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Technical Tidbits

The Hard Work of Work Hardening! This issue provides an in-depth discussion of strain hardening in metals.

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Strain Hardening

(This issue of Technical Tidbits continues the materials science refresher series on basic concepts of material properties.) Previous editions of Technical Tidbits have discussed **strain hardening** or **work hardening**, as a means of strengthening a metal prior to its delivery to the customer. The temper of an alloy is partially determined by the amount of strain hardening it undergoes at the production mill. However, strain hardening behavior is not limited to the mill, but occurs any time that the metal is permanently deformed. It is also a mechanical property that not only determines how a material strengthens, but how well it forms in a stamping die. This property also is derived from a material's true stress-strain curve.

The chart on the left side of Figure 1 shows the engineering and true stress-strain curve for Alloy C17410 copper beryllium strip that has appeared in previous editions of Technical Tidbits. However, there is now a third line added in green. This is an approximation of the plastic flow, or strain hardening, behavior of the material when the stress exceeds the yield strength. Its derivation is described below.

When one plots the base 10 logarithm of **true stress** against the base 10 logarithm of **true strain**, a interesting thing happens. The majority of the stress-strain curve falls onto two straight lines, as shown in the chart on the right side of Figure 1. The first line, shown in blue, represents the elastic portion of the stress-strain curve, where Hooke's law holds and the elastic modulus is constant (i.e., σ=E ε). The second line represents the plastic region of the curve where strain hardening occurs. Here, the stress-strain relationship can be summed up by a power law (i.e. σ=K ε^n). On the logarithmic scales, this exponential function is mapped onto a straight line ($\log \sigma = \log K + n \log \varepsilon$), whose slope is equal to the **strain hardening exponent** (n), and whose intercept with a true strain value of 1 is the **strength coefficient** (K). Often, the strain hardening exponent is referred to by its symbol, and is simply called the **n value**. In the case shown in Figure 1, linear regression of the curve in Figure 1 finds that n = 0.0713, Log_{10} K = 5.1577, and therefore K = 143780.5. The equation describing the plastic portion of the curve is thus $\sigma = 143780.5\varepsilon^{0.0713}$ psi. The green line in the plot on the left side of figure 1 shows that the power function is a good approximation of the plastic portion of the curve.

The strain hardening exponent (n) determines how the metal behaves when it is being formed. Materials that have higher n values have better formability than those with low n values. As metals work harden, their remaining capacity for work hardening decreases. This means that high strength tempers of a given material typically would have lower n values than lower strength tempers of the same alloy. (This is clearly illustrated by the chart on the right side of Figure 2.) Furthermore, since the yield strength is also higher, the K value also typically would increase for higher strength tempers. However, since these coefficients are derived from curve fitting, these trends will not necessarily hold true in reality.

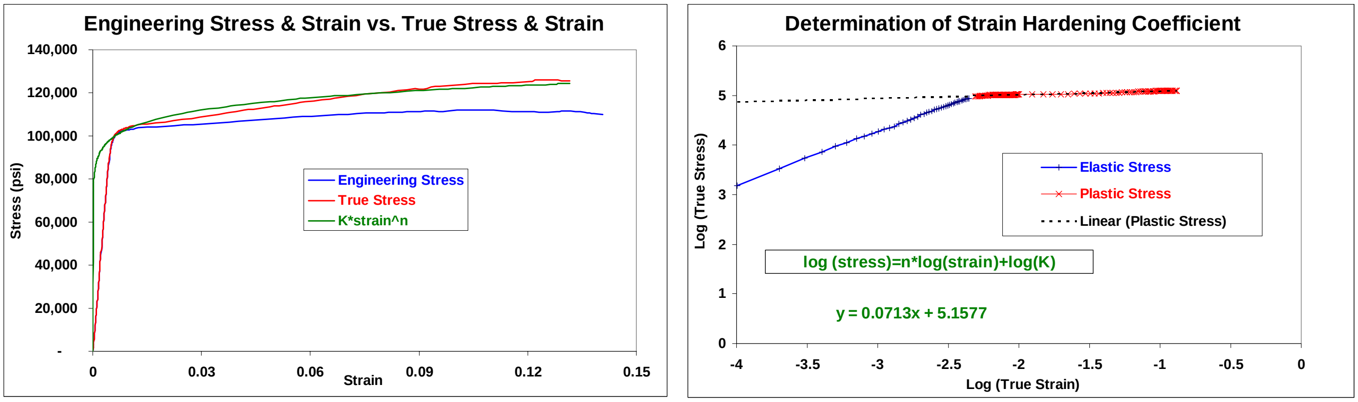

Figure 1. True Stress-Strain Curve on Linear Scale (Left), and True Stress-Strain Curve on Logarthmic Scale (Right)

