Interpretation of Stress-Strain Curves and Mechanical Properties of Materials

Tinius Olsen has prepared this general introduction to the interpretation of stress-strain curves for the benefit of those who are unfamiliar with them as well as a quick review of the basics.

Taking a First Look

Let's examine the stress-strain diagram shown in Figure 1. Notice that this chart is an arithmetic one. That means that the length of any increment along either the **X-axis** (the horizontal one) or the **Y-axis** (the vertical one) will be the same as the length of any other increment along the same axis. This is important to us because it means we can use simple arithmetic to find the mathematical relationships we need between any two points on the chart.

The vertical or **Y-axis** of the chart (ordinate) represents the load or force applied to the specimen, with the full height of the **Y-axis** equaling the capacity of the load range employed.

The horizontal or **X-axis** (abscissa) represents the strain (elongation or compression of the specimen under load). Tinius Olsen strain measuring instruments automatically record strain in fundamental inches per inch (in./in.) units regardless of the gauge length. For example, using an LS-4%-2A (S-1000-2A) extensometer, a setting of "B" (500x or 2%) on the magnification or range selector will produce a magnification of 500x, as shown in Figure 1. This means that each inch of chart on the **X-axis** represents 0.2% (0.002 in./in.) of specimen elongation or extension.

Referring to Figure 1, notice that the load-elongation (stress-strain) curve starts at the lower left as a straight line. This is because the load increases in **direct proportion** to the extension of the specimen during the initial part of the test.

The highest point attained before the line begins to curve is called the **Proportional Limit,** which is the maximum point at which extension remains proportional to load (Hooke's Law). Past this point, the proportional relationship between load and extension begins to increase more rapidly than load, thereby producing a curve.

As explained on page 3, the initial straight-line portion of the diagram is used to calculate the **Modulus** of the material, and one or more points along the curve are plotted to determine the **Yield Strength** at designated of **Offset** or **Extension Under Load** (EUL).

In brief, a stress-strain diagram will help you determine: Modulus of Elasticity, Elastic Deformation, Yield Strength, Proportional Limit, Proof Stress, Uniform Elongation, Total Elongation, Yield Point Elongation and n-Value.

In addition, stress-strain diagrams can be used to calculate hysteresis (permanently absorbed or lost energy that occurs during any cycle of loading or unloading when a material is subjected to repeated loading, e.g. cycling tests in which load is remove before the specimen fails).

