MATERION

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TECHNICALTIDBITS

MATERION PERFORMANCE ALLOYS

A BETTER RATE: FLOW STRESS, STRAIN RATE & STRAIN RATE SENSITIVITY

Go with the Flow! – How changes in speed affect the way that materials and environmental forces interact.

- **Strain Hardening**
- **Non-Uniform Elongation**
- **Strain Hardening Coefficient (K)**
- **Strain Hardening Exponent (n)**
- **Flow Stress**
- **Strain Rate Sensitivity**
- **Strain Rate Sensitivity Exponent / Strain Rate Hardening Exponent (m)**
- **Slow Strain Rate Tensile Testing**

The next issue of Technical Tidbits will discuss electrical and thermal conductivity.

Recall the results of a tensile test are plotted as stress-strain curves, as shown in Figure 1. The engineering stress-strain curve rises linearly to the point of plastic deformation then increases more slowly as the material **strain hardens** until it reaches the ultimate tensile strength. Then it starts to fall off as the sample begins to neck down in thickness. (This elongation after necking is called **non-uniform elongation**.) The true stress-strain curve rises continuously to the point of fracture.

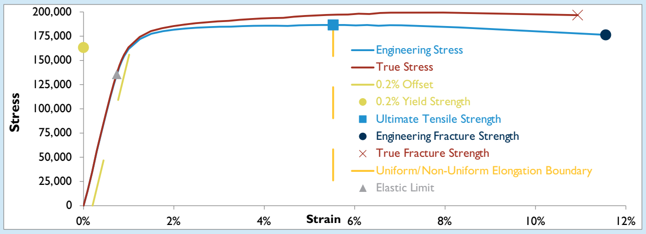


Figure 1. Engineering and True Stress-Strain Curves. Once strain hardening begins, the true stress-strain curve is always higher than the engineering stress-strain curve, since the instantaneous cross section after yielding is always smaller than the original cross section.

Furthermore, if you plot the true-stress-strain curve on log-log coordinates, you can generate a numerical expression for the strain hardening, as shown in Figure 2. The coefficients are the **strain hardening coefficient (K)** and the **strain hardening exponent (m)**. This exponent is a measure of how the stress changes with the instantaneous strain.

During plastic deformation, the stress level that is required to keep the deformation continuing is called the **flow stress**. This property is typically measured in a compression test, unlike most other properties associated with strain hardening, which are measured in tension. The sample usually is cylindrical with an aspect ratio of 3:2, as shown in Figure 3. Multiple flow stress tests are typically run on a material to quantify deformability of the material, usually at different strain rates and at different temperatures.

