

**Demonstrating The Effects Of Processing On Structure And Properties Via The
Annealing And Strain Hardening Of Copper:
Part Two - Mechanical Properties**

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Abstract of module:

An experimental laboratory to demonstrate the structure-properties-processing relationship fundamental to materials science is presented. This part of the exercise has been found to aid in the students' comprehension of the influence of processing in the form of strain hardening and thermal treatment on the resulting mechanical properties of hardness, strength, ductility and toughness. Tensile, hardness, and deflection measurements are made and correlated with corresponding processing conditions in order to determine recrystallization and grain growth temperatures as well as to identify the affects of annealing and cold working.

Module objective:

The objective of this laboratory is to explain the effects of strain hardening and annealing on engineering materials and how the resulting mechanical properties may be significantly modified.

Student learning objectives:

This work provides part two of a two part laboratory experiment that aids the student in understanding the affects of annealing and cold work on the properties and microstructure of copper. There are several learning objectives in this part for the students. At the completion of the exercise, it is hoped that the students will be familiar with the use of a hardness tester, tensile testing machine and simple deflection rig and understand the procedures employed to determine the mechanical properties resulting from different annealing temperatures and cold rolling regimens. An ability to define engineering terms such as stress, strain, deflection, deformation, ductility, hardness and toughness is expected. The students should also be able to graph the data and evaluate the trends in the data to determine the effect of annealing temperature on strength, ductility and static toughness. The primary intent is to provide the student with an understanding of the effects of strain hardening, recrystallization and grain growth via various processing methods on material structure and properties. Additionally, they should realize that

processing methods can be performed iteratively, since cold worked structure and properties will revert back to their pre-worked state when annealing treatments are applied.

MatEd core competencies covered:

- 0.B Prepare tests and analyze data
- 1.C Demonstrate Laboratory Skills
- 4.A Demonstrate effective work with teams
- 7.G Define stress and strength
- 7.H Define strain and deformation
- 8.B Apply mechanical testing processes to solid materials
- 8.E Perform appropriate tests of metallic materials
- 16.A** Explain effects of processing on material properties
- 17.B Describe techniques used in metals processing

Key words: annealing, strain hardening, rolling, recovery, recrystallization

Type of module/mode of presentation: laboratory

Time required: 2.5-3 hours with 20 students

Pre-requisite knowledge: basic understanding of microstructure of metallic materials, mechanical properties, structure-property relationship in metals

Target grade level: college undergraduate

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List of equipment and supplies needed

- ½ inch (12.7mm) x 4 inch (10.16cm) C11000 copper strips or cartridge brass (C26000) for tensile testing – One per anneal if dividing condition among groups or one per anneal per group, prepared in part one or in advance
- Bench top rolling mill
- Rockwell H hardness tester
- Tensile tester
- Dial indicator
- Clamps to hold magnetic plate and dial indicator with magnetic base in place
- Weights (one pound, 8 oz, 4oz) and basket to hold weights

Curriculum overview and notes to instructor:

Metallic materials will strain harden to different degrees depending on their ability to plastically deform and work-harden. To obtain a material in a particular shape and size, materials are strain hardened in various ways via cold rolling, extruding, drawing, stamping and forging. Strain hardening at ambient temperature is called cold working. (1) It is important to realize that upon strain hardening, the material microstructure is changed by an increase in the dislocation density and changes in the grain shape. Strength is increased due to inhibition of dislocation motion via dislocation-dislocation interactions. Ductility is decreased and properties become anisotropic. As ductility decreases, toughness, the ability of a material to plastically deform and absorb energy prior to failure, also decreases despite increases in strength. High toughness results from a good combination of strength and ductility. A metal with high strength and high ductility will have greater toughness than one with low strength and high ductility or one with high strength and low ductility. A simple method to measure static or material toughness is by calculating the area under the stress strain curve produced during a tensile test. (2) Annealing at high temperatures can remove the effects of strain-hardening via microstructural changes that generally occur in the following sequence: recovery, recrystallization and grain growth. During recovery, the dislocations reorganize into low energy configurations via diffusion mechanisms and the mechanical properties are virtually unchanged. During recrystallization, new equiaxed grains are formed and the strength is reduced. Grain growth is often avoided due to unfavorable mechanical properties. Strain hardening at high temperature is called hot working and allows the strain hardening and recrystallization processes to occur simultaneously. (3)

Module procedure:

Technicians or instructors provide safety instruction regarding use of equipment. The exercise is done in small teams of two to three students. Each group may do all anneal conditions and average the results. The variance in the results can be used to promote a discussion on experimental error. To save time, each group may do just one condition and shares the results with the other groups.

