Materials Testing Guide

July 2013

In this guide:

- Do Your Materials Measure Up? - Testing Basics
- Tensile Testing Tips and Trends
- Effects of Specimen Geometry on Elongation
- Measurement Errors

ADMET

Introduction

As a product designer, production manager, or quality inspector you may be faced with Material Testing issues. We've brought together four brief papers to cover some basic issues worth recapping to optimize your procedures.

We hope you find them useful and please check out our website for great blog articles, white papers, and videos at **ADMET.com**.

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Do Your Materials Measure Up?

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Materials testing is often the last step in the manufacturing process. Yet quality cannot be put in after the fact since it is the result of both the materials and the process. In forming materials, it's helpful to understand their properties in order to better predict the manufacturing outcome. For stamping and forming operations and for many products it is also helpful to have a profile of the material in order to detect variations in materials from suppliers over time.

This paper offers definitions for mechanical properties of materials that exhibit some Hookean (linear) behavior during loading. Metals and many plastics, polymers and composites exhibit Hookean behavior. This paper is intended as a tutorial or refresher for product designers and quality inspectors on the analysis of tensile test data. A glossary of important materials testing terms is included (Sidebar).

Tensile testing has several elements

The performance of a structure is frequently determined by the amount of deformation that can be permitted. A deflection of a few thousandths of an inch in an optical grinding machine would produce scrap lenses, whereas a bridge truss or joist might deflect several inches. Tensile Strength, Yield Strength and Young's Modulus of Elasticity are measured properties that must be considered when designing a structure.

Another important property is ductility, defined as the ability for plastic deformation in tension or shear. Ductility controls the amount a material can be cold formed which is the process used when forming automobile bodies or wire products. Two commonly used indices of ductility are total elongation and reduction of area. For suppliers, the mechanical properties are an important measure of product quality, and often times buyers require certification of the values.

The outcome of a forming process is dependent on both material characteristics and process variables such as strain, strain rate and temperature. Stress and strain fields are so diverse during a forming process that one test cannot be used to predict the formability of materials in all situations. However, an understanding of material properties is important to determining the success of a forming process.

Figure 1 - Tensile specimen pulled to fracture. Depicts region where necking occurred.

Material properties that have a direct or indirect influence on formability and product quality are Tensile Strength, Yield Strength, Young's Modulus, Ductility, Hardness, the Strain Hardening Exponent and the Plastic Strain Ratio. All of these parameters, except hardness, can be determined by cutting a test specimen from the blank and performing a tensile test.

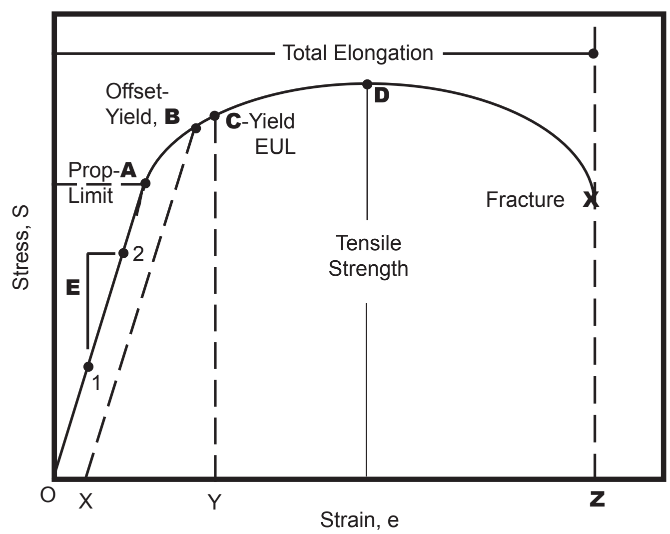

Figure 2 - Stress-Strain Curve.

A tensile test is employed to generate a stress-strain curve that provides a graphical description of the amount of deflection under load for a given material. A typical stress-strain curve is shown in Figure 2 and depicts several key measures of product quality.

The Tensile Test - The stress-strain curve is generated by pulling a metal specimen in uniaxial tension to failure. ASTM E8/E8M Standard Test Methods for Tension Testing Metallic Materials governs the methods used for the determination of Yield Strength, Ultimate Tensile Strength, Percent Elongation at Break and Reduction of Area.

Engineering stress (S) is obtained by dividing the force (F) at any given time by the original cross sectional area (A_o) of the specimen.

$S = F/A_o$ Eq. 1

Engineering strain (e) is obtained by dividing the elongation of the gage length of the specimen ($\triangle l$) by the original gage length (l_o).

$e = \triangle l/l_o = (l - l_o)/l_o$ Eq. 2

Figure 2 depicts a typical stress-strain curve. The shape and magnitude of the curve is dependent on the type of metal being tested. In Figure 2, point **A** represents the proportional limit of a material. A material loaded in tension beyond point **A** when unloaded will exhibit permanent deformation. The proportional limit is often times difficult to calculate, therefore, two practical measurements, Offset Yield Strength and Yield by Extension Under Load (EUL) were developed to approximate the proportional limit. The initial portion of the curve below point **A** represents the elastic region and is approximated by a straight line. It is commonly referred to as the linear elastic or Hookean region. The slope (E) of the curve in the elastic region is defined as Young's Modulus of Elasticity and is a measure of material stiffness.

$E = \triangle S / \triangle e = (S_2-S_1)/(e_2-e_1)$ Eq. 3

Point **B** represents the Offset Yield Strength and is found by constructing a line X-B parallel to the curve in the elastic region (ie. slope of line X-B equal to Young's Modulus (E)). Line X-B is offset a strain amount O-X that is typically 0.2% of the gage length (example: offset O-X = 0.2% = 0.002 in/in; for a 2 in gage length = 0.004 in). Point **C** represents the Yield Strength by Extension Under Load (EUL) and is found by constructing a vertical line Y-C. Line Y-C is offset a strain amount O-Y that is typically 0.5% of gage length. The Tensile Strength or peak stress is represented by point **D** in Figure 2.

Elongation at Fracture is the amount of uniaxial strain at fracture and is depicted as strain at point **Z**. It includes the amount of both elastic and plastic deformation just prior to the sudden decrease in force associated with fracture. Elongation at Fracture is generally measured with an extensometer that remains on the specimen through break. For materials that exhibit a high degree of elongation, such as plastics, crosshead travel may be substituted for direct strain measurement with an extensometer. Percent Elongation at Break is commonly determined after the test by fitting the fractured ends together and measuring the change in gage length, l_o, between two gage marks punched or scribed into the specimen prior to testing. (The gage length used for measurement is reported with the result.).

Elongation at Break(%) $= e_z = 100*(l_z-l_o)/l_o$ Eq. 4

Reduction of Area like Elongation at Break is another measure of ductility and is expressed in percent. Reduction of Area is calculated by measuring the cross sectional area at the fracture point.

