel and Copper Bars, *Metall. Trans. A*, Vol 6A, 1975, p 815–824 doi: 10.1007/BF02672305

29. C.M. Lombard, R.L. Goetz, and S.L. Semiatin, Numerical Analysis of the Hot Tension Test, *Metall. Trans. A*, Vol 24A (No. 9), Sept 1993, p 2039– 2047 doi: 10.1007/BF02666338

30. C. G'sell, N.A. Aly-Helal, and J.J. Jonas, *J. Mater. Sci.*, Vol 18, 1983, p 1731– 1742 doi: 10.1007/BF00542069

31. A.K. Ghosh, A Numerical Analysis of the Tensile Test for Sheet Metals, *Metall. Trans. A*, Vol 8A, 1977, p 1221– 1232 doi: 10.1007/BF02643836

32. S.L. Semiatin, A.K. Ghosh, and J.J. Jonas, A "Hydrogen Partitioning" Model for Hydrogen Assisted Crack Growth, *Metall. Trans. A*, Vol 16A, 1985, p 2039-47 doi: 10.1007/BF02662405

33. P.D. Nicolaou, S.L. Semiatin, and C.M. Lombard, Simulation of the Hot-Tension Test under Cavitating Conditions, *Metall. Mater. Trans. A.*, Vol 27A (No. 10), Oct 1996, p 3112– 3119 doi: 10.1007/BF02663861

34. S.L. Semiatin, R.E. Dutton, and S. Shamasundar, Materials Modeling for the Hot Consolidation of Metal Powders and Metal-Matrix Composites, *Processing and Fabrication of Advanced Materials IV*, T.S. Srivatsan and J.J. Moore, Ed., The Minerals, Metals, and Materials Society, 1996, p 39–52

35. P.D. Nicolaou and S.L. Semiatin, *Scr. Mater.*, Vol 36, 1997, p 83–88 doi: 10.1016/S1359-6462(96)00342-9

36. M.M.I. Ahmed and T.G. Langdon, Exceptional Ductility in the Superplastic Pb-62 Pct Sn Eutectic, *Metall. Trans. A*, Vol 8A, 1977, p 1832– 1833 doi: 10.1007/BF02646892

37. S.L. Semiatin, V. Seetharaman, A.K. Ghosh, E.B. Shell, M.P. Simon, and P.N. Fagin, Cavitation During Hot Tension Testing of Ti-6Al-4V, *Mater. Sci. Eng. A*, Vol A256, 1998, p 92–110 doi: 10.1016/S0921-5093(98)00814-4

38. C.C. Bampton and J.W. Edington, The Effect of Superplastic Deformation on Subsequent Service Properties of Fine-Grained 7475 Aluminum, *J. Eng. Mater. Tech.*, Vol 105 (No. 1), Jan 1983, p 55–60 doi: 10.1115/1.3225619

39. J. Pilling and N. Ridley, Cavitation in Aluminium Alloys During Superplastic Flow, *Superplasticity in Aerospace*, H.C. Heikkenen and T.R. McNelley, The Metallurgical Society, 1988, p 183–197

40. G.H. Edward and M.F. Ashby, Intergranular Fracture During Powder-Law Creep, *Acta Metall.*, Vol 27, 1979, p 1505– 1518 doi: 10.1016/0001-6160(79)90173-1

41. A.K. Ghosh, D.- H. Bae, and S.L. Semiatin, Initiation and Early Stages of Cavity Growth During Superplastic and Hot Deformation, *Mater. Sci. Forum*, Vol 304- 306, 1999, p 609–616 doi: 10.4028/www.scientific.net/MSF.304-306.609

42. S. Sagat and D.M.R. Taplin, Fracture of a Superplastic Ternary Brass, *Acta Metall.*, Vol 24 (No. 4), April 1976, p 307–315 doi: 10.1016/0001-6160(76)90005-5

43. A.H. Chokshi, The Development of Cavity Growth Maps for Superplastic Materials, *J. Mater. Sci.*, Vol 21, 1986, p 2073– 2082 doi: 10.1007/BF00547949

44. B.P. Kashyap and A.K. Mukherjee, Cavitation Behavior During High Temperature Deformation of Micrograined Superplastic Materials—A Review, *Res Mech.*, Vol 17, 1986, p 293–355