Prior to the lab: Strips are divided into lots and heat treated at temperatures of 300°F (149°C), 500°F (260°C), 600°F (316°C), 700°F (371°C), 800°F (427°C), 900°F (482°C), and 1200°F (649°C). Not all temperatures need be evaluated but at a minimum 300°F (149°C), 600°F (316°C), 700°F (371°C), 900°F (482°C), and 1200°F (649°C) should be tested. Samples are air cooled for 20 minutes. Some samples that have been heat treated at 1200°F (649°C) are subsequently rolled using a bench top rolling mill until hardness reaches the level of the as-received condition. Minimal rolling is needed and does not significantly alter the size or shape of the sample. Samples from part one of the lab can be used for this exercise.

During the lab, students measure on the Rockwell H scale and record the hardness of the copper strips in each condition.

Tensile strength is measured using a screw driven tensile tester. Tests are conducted for each condition and area under the curve, i.e., static toughness, and ultimate tensile strength recorded as well.

Area under the tensile curve is calculated as a function of annealing temperature for each condition.

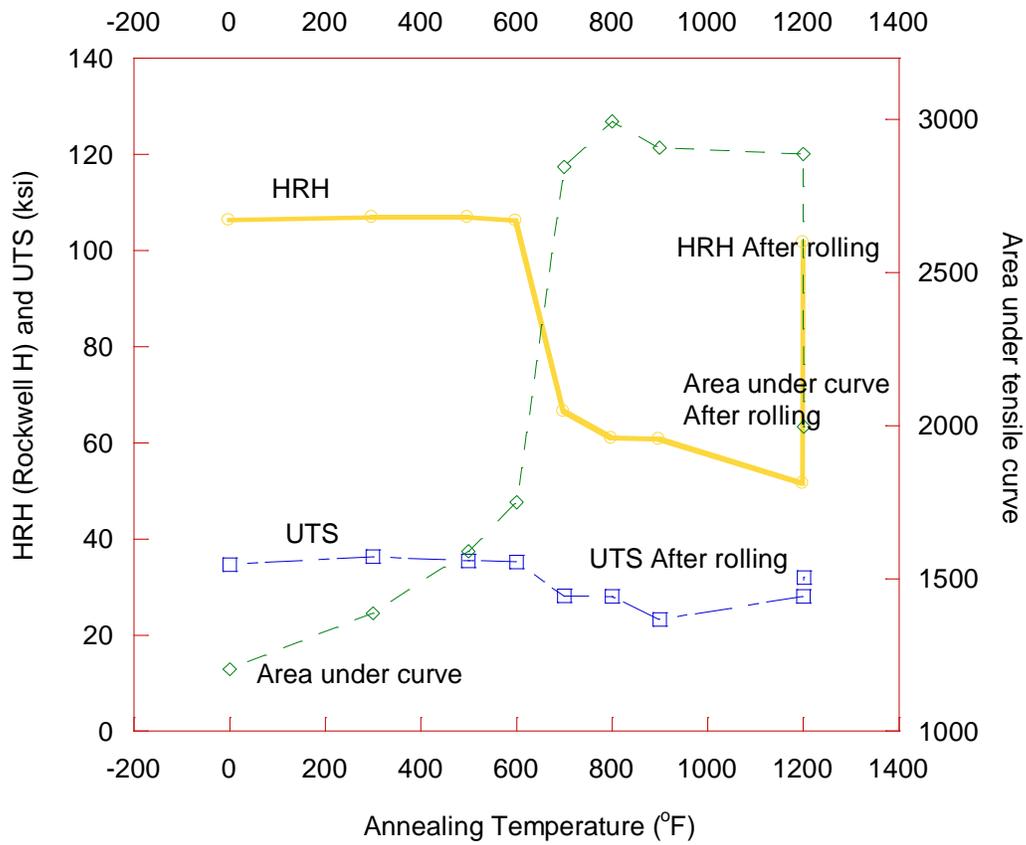