Reduction of Area(%) $= (A_o-A_z)/A_o$ Eq. 5

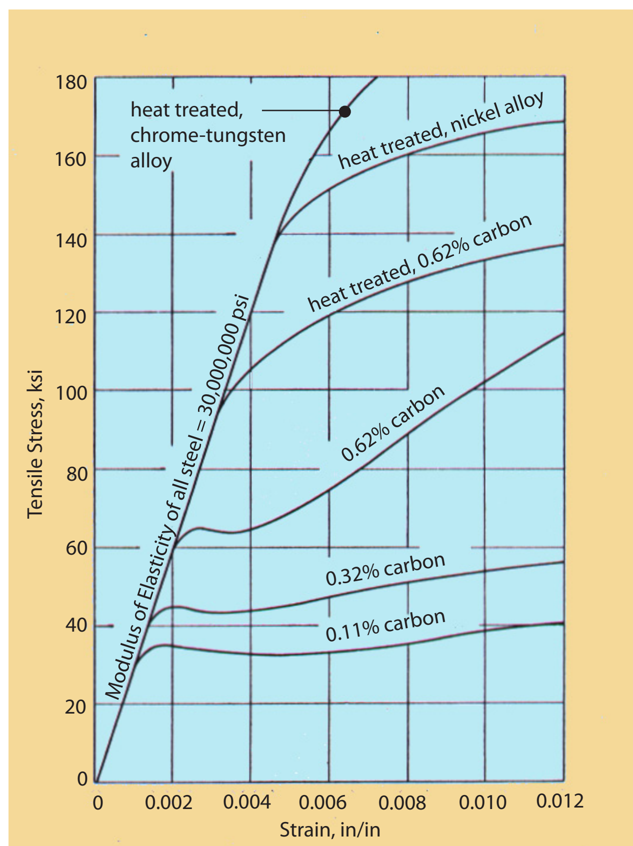

Figure 3 - Stress-strain diagram for various steels.
(from Muhlenbruch, C.W.: *Testing of Engineering Materials*, Van Nostrand, New York, 1944.)

A few words about mechanical properties

Figure 3 shows the relative magnitudes of the stress-strain curves for various steels. Figure 4 depicts the magnitudes of Tensile Strength, Yield Strength, Elongation and Reduction of Area as the carbon content of steel is varied.

- In general, as Reduction of Area increases, the minimum allowable bend radius for a sheet material decreases. Therefore, as the carbon content of steel increases the minimum bend radius increases.

- Yield Strength and Tensile Strength are not directly related to formability, however, the closer the magnitude of the two stresses, the more work hardened the metal. Therefore, as the carbon content of steel decreases the material appears as if it is more work hardened.

- Both elastic and plastic deformation occur during a forming process. Upon removal of the external forces, the internal elastic stresses relax. If the forming process is not designed properly, the stress relaxation or "springback" will cause the part to change shape or distort. A material with a lower value for Young's Modulus, E, and/or a higher value for Yield Strength will exhibit greater "springback" or shape distortion. Therefore, as the carbon content of steel increases the amount of "springback" increases.

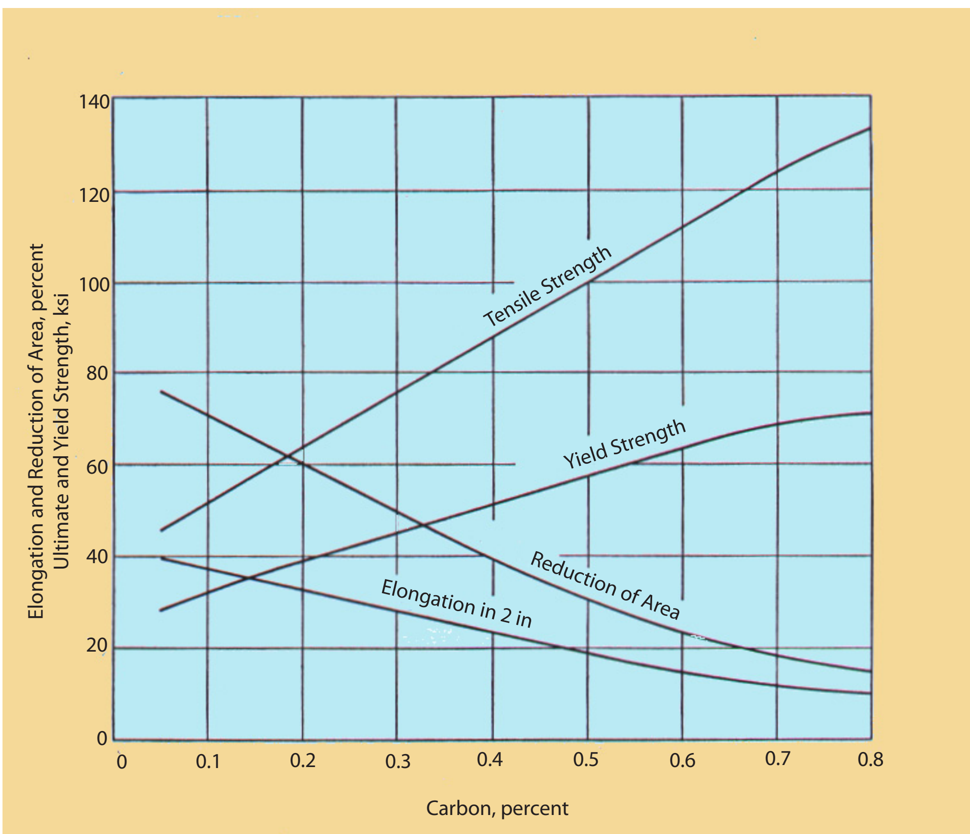

Figure 4- Effect of carbon on tensile properties of hot-worked carbon steels.
(from Sisco, F.T.: *Modern Metallurgy for Engineers*, Pitman, New York, 1948.

Some important points to keep in mind when testing

- Elongation at Fracture and Reduction of Area both increase with increasing cross-sectional area of the specimen. Percent Elongation decreases with increasing gage length because the region where localized necking occurs remains the same regardless of the gage length. Therefore, consistency in specimen dimensions and gage length are paramount for comparing results and ensuring process quality.

- The rate at which a test is performed can have a significant effect on tensile properties and is known as strain rate sensitivity. Tensile properties for plastics and polymers are very sensitive to testing rates. Steels are also sensitive to strain rates but aluminum alloys have little sensitivity. Materials that are sensitive to strain rates exhibit higher tensile strengths and lower elongations at faster speeds. Therefore, it is important that all testing rates are within the limits specified by the governing standard(s). I would even go one step further if you are comparing results across lots or batches of like materials and insist that the testing rates are identical.