45. A.C.F. Cocks and M.F. Ashby, Creep Fracture by Coupled Power-Law Creep and Diffusion Under Multiaxial Stress, *Met. Sci.*, Vol 16, 1982, p 465–478 doi: 10.1179/msc.1982.16.10.465

46. P.D. Nicolaou, S.L. Semiatin, and A.K. Ghosh, An Analysis of the Effect of Cavity Nucleation Rate and Cavity Coalescence on the Tensile Behavior of Superplastic Materials, *Metall. Mater. Trans. A*, Vol 31A, 2000, p 1425– 1434 doi: 10.1007/s11661-000-0260-6

47. J. Pilling, Effect of Coalescence on Cavity Growth During Superplastic Deformation, *Mater. Sci. Technol.*, Vol 1 (No. 6), June 1985, p 461–466 doi: 10.1179/mst.1985.1.6.461

48. P.D. Nicolaou and S.L. Semiatin, Modeling of Cavity Coalescence During Tensile Deformation, *Acta Mater*, Vol 47, 1999, p 3679– 3686 doi: 10.1016/S1359-6454(99)00237-2

49. P.D. Nicolaou and S.L. Semiatin, The Influence of Plastic Hardening on Surface Deformation Modes Around Vickers and Spherical Indents, *Acta Mater*, Vol 48, 2000, p 3441–3450 doi: 10.1016/S1359-6454(00)00140-3

50. L. Weber, M. Kouzeli, C. San Marchi, and A. Mortensen, On the Use of Considere's Criterion in Tensile Testing of Materials Which Accumulate Internal Damage, *Scr. Mater.* Vol 41, 1999, p 549–551 doi: 10.1016/S1359-6462(99)00159-1

51. C.M. Lombard, "Superplasticity in Near-Gamma Titanium Aluminides," Ph.D. Thesis, University of Michigan, Ann Arbor, MI, 2001

52. J. Lian and M. Suery, Effect of Strain Rate Sensitivity and Cavity Growth Rate on Failure of Superplastic Material, *Mater. Sci. Technol.*, Vol 2, 1986, p 1093– 1098 doi: 10.1179/mst.1986.2.11.1093

53. M. Zaki, Micronecking and Fracture in Cavitated and Superplastic Materials, *Metall. Mater. Trans. A*, Vol 27A, 1996, p 1043– 1046 doi: 10.1007/BF02649772

54. P.D. Nicolaou and S.L. Semiatin, A Theoretical Investigation of the Effect of Material Properties and Cavity Architecture/Shape on Ductile Failure During the Hot Tension Test, *Metall. Mater. Trans. A.*, Vol 29A, 1998, p 2621– 2630 doi: 10.1007/s11661-998-0234-7

Preview for: *Tensile Testing* (Second Edition), edited by J.R. Davis, ASM International, 2004
Full digital book available at https://doi.org/10.31399/asm.tb.tt2.9781627083553

Chapter 14: Tensile Testing at Low Temperatures

References

1. E.R. Parker, *Brittle Behavior of Engineering Structures*, John Wiley & Sons, 1957

2. R.P. Reed and A.F. Clark, Ed., *Materials at Low Temperatures*, ASM, 1983 doi: 10.31399/asm.tb.mlt.9781627083485

3. L.E. Neilsen and R.F. Landel, *Mechanical Properties of Polymers and Composites*, Marcel Dekker, NY, 1994, p 249–263

4. M.B. Kasen *et al*., Mechanical, Electrical, and Thermal Characterization of G-10CR and G-11CR Glass-Cloth/Epoxy Laminates Between Room Temperature and 4 K, *Advances in Cryogenic Engineering*, Vol 28, 1980, p 235–244 doi: 10.1007/978-1-4613-9859-2_24

5. R.P. Reed and M. Golda, Cryogenic Properties of Unidirectional Composites, *Cryogenics*, Vol 34 (No. 11), 1994, p 909–928 doi: 10.1016/0011-2275(94)90077-9