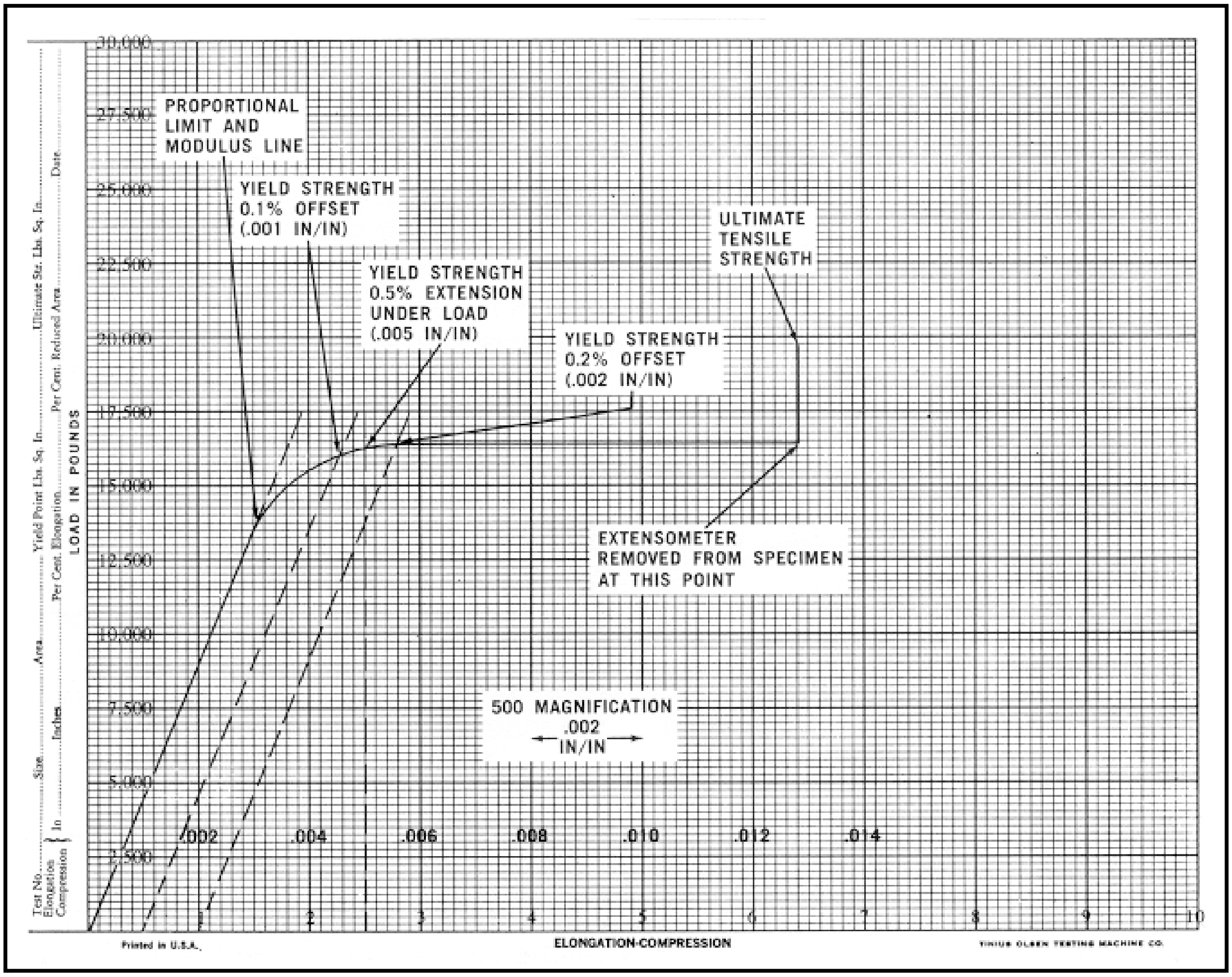

Figure 1 – Typical Load-Strain Recorder Chart

Steps in Interpreting a Stress-Strain Curve

1. Using a sharp pencil and a ruler, carefully draw a straight line through as much of the straight portion of the curve as possible, extending it from the bottom of the chart (Line A-B in Figure 2). This straight line is referred to as the **Modulus Line,** from which the **Modulus of Elasticity** will be calculated for the material tested.

   The intersection of the lower end of this drawn line with the **Y-axis** is the true origin of the curve, regardless of where the actual stress-strain curve begins. If proper care has been taken in the operation of the recorder and instrument, the drawn line should intersect at the same point of origin as the recorder-produced line.

2. Mark off the fundamental units of strain in inches per inch along the abscissa from the point of origin. If not known, the value of each inch of chart for the instrument measuring range used can be obtained from the appropriate instrumentation table furnished with the extensometer, or listed in the bulletin on Tinius Olsen strain instrumentation (currently Bulletin 96).

   If the "B" or 500x range of an LS-4%-2A (S-1000-2A) extensometer is used, each inch of chart will represent 0.2% (0.002 in./in.) of strain, and should be noted on the chart paper.

3. Since load on the **Y-axis** is expressed in pounds, a specimen of any cross-sectional area can be tested within the limits of the equipment. In order to make the necessary computations, the pertinent loads must be converted into pounds per square inch (psi or stress) by dividing the load by the cross-sectional area.

Determining Yield Strengths

There are two common methods of determining Yield Strength from a curve. Let's look briefly at both of them.

1. **The Offset Method:** The **offset** is the horizontal distance between the modulus line and any line running parallel to it. For example, the line C-D in Figure 2 is "offset" from the modulus line by 0.2% (0.002 in./in.).

   The value of the offset for a given material is usually expressed this way: **Yield Strength, 0.1% or 0.2% Offset.** What this means is that a certain percentage of the set equals a certain percentage of the fundamental extension units. For example, "0.2% Offset" means 0.2% of the fundamental extension units of inches per inch, or 0.002 in./in.

   Starting at the origin of the curve, measure off a distance equal to 0.002 in./in. along the **X-axis.** Now using that as the origin, draw a line (C-D) parallel to the modulus line. Notice that the line C-D intersects the stress-strain curve at a certain point (Y in Figure 2). The ordinate of this point (the amount of stress in psi) is the **Yield Strength at 0.2% Offset.**

   You can use the same method to determine the yield strength at a 0.1% offset by noting the intersection of the curve and a line drawn parallel to the modulus line with an offset of 0.001 in./in.

2. **The Extension Under Load Method:** This method involves drawing an ordinate line (that is, a completely vertical line) from the point on the **X-axis** where the elongation equals the specified extension, e.g. Yield Strength = 0.5% Extension.

   To make this determination, locate the point on the abscissa, which is equal to 0.5% (0.005 in./in.) of extension from the origin of the curve (E in Figure 2). Draw an ordinate line (E-F) from this point up through the curve. Convert the load value of this point into psi. The stress value is the **Yield Strength at 0.5% (0.005 in./in.) Extension Under Load.**

   In some cases, the yield strength may be given in other than strain fundamental units, e.g. Yield Strength = 0.1 in. / 2 in. Extension. In such cases, the limiting extension must first be converted into fundamental strain units (in./in.) A limiting extension of 0.01 in with a 2 in gauge length is equal to 0.005 in./in. extension.