- During the rolling process used to produce metals in sheet form and the subsequent annealing, the grains become elongated in the rolling direction resulting in an anisotropic material. This causes a variation in tensile properties when the direction of loading is changed in relation to the orientation of the grains. Therefore, it is common practice to test specimens cut parallel to the rolling direction and at 45^o and 90^o to this direction and include the direction with the results.

- One of our most frequent support calls is from a frantic customer who states "my Yield Strength and Modulus values are not correct". After obtaining a copy of the stress-strain curve it is determined that the strain extensometer has slipped on the specimen at some point in the linear elastic region. There are several reasons why slippage may occur, chief among them are a) the specimen has not been prepared properly or is bent; b) the gage length stop is out of adjustment; c) the knife edges are worn; d) the clamping force is too small; or e) the extensometer is damaged. It is recommended that a maintenance program based on the frequency of extensometer use be instituted.

- Oftentimes the strain goes negative or a slight amount of extensometer slippage occurs just after loading begins. As a result, calculation errors may occur in programs that automatically calculate Modulus. To eliminate the non-linearity in the strain data in the elastic region, raise the logging threshold in the testing software.

Materials properties definitions:

Mechanical Properties - those properties of a material that are associated with the elastic and plastic reaction when force is applied.
Engineering Stress - the normal stress, expressed in units of applied force per unit of original cross-sectional area.
Engineering Strain - a dimensionless value that is the change in length per unit length of the original linear dimension along the loading axis of the specimen. Frequently expressed in inches per inch or percent.
Gage Length - the original length of that portion of the specimen over which strain or change in length is determined.
Extensometer - a device for measuring strain.
Ductility - the ability of a material to deform plastically before fracture.
Young's Modulus of Elasticity - the ratio of stress to corresponding strain below the proportional limit.
Elastic Limit - the greatest stress which a material is capable of sustaining without any permanent strain remaining upon complete release of stress.
Proportional Limit - the greatest stress which a material is capable of sustaining without deviation from a linear relationship of stress to strain.
Hooke's Law - within certain force limits, the stress in a material is proportional to the strain which produced it.
Yield Strength - the engineering stress at which, by convention, it is considered that plastic elongation of the material has commenced.
Tensile Strength - the maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum force during a tension test carried to rupture and the original cross-sectional area of the specimen.
Reduction of Area - the difference between the original cross-sectional area of a tension test specimen and the area of its smallest cross-section. The reduction of area is expressed as a percentage of the original cross-sectional area.
Total Elongation - the elongation determined after fracture by realigning and fitting together the broken ends of the specimen.
Hardness - the resistance of a material to deformation, particularly permanent deformation, indentation, or scratching.
Many of these definitions are taken from ASTM E6 Standard Terminology Relating to Methods of Mechanical Testing.

Tensile Testing Basics, Tips and Trends

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More lab managers and testing machine operators are asking about;

- Automatically transferring test results from their testing machines into their company's computer system or database, to eliminate data entry errors.
- Automatically calculating test results, to reduce test times.
- Verifying test results, to ensure there were no calculation errors.
- Verifying that a test was performed according to specification, to ensure the loading rates or rates of travel were correct.
- Easily comparing old test results to more recent results.
- Methods of transferring results and data to customers so that they can authorize product shipment more quickly.
- Simplifying test procedures to reduce test times.
- Improving the accuracy and reliability of their testing machine.

Success in today's marketplace requires that you improve the efficiency, quality and accuracy of your testing facilities. Purchasing new testing machines is one way to make improvements. Another option is to retrofit or upgrade your existing testing machines. Oftentimes this is the best solution because you get performance equal or better than a new machine at a lower price.

Why Test?

Testing machines are employed for essentially two reasons. The first is to develop new or better information on known materials or to develop new materials. The second is for maintaining the quality of materials. In other words, is this batch as good as the last one? Can I substitute this for that? For suppliers, the mechanical properties are an important measure of product quality, and testing is required to certify the product.

What is the strength of a material?

In a broad sense, strength refers to the ability of a structure to resist loads without failure. Failure may occur by rupture due to excessive stress or may take place owing to excessive deformation. Tensile properties include the resistance of materials to pulling or stretching forces. The amount of force required to break a material and the amount it extends

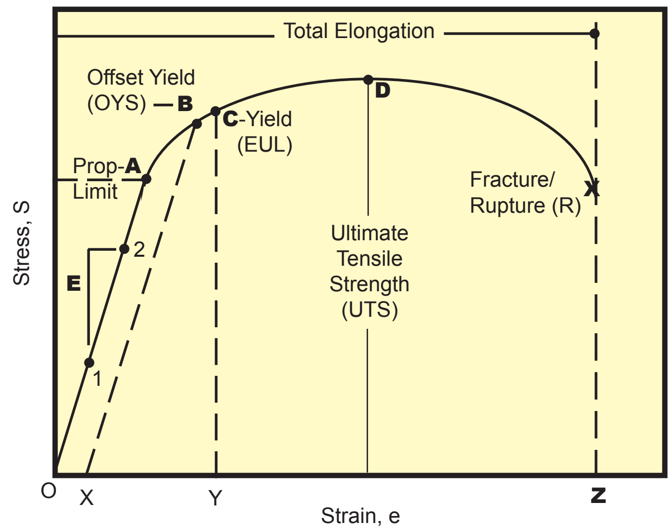


Figure 1 - Engineering Stress-Strain Curve.

before breaking are important properties. For most materials, the initial resistance to force or modulus, and the point at which permanent deformation occurs are obtained from plots of force against elongation. Analysis of force-elongation or stress-strain curves can convey a great deal about the material being tested and can help in predicting its behavior. The typical points of interest are illustrated on the engineering stress-strain curve, including Ultimate Tensile Strength (UTS) as the maximum load/stress value, Offset Yield Strength (OYS), and the Rupture (R) or Fracture point where the specimen fails.

Some Theory

A graphical description of the amount of deflection under load for a given material is the stress-strain curve (Figure 1). Engineering stress (S) is obtained by dividing the load (P) at any given time by the original cross sectional area (A_o) of the specimen.

$S = P/A_o$ Eq. 1

Engineering strain (e) is obtained by dividing the elongation of the gage length of the specimen ($\triangle l$) by the original gage length (l_o).

$e = \triangle l/l_o = (l - l_o)/l_o$ Eq. 2

Figure 1 depicts a typical stress-strain curve. The shape and magnitude of the curve is dependent on the type of metal being tested. In Figure 1, point **A** represents the proportional limit of a material. A material loaded in tension beyond point **A** when unloaded will exhibit permanent deformation. The proportional limit is often times difficult to calculate, therefore, two practical measurements, Offset Yield Strength and Yield by Extension Under Load (EUL) were developed to approximate the proportional limit. The initial portion of the curve below point **A** represents the elastic region and is approximated by a straight line. The slope (E) of the curve in the elastic region is defined as Young's Modulus of Elasticity and is a measure of material stiffness.