6. E.P. Popov, *Mechanics of Materials*, 2nd ed., Prentice-Hall, NJ, 1976

7. J.P. Hirth and M. Cohen, *Metalls. Trans.*, Vol 1, Jan 1970, p 3 doi: 10.1007/BF02642816

8. G. Hartwig and F. Wuchner, Low Temperature Mechanical Testing Machine, *Rev. Sci. Instrum.*, Vol 46, 1975, p 481–485 doi: 10.1063/1.1134246

9. R.P. Reed, A Cryostat for Tensile Test in the Temperature Range 300 to 4 K, *Advances in Cryogenic Engineering*, Vol 7, Plenum Press, NY, 1961, p 448–454 doi: 10.1007/978-1-4757-0531-7_54

10. J.H. Lieb and R.E. Mowers, Testing of Polymers at Cryogenic Temperatures, *Testing of Polymers*, J.V. Schmitz, Ed., Vol 2, John Wiley & Sons, 1965, p 84–108

11. R.P. Reed and R.L. Durcholz, Cryostat and Strain Measurement for Tensile Tests to 1.5 K, *Advances in Cryogenic Engineering*, Vol 15, Plenum Press, NY, 1970, p 109–116 doi: 10.1007/978-1-4757-0513-3_16

12. C. Ferrero, Stress Analysis Down to Liquid Helium Temperature, *Cryogenics*, Vol 30, March 1990, p 249–254 doi: 10.1016/0011-2275(90)90086-R

13. R.P. Reed and R.P. Walsh, Tensile Strain Effects in Liquid Helium, *Advances in Cryogenic Engineering*, Vol 34, Plenum Press, 1988, p 199–208

14. C.C. Perry, Strain Gage Reinforcement Effects on Low Modulus Materials, *Manual on Experimental Methods for Mechanical Testing of Composites*, R.L. Pendelton and M.E. Tuttle, Ed., Society for Experimental Mechanics, 1989, p 35–38 doi: 10.1007/978-94-009-1129-1_7

15. R.P. Reed and R.P. Walsh, Tensile Properties of Resins at Low Temperatures, *Advances in Cryogenic Engineering*, Vol 40, Plenum Press, NY, 1994, p 1129– 1136 doi: 10.1007/978-1-4757-9053-5_143

16. R.P. Walsh, J.D. McColskey, and R.P. Reed, Low Temperature Properties of a Unidirectionally Reinforced Epoxy Fibre-glass Composite, *Cryogenics*, Vol 35 (No. 11), 1995, p 723–725 doi: 10.1016/0011-2275(95)90899-Q

Chapter 15: High Strain Rate Tensile Testing

References

1. F.I. Niordson, A Unit for Testing Materials at High Strain Rates, *Exp. Mech.*, Vol 5, 1965, p 29–32 doi: 10.1007/BF02320901

2. C.R. Hoggatt and R.F. Recht, Stress-Strain Data Obtained at High Strain Rates Using an Expanding Ring, *Exp. Mech.*, Vol 9, 1969, p 441–448 doi: 10.1007/BF02410405

3. D.E. Grady and D.A. Benson, Fragmentation of Metal Rings by Electromagnetic Loading, *Exp. Mech.*, Vol 28, 1983, p 393–400 doi: 10.1007/BF02330054

4. A.M. Rajendran and I.M. Fyfe, Inertia Effects on the Ductile Failure of Thin Rings, *J. Appl. Mech.*, Vol 104, 1982, p 31–36 doi: 10.1115/1.3162066

5. L.M. Barker and R.E. Hollenback, Laser Interferometer for Measuring High Velocities of Any Reflecting Surface. *J. Appl. Phys.*, Vol 43, 1972, p 4669– 4674 doi: 10.1063/1.1660986

6. R.H. Warnes, *et al.*,An Improved Technique for Determining Dynamic Material Properties Using the Expanding Ring, in *Shock Waves and High-Strain-Rate Phenomena in Metals*, M.A. Meyers and L.E. Murr, Ed., Plenum Press, New York, 1981 doi: 10.1007/978-1-4613-3219-0_2

7. D. Bauer and S.J. Bless, Strain Rate Effects on Ultimate Strain of Copper, in *Shock Waves in Condensed Matter*, North Holland, Amsterdam, 1983

8. G.R. Fowles, Experimental Technique and Instrumentation, in *Dynamic Response of Materials to Intense Impulse Loading*, P.C. Chou and A.K. Hopkins, Ed., Air Force Materials Laboratory, Wright-Patterson AFB, OH, 1973