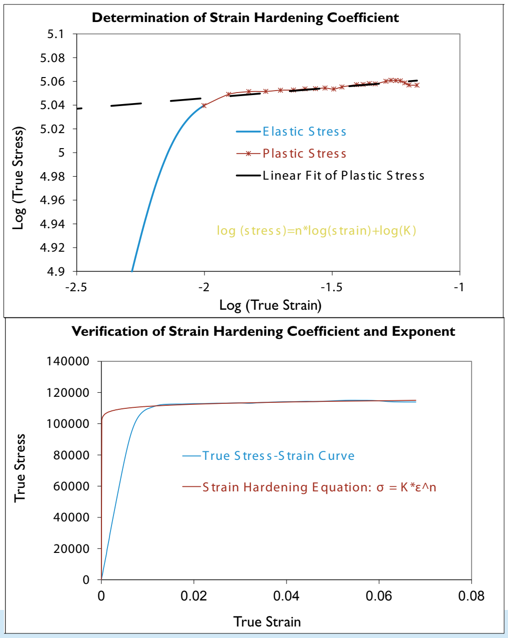


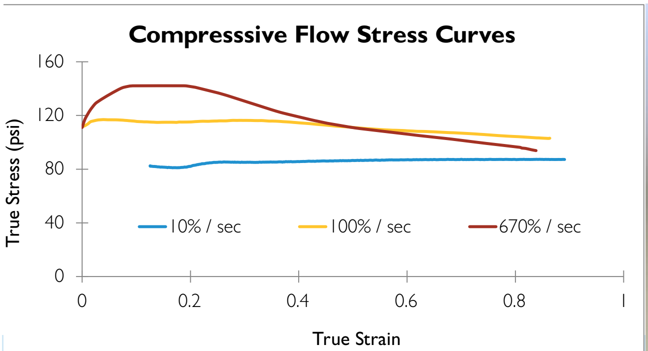
Figure 2. Strain Hardening Behavior of a High Strength Copper Alloy. Note that the linear fit of the plastic strain region on the log-log scale is very good, so that it is easy to calculate the strain hardening coefficient and exponent. However, the fit in the elastic region and in the knee of the curve is not so good. This is why the full true stress-strain curve or even a bilinear approximation of it is preferred for Finite Element Analysis.

A BETTER RATE: FLOW STRESS, STRAIN RATE & STRAIN RATE SENSITIVITY (CONTINUED)

In this case, the results of the flow stress test illustrate that the peak stress is higher as the strain increases. If the material shows different behaviors at different strain rates, it is said to have strain rate sensitivity. Like the strain rate exponent (n) governs the slope of the stress-strain curve at a given strain, the strain rate sensitivity exponent (m), also known as the strain rate hardening exponent, governs the slope of the stress strain-curve at a given strain rate. The astute reader will note that this means that the n exponent is a function of strain rate, and is therefore not a constant, unless m=0.

$$\textit{Strain Hardening Exponent (n)} = \frac{\partial \sigma}{\partial \varepsilon} = \frac{\log(\sigma_2/\sigma_1)}{\log(\varepsilon_2/\varepsilon_1)}$$

$$\textit{Strain Rate Sensitivity Exponent (m)} = \frac{\partial \sigma}{\partial \varepsilon} = \frac{\log(\sigma_2/\sigma_1)}{\log(\varepsilon_2/\varepsilon_1)}$$



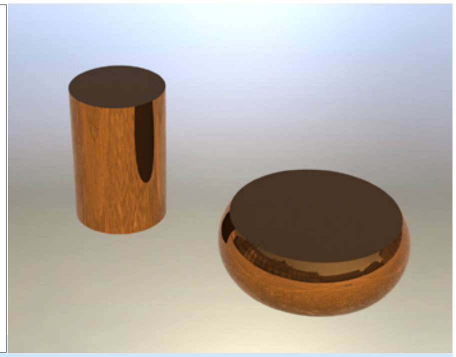


Figure 3. Compressive flow stress curve of a copper alloy (left) and representative samples, before and after testing (right).
Note that as the strain rate increases, it takes a higher amount of flow stress to continue deforming the material. This means that the material effectively has a higher strength when the deformation is faster.

The strain rate sensitivity exponent governs how a material deforms. If the exponent is positive, then, tensile properties such as yield strength, tensile strength, percent elongation, and reduction of area increase as strain rate increases. The material can better spread the deformation associated with necking, leading to greater non-uniform elongation and improved formability. Since all these effects result in more area under the stress strain curve, toughness improves as well. A negative exponent will result in forming difficulties, as the material will be unable to spread the non-uniform deformation, and failure will begin immediately at the point of necking.

As an aside, in **slow strain rate testing (SSRT)**, a tensile sample is pulled to failure at a very low strain rate in an environment known to promote stress corrosion cracking or hydrogen embrittlement in the particular material tested. The slow strain rate is not chosen for its effect on the mechanical properties of the material, but rather for its tendency to encourage stress corrosion cracking of the material in the test environment. Nevertheless, the measured ductility of the specimens at failure is usually directly proportional to the strain rate.

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Materion Performance Alloys
6070 Parkland Blvd.
Mayfield Heights, OH 44124

MATERION

Sales
+1.216.383.6800
800.321.2076
BrushAlloys@Materion.com

Technical Service
+1.216.692.3108
800.375.4205
BrushAlloys-Info@Materion.com

Written by Mike Gedeon of Materion Performance Alloys Marketing Department. Mr. Gedeon's primary focus is on electronic strip for the automotive, telecom, and computer markets with emphasis on application development.

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