$E = \triangle S / \triangle e = (S_2 - S_1)/(e_2 - e_1)$ Eq. 3

Point **B** represents the Offset Yield Strength and is found by constructing a line X-B parallel to the curve in the elastic region. Line X-B is offset a strain amount O-X that is typically 0.2% of the gage length. Point **C** represents the Yield Strength by Extension Under Load (EUL) and is found by constructing a vertical line Y-C. Line Y-C is offset a strain amount O-Y that is typically 0.5% of gage length. The Ultimate Tensile Strength or peak stress is represented by point **D** in Figure 1. Total elongation, which includes both elastic and plastic deformation, is the amount of uniaxial strain at fracture and is depicted as strain at point **Z**. Percent elongation at break is determined by removing the fractured specimen from the grips; fitting the broken ends together and measuring the distance between gage marks. Percent elongation at break reports the amount of plastic deformation. (The gage length used for measurement is reported with the result.).

elongation at break(%) = $e_z = 100*(l_z - l_o)/l_o$ Eq. 4

Reduction of area, like elongation at break, is a measure of ductility and is expressed in percent. Reduction of area is calculated by measuring the cross sectional area at the fracture point (Az).

reduction of area(%) = $(A_o - A_z)/A_o$ Eq. 5

Translating theory to reality

In the laboratory, there are many things that can trip you up. If you are the one signing your name to the report, always question the assumptions and methods used to obtain the results. Following are a list of things you should consider when determining if your results are correct.

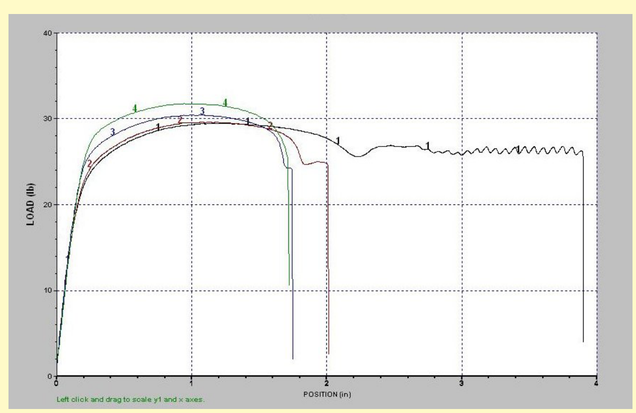
Test to the correct specification

Check the ASTM test method or other test specification and be sure the correct test speeds, loading profile and calculations are being used. On numerous occasions it has been discovered that the technician was not following the test specification. When questioned they frequently respond, "this is the way we have been doing it for years". This can be avoided by studying the specification, understanding it, then being conversant in its important points so that you can talk to the machine operators and correct their procedures if they are in error.

The rate at which a test is performed can have a significant effect on tensile properties and is known as strain rate sensitivity. Tensile properties for plastics and polymers are very sensitive to testing rates. Steels are also sensitive to strain rates but aluminum alloys exhibit little sensitivity. Materials that are sensitive to strain rates exhibit higher tensile strengths and lower elongations at faster speeds. Therefore, it is important that all testing rates are within the limits specified by the

Strain Rate Sensitivity Example - Wire Tie Test

Curve #	Speed (in/min)	Peak Load (lb)	Elongation (in)
1	2	29.5	3.90
2	4	29.6	2.01
3	8	30.4	1.75
4	16	31.7	1.72



Wire ties were pulled until fracture. Table and force-extension curves show how test speed effects peak load and maximum elongation. As the speed was doubled from 2 to 4 inches/min the maximum elongation was reduced by almost half. As the speed was increased from 2 to 16 inches/min the maximum force increased by 7.5%.

governing standard(s). If you are comparing results across lots or batches of like materials you should insist that the testing rates be identical.

Work within your testing machine's limitations
ASTM requires that you calibrate your load and strain measuring devices annually. If any device has been damaged or is subjected to excessive use, more frequent calibrations should be performed. Calibration records should be kept to determine when its time to replace or refurbish a device. Each device has its own certified range and ,therefore, no results should be reported outside the certified ranges.

Another important issue were the changes made in 2001 to ASTM E4 Standard Practices for Force Verification of Testing Machines. With the new E4 changes, the minimum certifiable force for a given range increased from 100 to 200 times the force resolution. Resolution on dial gages and pen recorders is dependent on the distance between graduation marks and the width of the needle or pen. Oftentimes with these types of devices it is not clear what the resolution should be and is subject to much interpretation. Based on the new E4, tests formerly conducted at the low end of a given force range may no longer be valid.

Basic Testing Machine Design
There are many types of testing machines, the most common are universal testing machines which test materials in tension, compression or bending. The primary use of the testing machine is to create the stress-strain diagram (Figure 1). Once the diagram is generated, a pencil and straight edge or computer algorithm can be used to calculate Yield Strength, Young's Modulus, Tensile Strength or Total Elongation. There are two classes of testing machines, electromechanical and hydraulic, the principal difference is how the load is generated (for purposes of this paper only static or quasi-static machines are considered.). The electromechanical machine employs a variable speed electric motor, gear reduction system and one, two or four screws to move the crosshead up or down. This motion loads the specimen in tension or compression. A range of crosshead speeds can be achieved 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. A hydraulic testing machine employs either a single or dual acting piston to move the crosshead up or down. Most static hydraulic testing machines use 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 servovalve for precise control. In general the electromechanical machine is capable of a wider range of test speeds and longer crosshead displacements, whereas the hydraulic machine is more cost effective solution for generating higher forces.

Figure 2 - Images of a dual screw electromechanical and quasi static servo hydraulic testing machines.

Retrofitting brings your machine up-to-date
The overwhelming reason why people upgrade their testing machine is that they achieve performance equal to or greater than a new machine at a lower cost. By adding digital controllers or Windows-based software, customers are able to continue to use the most expensive and durable component of the testing system – the load frame.

In general, a retrofit costs between $500 for the integration of a simple digital indicator to $35,000 for a new servo-hydraulic power unit with a Windows-based materials testing system. Retrofits can be installed at the customer's site in one to three days. A new 400,000 lb. universal testing machine costs between $150,000 and $200,000, so a retrofit would save well over $100,000. Even for a 60,000 lb. machine, which would cost $50,000 to $55,000 to replace, the savings would be in the tens-of-thousands of dollars. As a rule, the dollar savings increase as the capacity of the machine increases. Other reasons why you would want to retrofit your testing machine.

- You have a large investment in grips, fixtures and test jigs for your existing machine(s).
- Your machine is broken and in need of a quick repair and the lead time for a new machine is too long.
- All of your machines are identical and you want or are required to keep it that way.