Young's Modulus of Elasticity

The modulus of elasticity (Young's Modulus) is the ratio of stress in pounds per square inch (psi) to strain in inches per inch (in./in.) as computed from the modulus line (A-B).

$$\text{Modulus (psi)} = \frac{\triangle \text{ Stress (psi)}}{\triangle \text{ Strain (in./in.)}}$$

To find the modulus, take any two points (K & L) on the modulus line (A-B), and divide the differential between their stress values in psi from the strain differential in in./in. The result of this division is the modulus of the material tested. For Example:

	Load lbs.	**Strain in./in.**
Point K	17,400	0.003
Point L	5,800	0.001
Difference (△)	11,600	0.002

This load (11,600 lbs.) must be converted into psi by dividing the load in pounds by the cross-sectional area of the specimen. For example, a standard .505 in. dia. test bar has an area of 0.200 sq. in. Therefore, a load of 11,600 lbs. would be equal 58,000 psi (11,600 divided by 0.200).

Computing the Modulus of Elasticity from the above example:

$$\text{Modulus} = \frac{58{,}000 \text{ psi}}{0.002 \text{ in./in.}} = 29{,}000{,}000 \text{ psi (or 29.0 mpsi)}$$

To obtain better readability and greater convenience, it is recommended that you use points near the end of the modulus line that are the intersection of easily interpreted load and extension lines.

Further, the final modulus of elasticity of a material should never be based on the stress-strain curve from a single test. It should be the average of values calculated for several tests with comparable specimens.

Proportional Limit and Proof Strength

As previously discussed, the proportional limit is the greatest stress that a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's Law). This should not be confused with the elastic limit, which is the maximum stress that can be applied without any permanent strain remaining when the stress is released.

Both of these values are extremely difficult to accurately determine because of the problem of finding the exact point where the curve ceases to be linear. For this reason, it's generally recommended that you use a yield strength measurement instead with a small offset (0.01%) for tests on critical materials.

To do this, follow the offset method previously described, but use a small arbitrary number for the offset. The resulting yield strength is called the **Proof Strength** or **Proof Stress** of a specimen. Using this method gives you a straight line that intersects the curve at a load point (Point W in Figure 2), which unlike the proportional or elastic limit can be easily located.

For more information, please refer to ASTM Standards **E 6, E 8** and **D 638** published by the ASTM International & Materials, and the American Society for Metals publication "Metals Handbook, Volume 8, Mechanical Testing," as well as the Tinius Olsen Bulletins on Electronic Recorders, Strain Instruments & Software.