9. J.A. Zukas, T. Nicholas, H.F. Swift, L.B. Greszczuk, and D.R. Curran, *Impact Dynamics*, John Wiley & Sons, New York, 1982

10. R.G. McQueen, S.P. Marsh, J.W. Taylor, J.N. Fritz, and W.J. Carter. The Equation of State of Solids from Shock Wave Studies, in *High Velocity Impact Phenomena*, R. Kinslow, Ed., Academic Press, New York, 1970 doi: 10.1016/B978-0-12-408950-1.50012-4

11. S.P. Marsh, *LASL Shock Hugoniot Data*, University of California Press, Berkeley, 1980

12. L.M. Barker and E.G. Young, “SWAP-9: An Improved Stress Wave Analyzing Program,” Sandia National Laboratories Report No. SLA-74-0009. Albuquerque, NM, 1974

13. G.T. Gray, III, Classic Split-Hopkinson Pressure Bar Testing, *Mechanical Testing and Evaluation*, Vol 8, *ASM Handbook*, ASM International, 2000, p 462–476 doi: 10.31399/asm.hb.v08.a0003296

14. High Strain Rate Tension and Compression Tests, *Mechanical Testing and Evaluation*, Vol 8, *ASM Handbook*, ASM International, 2000, p 429–446 doi: 10.31399/asm.hb.v08.a0003294

15. A. Gilat, Torsional Kolsky Bar Testing, *Mechanical Testing and Evaluation*, Vol 8, ASM Handbook, ASM International, 2000, p 505–515 doi: 10.31399/asm.hb.v08.a0003300

16. U.S. Lindholm and L.M. Yeakley, High Strain Rate Testing: Tension and Compression, *Exp. Mech.*, Vol 8, 1968, p 1–9 doi: 10.1007/BF02326244

17. H.C. Mann, High Velocity Tension Impact Tests, *Proc. ASTM*, Vol 36 (part 2), 1936, p 85–109

18. R.O. Fehr, E. Parker, and D.J. DeMichael, Measurement of Dynamic Stress and Strain in Tensile Test Specimens, *J. Appl. Mech. (Trans. ASME)*, Vol 6A, 1944, p 65–71 doi: 10.1115/1.4009351

19. R. Dormeval and M. Stelly, Influence of Grain Size and Strain Rate of the Mechanical Behavior of High-Purity Polycrystalline Copper, Second Conf. on Mechanical Properties at High Rates of Strain, 1979 (Oxford), Institute of Physics, London, Serial No. 47, p 154–165

20. C.E. Frantz, P.S. Follansbee, and W.E. Wright, New Experimental Techniques with the Split Hopkinson Pressure Bar, *High Energy Rate Forming*, Berman and Schroeder, Ed., American Society of Mechanical Engineers, 1984, p 229 doi: 10.2172/6854600

21. A.M. Lennon and K.T. Ramesh, A Technique for Measurement of the Dynamic Behaviour of Materials at High Temperatures, *Int. J. Plast.*, Vol 14 (No. 12), 1998, p 1279– 1292 doi: 10.1016/S0749-6419(98)00056-4

Glossary of Terms

Selected References

- *Compilation of ASTM Standard Definitions*, 8th ed., ASTM, 1994
- H.E. Davis G.E. Troxell and G.F.W. Hauck, *The Testing of Engineering Materials*, 4th ed., McGraw Hill, 1982
- J.R. Davis Ed., *ASM Materials Engineering Dictionary*, ASM International, 1992
- G.E. Dieter, Mechanical Metallurgy, 2nd ed., McGraw Hill, New York, 1976
- *Glossary of Metallurgical Terms and Engineering Tables*, American Society for Metals, 1979
- D.N. Lapedes Ed., *Dictionary of Scientific and Technical Terms*, 2nd ed., McGraw Hill, 1974
- A.D. Merriman, *A Dictionary of Metallurgy*, Pitman Publishing, London, 1958
- "Metal Test Methods and Analytical Procedures," *Annual Book of ASTM Standards*, Vol 03.01 and 03.02, ASTM, 1984
- J.G. Tweeddale, *Mechanical Properties of Metals*, American Elsevier, 1964