Figure 3 - Two older retrofitted machines, Baldwin Hydraulic and Instron Corp Electromechanical, that are ideal candidates for retrofit.

Test technician's procedures still matter
Worn machine components can result in misalignment that creates bending stresses which lower tensile stress readings. Check the test machine's alignment and play to ensure concentricity of the crosshead over the full travel.

With the advent of microprocessor based test systems, applied loads can inadvertently be "zeroed out", resulting in lower stress readings. I can remember a customer who reported that he was achieving Yield and Ultimate Strengths 10,000 psi lower than previously measured. We had the customer email us stress vs. strain curves and machine calibration information only to find nothing wrong with the data. Later, it was learned that they hired a new machine operator. While speaking with the operator on the phone, it was determined that he was clamping the specimen in both grips then zeroing the load which was eliminating roughly 500 lbs of tensile force. This was equivalent to 10,000 psi of stress on the specimen. To prevent this, clamp the specimen in the upper grip, then zero the load, then close the lower grip.

When testing most metals, strains are usually too small to be measured by using testing machine crosshead or piston displacement. Measuring small strains typical of a high-strength metals test (0.0001in.or less) is the task of an *extensometer* and strain measuring electronics. *Selecting an extensometer*- Select one with a gage length, travel range and magnification ratio appropriate for the material being tested and anticipated elongation. Standard sizes are one-, two-, and eight-inch gage lengths. Extensometer travel is typically +/- 5%, 10%, 20%, 50% or 100%. Stiffer materials require less travel and an extensometer with too much travel may have insufficient resolution to read small strains correctly. Many test methods require extensometers to possess certain accuracy characteristics; see ASTM E83 for guidance.

Oftentimes we receive a frantic call from a customer who says "my yield values are not correct". Upon review of the stress-strain diagram it becomes obvious why – the extensometer slipped on the specimen during the test. Causes of extensometer slippage range from worn knife edges to a poorly adjusted zero point or gage length to low clamping forces to bent or improperly prepared specimens. To help prevent extensometer slippage, the clamping force and the zero point should be checked regularly and worn knife edges replaced.

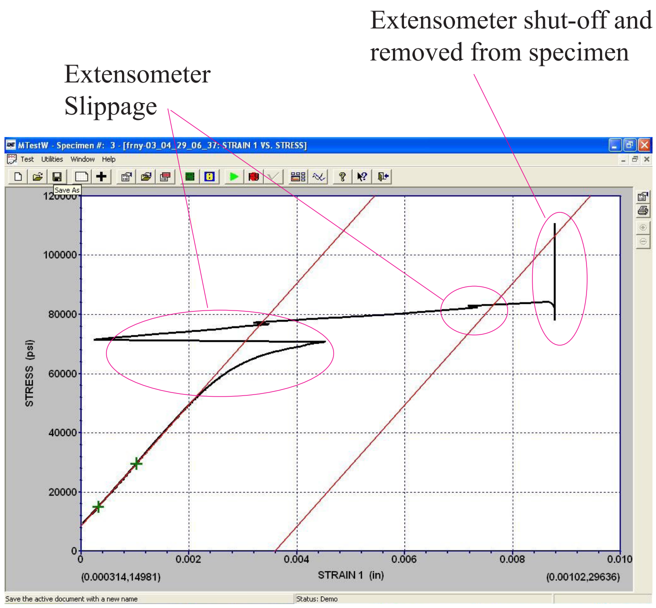


Figure 4 - Stress-strain curve showing extensometer slippage.

Wedge action grips are the most common style used in metals testing. As the axial load increases the wedge acts to increase the squeezing pressure applied to the specimen. Wedge grips are manually, pneumatically or hydraulically actuated. For high volume testing, it is recommended that pneumatic or hydraulic actuated grips be employed. Worn or dirty grip faces can results in specimen slippage which often times renders the stress-strain diagram useless. The grip faces should be inspected periodically. Worn inserts should be replaced and dirty inserts cleaned with a wire brush.

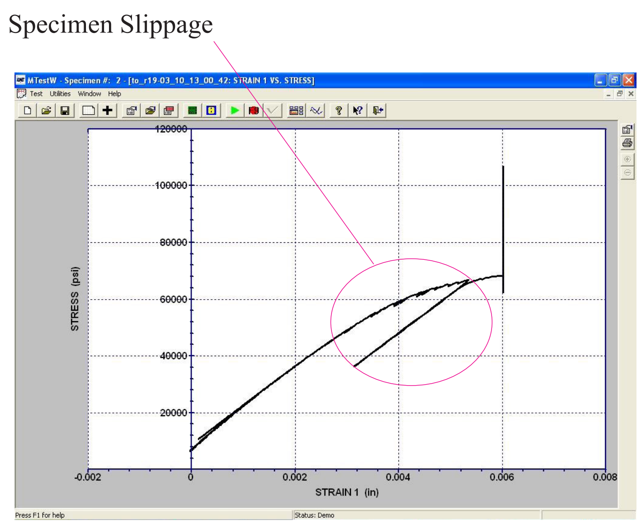


Figure 5 - Stress-strain curve showing numerous areas of specimen slippage causing invalid test.

Proper alignment of the grips and the specimen when clamped in the grips is important. Offsets in alignment will create bending stresses and lower tensile stress readings. It may even cause the specimen to fracture outside the gage length.

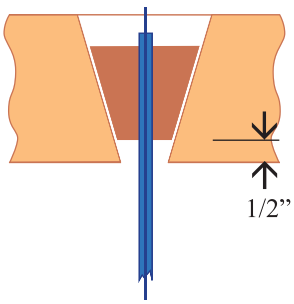


Figure 6 - Diagram showing specimen fully engaged in grip faces and grip faces properly supported inside grip pockets.

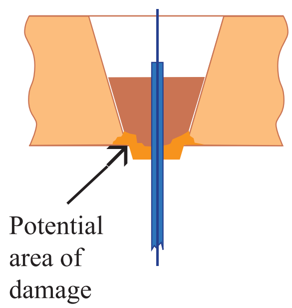


Figure 7 - Diagram showing specimen fully engaged in grip faces and grip faces not fully supported inside grip pockets. Arrangement can cause permanent damage to grip pockets and may lead to specimen slippage.

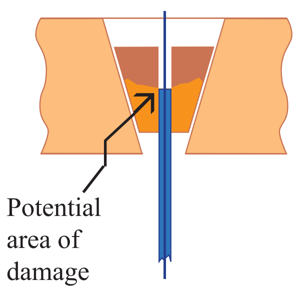


Figure 8 - Diagram showing specimen partially engaged in grip faces and grip faces properly supported inside grip pockets. Arrangement can cause permanent damage to grip inserts and may lead to specimen slippage.