Students measure the deflection as a function of applied load for the as-received, rolled, and annealed specimens in the bend test equipment to provide almost immediate data feedback in the form of visual observations and easily plotted results that quickly and clearly demonstrate the effects of material processing on material properties. Each sample is clamped to the test bench and weight added to the basket hanging from the sample. Deflection is measured using a dial gauge with magnetic base that sits on a magnetic plate to hold it in place. Load versus deflection data for each condition are plotted on the same graph and compared.

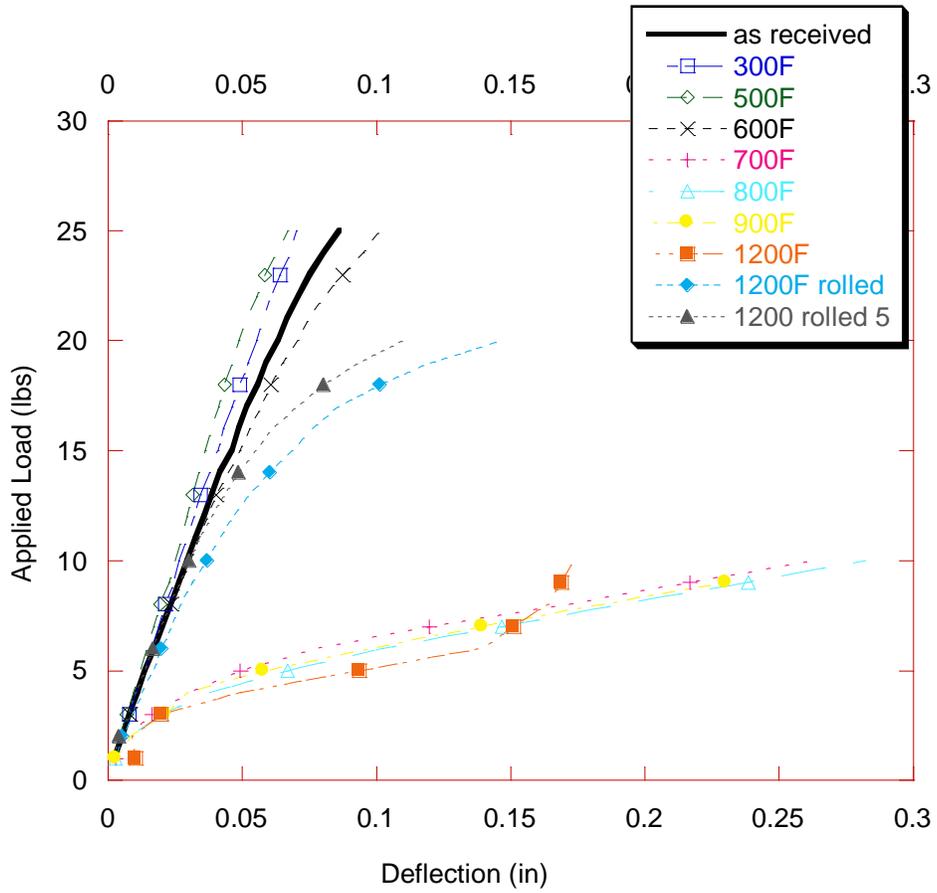
Supporting handouts and materials:

Table 1. Hardness and toughness for various conditions of cold rolled copper.

	As Rec.	Annealed 300°F (149°C)	Annealed 500°F (260°C)	Annealed 600°F (316°C)	Annealed 700 °F (371°C)	Annealed 800°F (427°C)	Annealed 900°F (482°C)	Annealed 1200°F (649°C)	Annealed 1200 °F (649°C)+ Rolled	Annealed 1200 °F (649°C)+ Rolled 5X
Average Hardness (Rockwell H)										
Static Toughness (in-lbs/kg-cm)										
TS (ksi/MPa)										
Microstructural Appearance										



Sample data exhibiting trends with annealing temperature. The last point in each series is for a cold rolled specimen, cold rolled multiple times to demonstrate how strength and hardness can be restored via cold rolling while static toughness (area under the curve) is reduced.