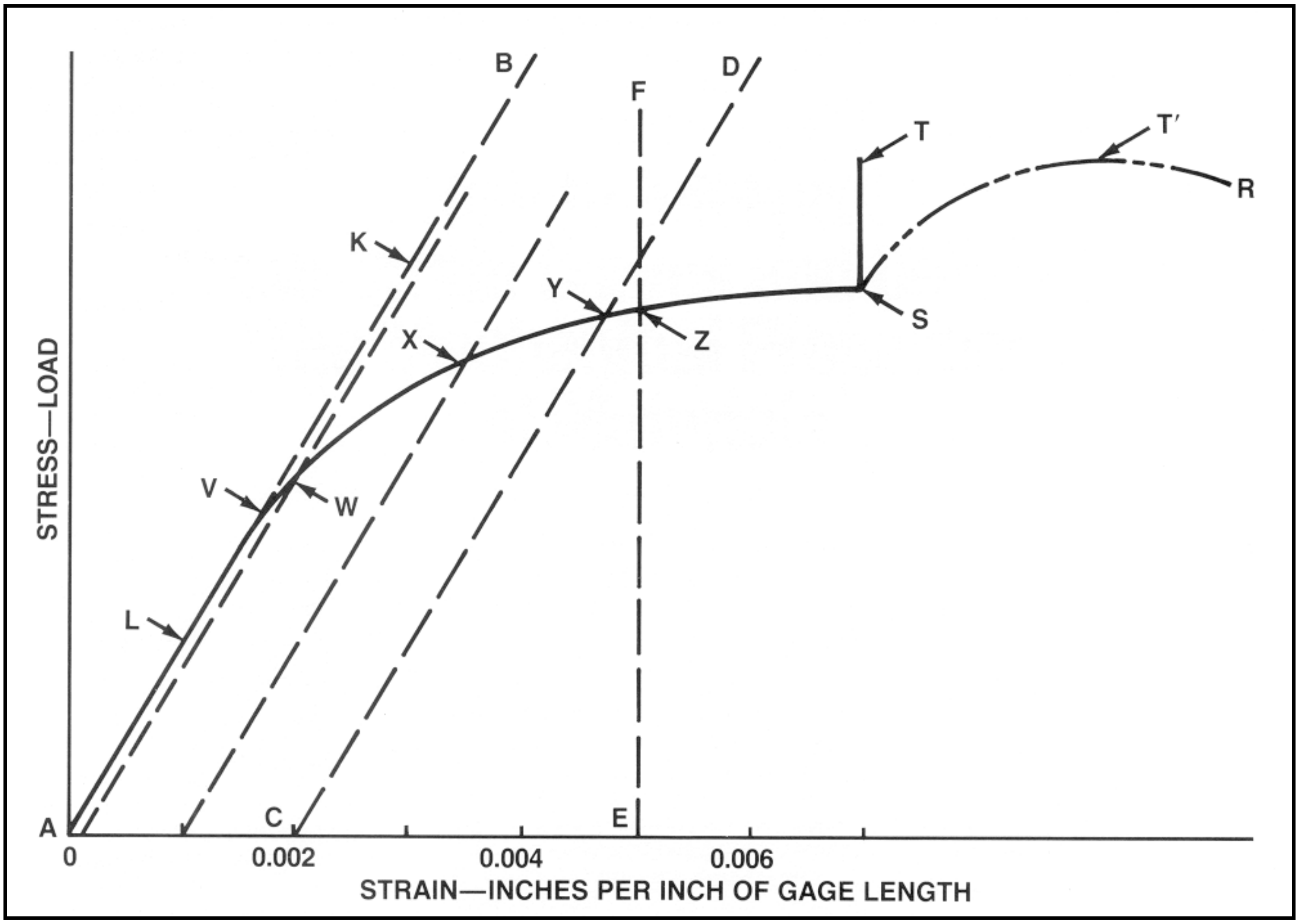

Figure 2 – Typical Tension Stress-Strain Diagram

Calculation of Tensile Properties of Materials:

Line A-B is Modulus Line; Young's Modulus of Elasticity = slope of initial straight portion of curve expressed as ratio of stress (psi) divided by strain (in./in.).

Line C-D is the 0.2% (0.002 in./in.) Offset Line.

Line E-F is the 0.5% (0.005 in./in.) Extension Line.

Curve A-R is a complete Stress-Strain Curve to specimen failure.

Segment S-R can be obtained with an instrument with the appropriate measuring capacity.

Point V = Proportional Limit.

Point W = Proof Stress, 0.01% Offset.

Point X = Yield Strength, 0.1% Offset.

Point Y = Yield Strength, 0.2% Offset.

Point Z = Yield Strength, 0.5% Extension Under Load (conventional Yield Point).

At Point S, the extensometer was removed.

Point T or T' = Ultimate Tensile Strength.

Note: A complete Stress-Strain Curve (similar to Curve A-R) may be obtained using special Olsen Instrumentation.

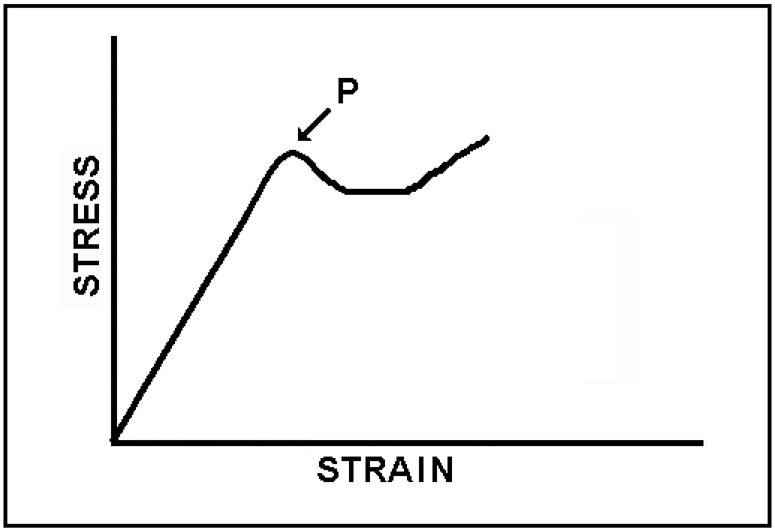

Figure 3 – Stress-Strain Curve with Yield Point

Point P = Yield Point for Material which produces a “sharp-kneed” Stress-Strain Curve.

Note: When the Yield Point is specified for a material, which does not exhibit a “sharp-kneed” curve, the conventional yield point (Point Z in Figure 2) is usually substituted.

IMPORTANT: When using the terms Yield, Yield Strength or Yield Point, one should always make certain that the specific type of yield required is clearly defined and specified as to limiting extension, offset value, or drop-of-the-pointer, etc. in order to avoid confusion and erroneous values.