Most ASTM or similar test methods require a shaped specimen that will concentrate the stress within the gage length. If the specimen is improperly machined, fracture could occur outside the gage length resulting in strain errors. Improper reading of specimen dimensions will create stress measurement errors. Worn micrometers or calipers should be replaced and care should be taken when recording specimen dimensions. Some computer based test systems will read the micrometer or caliper directly, thus eliminating data entry errors. Although most tests are conducted at ambient temperature, some specifications require materials to be tested at a specific temperature. Metals properties are affected by temperature which, if ignored, can result in testing errors.

Today’s software algorithms are good at calculating the correct results for a given stress vs. strain curve. It is usually the data input into the algorithm (i.e.. the shape and magnitude of the stress vs. strain curve) that produces the bad results. That is why the test technicians job is so important. The technician must be responsible for performing the test according to specification. He/she should be aware of the potential errors introduced by the machine, extensometer, grips and specimen irregularities; and should alert the lab supervisor when problems arise. In short, the technician should be trained in correctly generating the stress vs. strain curve of Figure 1 for a given test method. One indirect way of checking your results is to send specimens to at least two other testing laboratories so that you can compare results.

Conclusion

This is an exciting time for scientists and engineers like you who are developing new materials and new uses for all materials. From low to zero emissions automobiles to nano-machines to increasingly smaller and more powerful electronics to stronger fabrics that are lighter weight, these new materials and products will help to transform our lives. As a result, we will see an expansion in the scope of materials testing and we can also expect that it will become more complicated. As your enterprise attempts to remain competitive, the need to reduce test times, eliminate data entry errors, and speed the time of product shipments becomes increasingly important. Employing testing systems that automatically perform the tests according to specification, automatically calculate results and seamlessly communicate with other computers and programs running on your corporate network will be paramount to success.

The Effects of Specimen Geometry on Elongation

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Elongation is defined in ASTM E6 as the increase in the gage length of a test piece subjected to a tensile forces divided by the original gage length. Elongation is expressed as a percentage of the original gage length. ASTM E6 also indicates the following:

- The increase in gage length may be determined either at or after fracture.
- The gage length shall be stated with reported values of elongation.
- Elongation is affected by test-piece geomtery, including gage length, width and thickness of the gage section; plus test procedure variables, such as alignment and speed of pulling.

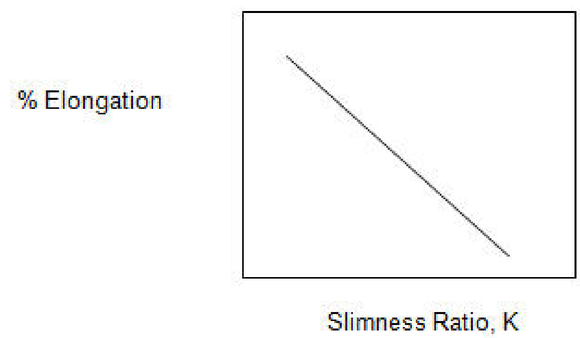
Effect of Gage Length and Necking. The gage length must be specified prior to the test and it must be reported with the value. Gage length is very important to elongation values, however, as the gage length increases, elongation values become independent of the gage length. When a specimen is pulled in tension to fracture a region of local deformation occurs and is called the neck. Necking occurs as the force begins to drop after the maximum force has been reached on the stress strain curve. Up to the point at which the maximum force occurs, the strain is uniform along the gage length; meaning that the strain is independent of gage length. However, once necking starts, the gage length becomes very important. When the gage length is short, the necking region occupies a much larger portion of the gage length. Conversely, for longer gage lengths, the necking occupies a smaller portion of the gage length. As a rule, the larger the gage length the smaller the measured elongation for a given material.

Effect of Specimen Dimensions/Section Area. The cross sectional area of the specimen also has a significant effect on elongation measurements. The slimness ratio, K, defined as the gage length divided by the square root of the crossectional area is given below.

$K = L/ \sqrt{A}$

where, L is the gage length.
A is the crossectional area.

Experiments have shown that as the slimness ratio decreases the measured elongation increases. A graphical depiction of the relationship between slimness ratio and elongation is given below. One way to properly compare elongation results is to ensure that each test specimen has the same slimness ratio.



Measurement Errors in Materials Testing

by Richard Gedney
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"Weights and measures may be ranked among the necessaries of life, to every individual of human society. They enter into the economical arrangements and daily concerns of every family. They are necessary to every occupation and human industry; to every transaction of trade and commerce; to the labors of the husbandman; to the ingenuity of the artificer; to the studies of the philosopher; to the researches of the antiquarian; to the navigation of the mariner; and the marches of the soldier; to all the exchanges of peace, and all of the operations of war. The knowledge of them, as in established use, is among the first elements of education, and is often learnt by those who learn nothing else, not even to read and write. This knowledge is riveted in memory by the habitual application of it to the employments of men throughout life." John Quincy Adams

Materials Testing is that part of engineering design, development and research that relies on laboratory testing of one kind or another to answer questions. Testing is also required during manufacturing to ensure a material or product meets some predefined specification. A universal testing machine is used to measure the mechanical properties of materials in tension, compression, bending or torsion. Common properties of interest in tension are Offset Yield Strength, Young's Modulus, E, Tensile Strength and Total Elongation. In tension, the testing machine is used to create a stress-strain diagram (Figure 1) from which all mechanical properties are derived. A true picture of the stress-strain diagram can only be obtained through accurate measurements. On numerous occasions a company has contacted us because their test results did not match results from another lab or the results they were presently obtaining were different than historical values even though their manufacturing process had not changed. Oftentimes we find that the operator is not performing the test properly or the testing machine is not configured properly in order to take accurate readings.

Mechanical testing, requires not only familiarity with measurement systems, but also some understanding of the planning, execution, and evaluation of experiments. Much experimental equipment is often "homemade" especially in smaller companies where the high cost of specialized instruments cannot always be justified. If the designer of the "homemade" equipment does not carefully consider how his/her design behaves under test, then the stress vs. strain diagram may be in error. Examples of this will be given later.

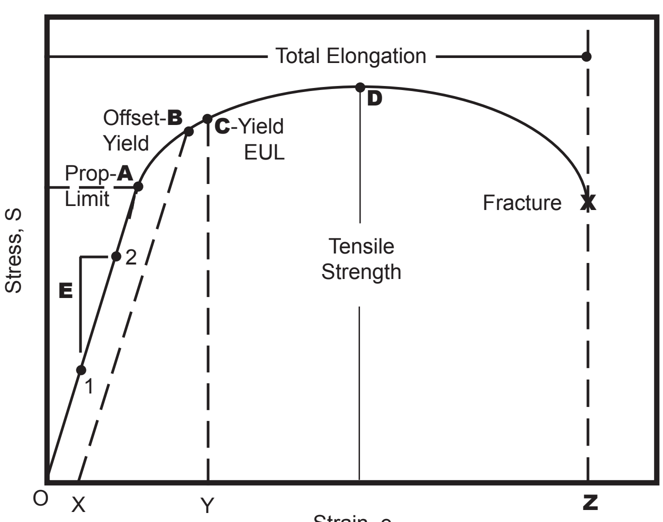

Figure 1 - A stress vs. strain diagram.

