Issue No. 19 – July 2010

Updated from Original January 2001 Publication

The Best Way to Pump Up your Copper – A summary and comparison of material strengthening mechanisms discussed in the last 4 issues of Technical Tidbits.

- **Grain Size Refinement**
- **Strain Hardening**
- **Solid Solution Hardening**
- **Quench Hardened**
- **Dispersion Strengthened**
- **Spinodally Decomposed**
- **Precipitation Age Hardened**

The next issue of Technical Tidbits will discuss the use of cantilever beam theory in spring design.

Strengthening Mechanisms Summary

Over the past several months, Technical Tidbits has explored various strengthening mechanisms used in copper alloys. A detailed description of each mechanism was discussed in each of the past 4 issues. However, to gain an appreciation for the effectiveness of each strengthening method, they must be compared to one another.

The first method discussed was **grain size refinement**. An alloy will be stronger and more formable with a smaller grain size. However, the effect on strength is relatively minor. Figure 1 shows the ductility (percent elongation) vs. yield strength for C50500 phosphor bronze. The cold work increases from the annealed temper in the upper left corner to the extra hard temper in the lower right corner of the graph. Note that the 0.015 mm grain size is slightly stronger and more ductile than the 0.035 mm grain size in the softer tempers, although the effect diminishes at harder tempers. Note also that the strengthening effect of the grain size is negligible compared to the strengthening effect of increased cold work.

Figure 2 shows the ductility vs. strength for many copper alloys and tempers. They are marked on the chart according to their primary strengthening mechanism. The effect of grain size refinement is insignificant compared to other methods, and is not included. **Strain hardening** (cold work) is indirectly included; annealed tempers are at the top left corner of the graph, and harder tempers are at the lower right. The most ideal situation would be for an alloy to have very high strength and ductility, corresponding to the upper right portion of the graph. The most effective strengthening mechanisms are those closest to this corner. Conversely, the least ideal combination of properties would appear at the lower left of the graph.

All copper alloys containing greater than 99.5% copper (by weight) are shown on the chart as unalloyed copper. These have high conductivity, although the strength-ductility relationship is farthest from optimal. They are shown on the graph as solid diamonds. A more effective method is **solid solution hardening** (hollow triangles). All copper alloys are hardened this way, however, only those not hardened by additional means are shown here. The **quench hardened** alloys (asterisks) fall into the middle of this range. The **dispersion strengthened** alloys (hollow circles) are next, followed by th**e spinodally decomposed** alloys (squares), and the mill hardened precipitation hardened alloys (plus signs). The best combination of strength and ductility is found in alloys that underwent **precipitation age hardening** (solid triangles). These alloys and the spinodal alloys are shown with ductility before heat treatment (optimal forming) and strength after heat treatment (optimal service properties). This is why the age hardenable alloys have such good performance.

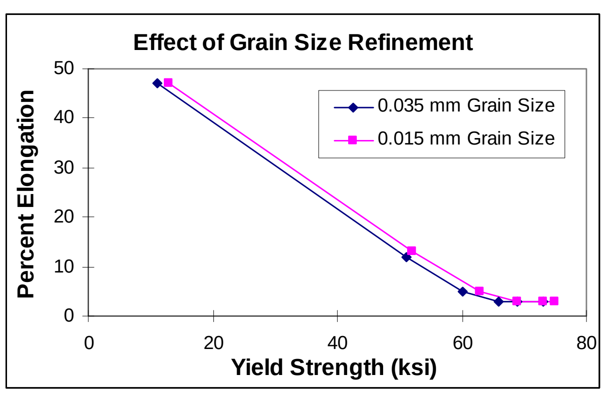
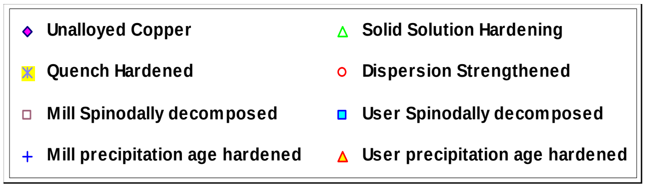


Figure 1. Relatively Small Effect of Grain Size Refinement on Yield Strength

Strengthening Mechanisms Summary (continued)



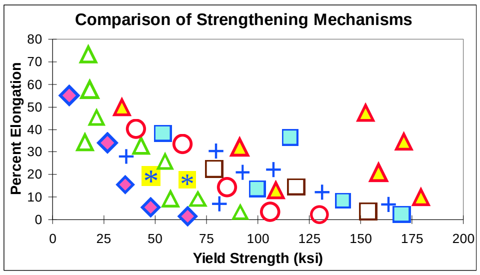


Figure 2. Ductility vs. Strength for Various Copper Alloys

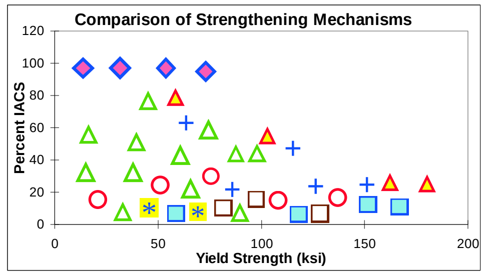


Figure 3. Conductivity vs. Strength for Various Copper Alloys

Figure 3 shows how conductivity varies with strength for different alloy systems. Optimal combination of properties is at the upper right corner of the graph, while the lower left shows properties farthest from ideal. Most of the solid solution hardened alloys show strength and conductivity relationships farthest from ideal. This is because additions of alloying elements necessary to boost strength dramatically decrease conductivity. Almost all the alloys with conductivity greater than 80% IACS contain more than 99.5% copper. Quench hardening or spinodal decomposition require a high content of alloying elements and therefore have very low conductivity. Dispersion strengthened alloys show a more ideal combination of properties, getting good strength with moderate conductivity. The precipitation hardened alloys show a very good combination of strength and conductivity, yet some mill hardened tempers fall into the range of the dispersion strengthened alloys.

Many combinations of strength, ductility, and conductivity are possible with copper alloys. Grain size refinement offers better formability but little effect otherwise. Strain hardening effectively offers strength to all copper alloys but ductility is lost. Solid solution hardening and quench hardening give copper a reasonable increase in strength but adversely affect conductivity. Dispersion strengthening gives a better combination of strength, ductility, and conductivity than solid solution hardening. Spinodal decomposition offers very good strength with good ductility, although the conductivity is low. Precipitation hardening gives exceptional strength and conductivity with decent ductility in the mill hardened tempers and very good ductility in the age hardenable tempers.

Written by Mike Gedeon of Brush Wellman's Alloy Customer Technical Service Department. Mr. Gedeon's primary focus is on electronic strip for the telecommunications and computer markets with emphasis on Finite Element Analysis (FEA) and material selection.

TECHNICAL TIDBITS

Brush Wellman Inc.
6070 Parkland Blvd.
Mayfield Heights, OH 44124
(216) 486-4200
(216) 383-4005 Fax
(800) 375-4205 Technical Service

Reference:
Davis et. al.
ASM Handbook V. 2
ASM International
1990

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