Recall that cold-rolled tempers of a material are defined by the amount of strain hardening, or cold work, to which they are subjected after the final anneal. The chart on the left side of Figure 2 shows the true stress-strain curves for 4 cold-rolled tempers of N03360 nickel beryllium alloy strip plotted on the same set of axes. The elastic moduli of all 4 samples are equal, but the strain hardening regions are very different. As the temper increases, the yield strength increases as is evidenced by the progressively higher curves. The amount of elongation decreases with the temper, as is evidenced by the progressively shorter curves. However, remember that by ASTM temper definitions 1/4 H temper material is simply annealed strip that has been given 10.9% cold work, or 0.116 true strain. Furthermore, 1/2 H temper has been given 20.7% cold work and 0.232 true strain, and H temper has been cold worked 29.4% for 0.347 true strain. If the true stress-strain curves are replotted with the initial strain taken into consideration, the reasons for the trends in strength and elongation become obvious. This is graphically shown in the chart on the right of Figure 2. The plastic portions of the higher strength temper nearly form a continuous curve along the curve for the annealed temper. The samples shown below are from separate heats, each processed to different ready-to-finish gauges at the final anneal and different final thicknesses, which accounts for the variation. If they were identically processed from the same material and just given the different amounts of cold work at the final step, then the curves would have been expected to line up exactly (barring minor differences due to differing thicknesses).

The key points to take away from all this are that a material's capacity to be permanently deformed depends on the strain hardening exponent. Higher strength tempers of a given alloy will have less formability than lower strength tempers of the same alloy, because some of their capacity for strain hardening has already been used up in the cold rolling process. This is why formability of strip material decreases with increasing temper. Also, this is why precipiation hardenable alloys like copper beryllium or nickel beryllium tend to have better strength to formability ratios than alloys that are strengthened entirely by cold work, since alloys that are heat treated do not require as much cold work to reach a given strength level.

A material's formability is dictated by how it strain hardens when permanently deformed. Alloys with high strain hardening exponents will tend to form better than materials with low values.

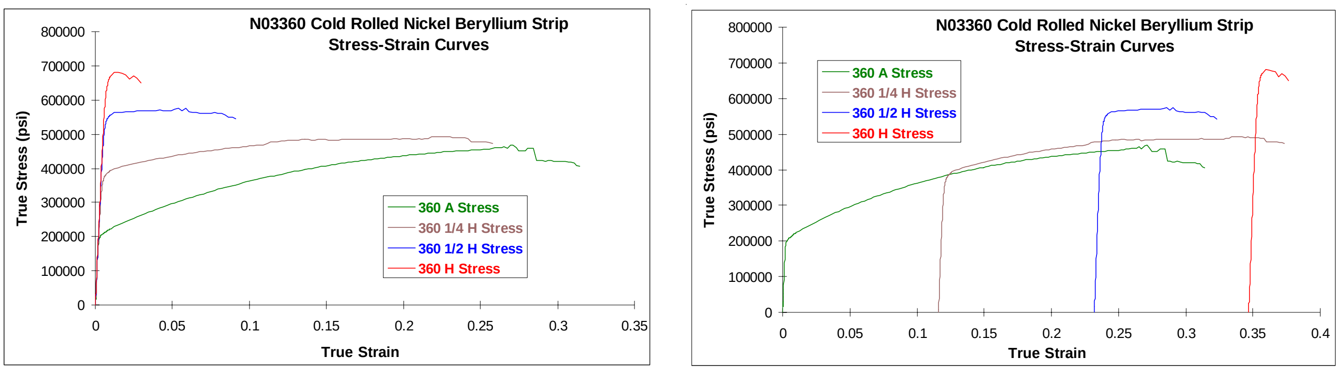

Figure 2. True Stress-Strain Curves for Alloy 360 Nickel Beryllium Strip Plotted with All Curves Starting at the Origin (Left), and with All Curves Adjusted for the Strain Imparted by the Cold Working Process (Right).

Coming Next Issue: The next edition of Technical Tidbits continues the discussion on strain hardening.

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References:

Health and Safety

Handling copper beryllium in solid form poses no special health risk. Like many industrial materials, beryllium-containing materials may pose a health risk if recommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals. The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) before working with this material. For additional information on safe handling practices or technical data on copper beryllium, contact Brush Wellman Inc.