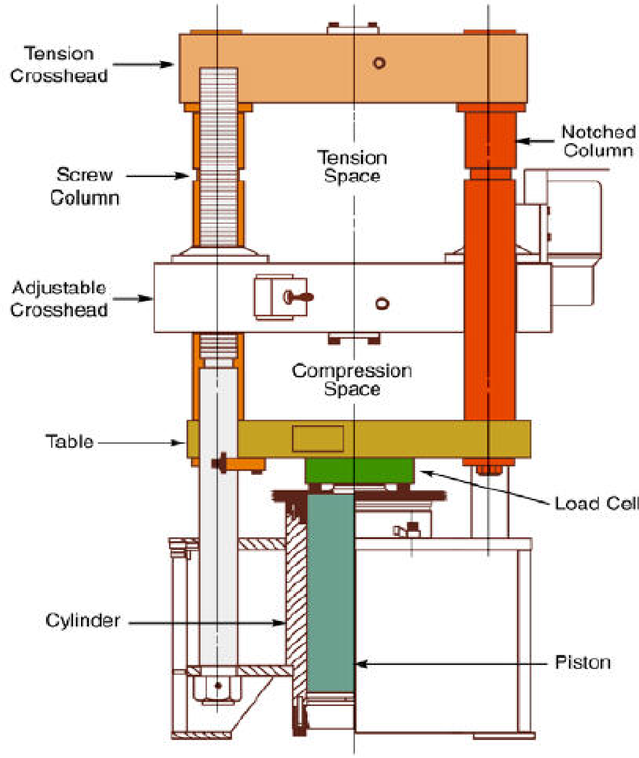

Figure 2 - Anatomy of a hydraulic universal testing machine.

There are two classes of testing machines, electromechanical and hydraulic, the principal difference is how the load is applied (for purposes of this paper only static or quasi-static machines are considered.). The electromechanical machine (Figure 3) employs a variable speed electric motor, gear reduction system and one, two or four screws to move the crosshead up or down. This motion loads the specimen in tension or compression. A range of crosshead speeds can be achieved 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. A hydraulic testing machine (Figure 2) employs either a single or dual acting piston to move the crosshead up or down. Most static hydraulic testing machines use 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 servovalve for precise control.

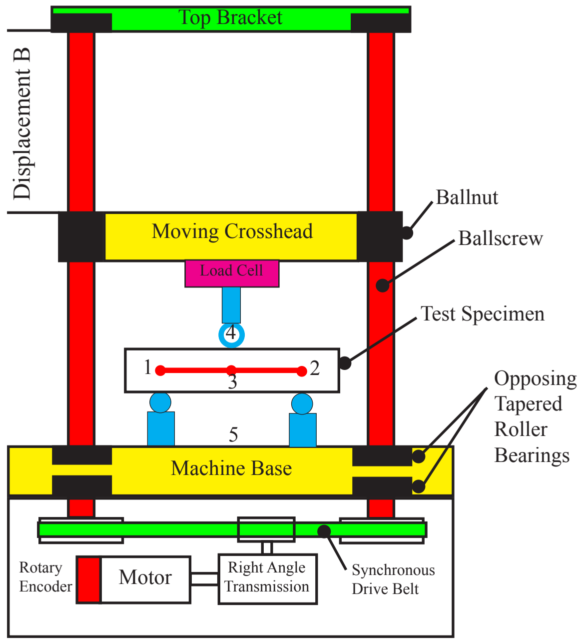

Figure 3 - Anatomy of an electromechanical testing machine.

In general the electromechanical machine is capable of a wider range of test speeds and longer crosshead displacements, whereas the hydraulic machine is more cost effective solution for generating higher forces.

Table 1 - Characteristics of Electromechanical and Hydraulic Testing Machines.

Machine Type	Test Speeds (in/min)	Max Crosshead Displacement (in)	Load Capacity (lb)
Electromechanical	0.0001 - 40	40	100 - 60,000
Hydraulic	0.005 - 3	6-12	60,000 - 1 million

A good test engineer must have an excellent understanding of the sources of errors that may be introduced during a test. Before commencing testing, the test engineer should review the choice of sensors and measurement instruments keeping in mind the suitability and accuracy of each. In order to make accurate measurements, in other words, one should know how to measure the errors in order to keep them from creeping into the results. Sensors are at the heart of all mechanical testing measurements. The test frame, power transmission, grips and fixtures also affect the accuracy and repeatability of it's sensors. Sensors that are mounted in the wrong position, are heated up, or are deformed by mounting bolts all introduce measurement errors.

Accuracy, Repeatability and Resolution

There are three basic definitions to remember with respect to how well a testing machine can measure stress and strain. They are accuracy, repeatability (precision) and resolution. In order to explain the meaning of each, let us consider the positioning of the crosshead on an electromechanical testing machine.

Accuracy is the ability to tell the true position of the crosshead. Accuracy is the maximum error between any two crosshead positions.

Repeatability (precision) is the ability of the crosshead to return to the same position over and over again. Repeatability is the error between a number of successive attempts to move the crosshead to the same position.

Resolution is the larger of the smallest programmable steps in crosshead position or the smallest mechanical step the crosshead can make.

Although these definitions seem straightforward, how measurements are best made to determine them is often a hotly debated topic. The biggest concern is what is the certainty of the measurements themselves used to characterize the machine.

Factors that Affect Accuracy, Repeatability and Resolution

Hysteresis is the maximum difference in sensor output between measurements made from 0-100% full scale output (FSO) and from 100-0% FSO. Although hysteresis is easily measured, its mechanism is not fully understood.

Linearity is the variation in the constant of proportionality between the sensor's output signal and the measured physical quantity. It is often expressed in terms of a percentage of full scale output. No sensor is truly linear so one must fit a straight line to the sensor's output versus input graph. A least squares fit is the most common method of fitting a straight line to the sensor's output graph. The least squares line is the line drawn through the sensors response curve such that the sum of the squares of the deviations from the straight line is minimized. Before microprocessors, the accuracy of the system was largely dependent on the linearity of the sensor. However, it is now possible through multi-point calibrations to effectively map out the non-linearities.

Noise is the magnitude of any part of the sensor's output that is not directly related to the physical quantity being measured. Force and strain resolutions on most testing systems are user programmable. The programmed resolution should always be greater than or equal to the noise.

Sensor Location

The most important consideration in mounting a sensor is where to mount it in order to ensure that the desired quantity is accurately measured. One thing to consider is whether the sensor should be mounted on the input or output ends of a transmission. If the sensor is mounted on the input end of a transmission along with a motor, then the resolution of the system will be enhanced by a factor equal to the transmission ratio. However, backlash and compliance in the transmission, belts, ballscrews, test frame, grips and fixtures will also affect the output of the sensor. On the other hand, if the sensor is mounted on the output end of the transmission, it will more accurately measure the process but the resolution will be reduced.

A Sensor Location Example - Measuring the Modulus of Plastic in Flexure

ASTM D790 governs the determination of the flexural modulus of unreinforced and reinforced plastics. ASTM D790 requires a bar of rectangular cross section resting on two supports be loaded by means of a loading nose midway between the supports. Figure 3 depicts such a test setup. The supports and loading nose are shown in light blue. The loading nose contacts the rectangular specimen at point 4 and is directly connected to the load cell. The test procedure involves deflecting the specimen until rupture occurs in the outer surface of the test specimen or until a maximum strain is reached.

Tangent Modulus, Secant Modulus and Chord Modulus are three properties of interest. All three require accurate force and flexural strain measurements in order to obtain proper modulus readings. Flexural strain is directly related to the deflection of the test specimen at the point midway between the supports.

The test setup shown in Figure 3 has the load cell directly coupled to the loading nose. Assuming the load cell has been verified to meet ASTM E4 accuracy requirements, we will say that all force measurements accurately represent the force applied to the specimen. Representative modulus values will therefore result, if accurate flexural strain measurements are obtained.

Example 1 - Using the Rotary Encoder Mounted on the Motor to Measure Flexural Strain

Most modern day electromechanical testing machines measure linear crosshead position with a rotary encoder mounted to the motor (The rotary encoder is shown in red in Figure 3.). The motor shaft, right angle transmission, synchronous belt, tapered roller bearings, ballscrew, ballnut, moving crosshead, load cell and loading nose are between the rotary encoder and the test specimen. When a force is applied to the specimen, strain measurement errors are introduced by the following:

- Torsional compliance in the motor shaft due to the applied torque. Because no machine component is truly rigid, one can think of the motor shaft as a torsion spring with a certain amount of torsional stiffness.
- Torsional compliance and mechanical backlash between mating gears in the right angle transmission.
- Stretch in the synchronous drive belt.
- Compliance in the tapered roller bearings. Tapered roller bearings deform non-linearily, especially at loads which are a fraction of their rating. Preloading the bearings causes a proportionately smaller amount of deflection but may reduce the effective repeatability and resolution of the moving crosshead.
- Compliance and lead error in the ballscrews. A compressive load applied to the specimen will create a tensile load in the ballscrews which will cause them to stretch.
- Backlash in the ballnuts. When in the unloaded condition, gravity will cause the ball bearings in the ballnuts to be in contact with the upper bearing race. When the applied compressive load exceeds the weight of the moving crosshead, load cell and loading nose, the ball bearings will switch to contacting the lower bearing race.
- Compliance in the moving crosshead, load cell, loading nose, specimen supports and machine base. Again, no machine component is truly rigid, one can think of each component as a spring.

With this in mind, the important questions is: “How large is the total error compared to the strain I am trying to measure?”. There is no clear cut answer but if the overall stiffness of the machine is much greater than the stiffness of the specimen, one may be able to use this method for measuring flexural strain. A careful analysis of your test setup would be in order prior to measuring the flexural strain with the motor encoder.

Note: If one could replace the test specimen with a specimen that was infinitely rigid, the load vs. strain curve as measured by the rotary encoder would be non-linear. The non-linearities make it very difficult to map out the machine errors in software.

Example 2 - Using a Linear Displacment Transducer between the Moving Crosshead and Top Bracket to Measure Flexural Strain

A second approach to measuring flexural strain might be to install a linear displacement transducer between the top bracket (in green) and the moving crosshead. In

Figure 3 it is shown as Displacement B. For this arrangement, when a force is applied to the specimen, strain measurement errors are introduced by the following:

- Compliance in the tapered roller bearings.
- Compliance in the ballscrews.
- Backlash in the ballnuts.
- Compliance in the moving crosshead, load cell, loading nose, specimen supports and machine base.

Because the Displacement B Transducer is closer than the rotary encoder to the specimen, there are fewer sources of error. Like example 1, however, there is no clear cut answer as to whether the errors introduced by measuring the relative movement between the moving crosshead and top bracket are small enough to be inconsequential. Again, a careful analysis of the test setup and results are in order.

Suggested Methods of Measuring Flexural Strain

When the methods used to measure flexural strain as outlined in example 1 and 2 are not sufficient, a device that measures the relative displacement between the underside of the specimen midway between the supports (point 3 in Figure 3) and the machine base (point 5) is commonly used. One such device is a deflectometer which is shown in Figure 4. Errors introduced by compliance in the supports and machine base are usually much smaller than the flexural strain in the specimen.

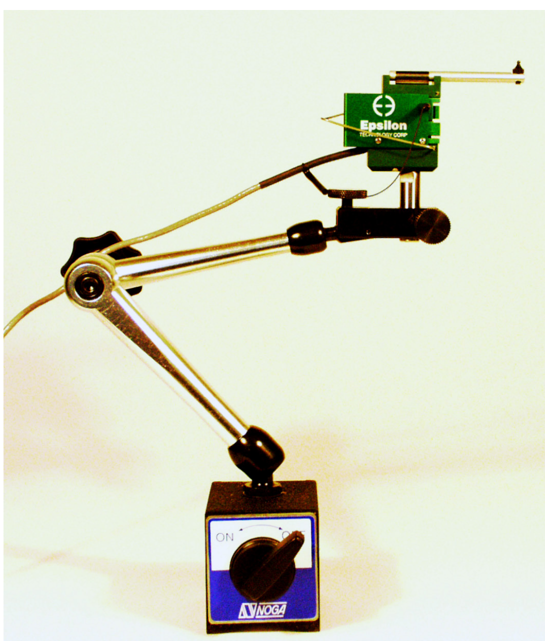

Figure 4 - A deflectometer mounted on a magnetic base.

The method with the smallest measurement error involves attaching two bars on opposite sides of the specimen at points 1 and 2 (See Figure 3) only. Points 1 and 2 are directly above the supports and reside on the neutral axis of the specimen. The bars only contact the specimen at points 1 and 2 and remain straight and unstressed when a load is applied to the specimen. A linear transducer is then affixed to the bar midway between the supports and measures the deflection of the specimen at point 4.

Conclusion

All experimental measurements include errors. Before commencing testing, a good test engineer will always ask the question: "Are my measurement errors small enough to not matter?" A thorough understanding of the sources and magnitudes of the errors is paramount to making accurate measurements.