Sample data for load versus elongation experiments at various annealing temperatures and rolling conditions.

Summary of results for class discussion:

As-received plate, most likely in the H02 condition as inferred from measured properties (4), may have had some cold work performed on it to optimize properties. This is beneficial as some minimum value of cold work is required for recrystallization to occur. The expected recrystallization temperature is typically one third to one half of the absolute melting temperature, with the exact value depending on the amount of initial cold work and material impurities. (5) The corresponding expected range in recrystallization temperature for Cu is 355-763°F (180-406°C). For samples annealed above 600°F (316°C), the amount of deflection is notably larger for a given load level, indicating yielding at low values of load. Figures show a decrease in hardness and UTS, and an increase in static toughness (area under tensile curve) for samples annealed above 600°F (316°C). Therefore, the data indicates a recrystallization temperature between 600 and 700°F (316-371°C), which falls within the range of expected values. Annealed samples when rolled multiple times (five times in this example) demonstrated properties approaching those for the as-received samples (which were most likely in the cold worked state).

References:

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2. D.R. Askeland, P.P Phule, *The Science and Engineering of Materials*, 5th ed., Thomson, 2006, pp. 289-290.
3. 2008 ASM Handbook, H. Baker, et al, editors, Vol 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, ASM International, Materials Park, Ohio, 1992. pp. 265-266.
4. W.D. Callister, Jr. and D.G. Rethwisch, *Fundamentals of Materials Science and Engineering: An Integrated Approach*, John Wiley and Sons, Inc, 3rd edition, 2008. pp 263-265.

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- 2008 ASM Handbook, H. Baker, et al, editors, Vol 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, ASM International, Materials Park, Ohio, 1992. pp. 265-266.
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Evaluation packet

Student evaluation questions (discussion or quiz):

1. What is the effect of annealing on strength, ductility and static toughness? *After cold working, annealing allows the material to recover ductility but will also cause the material to lose strength and hardness. If heat treatments are controlled, strength and ductility can be maintained such that toughness is enhanced.*
2. What is the effect of annealing temperature on strength? At which temperature would you suspect that recrystallization has taken place? What fraction of the melting temperature does this temperature correspond to? *As temperature increases and the recrystallization temperature is surpassed, strength will decrease. According to the data, recrystallization occurs somewhere between 600°F (316°C) and 700°F (371°C), less than one half the absolute melting temperature.*
3. What is the effect of annealing temperature on static toughness? *As temperature increases and the recrystallization temperature is surpassed, ductility will return and so will static toughness until all strength is gone.*
4. If we wish to use this copper material for an electrical application, which condition(s) would you choose and why? *Cold working will slightly decrease the electrical conductivity of materials and so after drawing copper wire for electrical applications, the material should be annealed above the recrystallization temperature.*
5. How does the strength of the annealed + rolled condition compare to the as received condition. What would be the purpose of annealing a rolled material, only to roll it again? *After annealing, rolling returns the material to the cold worked state, similar to the as received plate condition. Annealing allows the material to regain ductility so that it can be worked or formed further into final shapes without embrittling.*
6. How can microstructural changes noted in part one be related to what was seen in terms of mechanical behavior as a result of rolling or annealing?
Some grain elongation in the as-received condition persists until the 600°F (316°C) annealing temperature. The specimen annealed at 700°F (371°C) shows an equiaxed grain structure, supporting that recrystallization has taken place. Annealed samples when rolled multiple times (five times in this example) demonstrated properties approaching those for the as-received samples (which were most likely in the cold worked state).

Instructor evaluation questions:

1. For what grade level and engineering program is this appropriate?
2. Was the level and rigor of the module what you expected? If not, how can it be improved?
3. Is the demonstration difficult to recreate? Did the demonstration work as presented? Did it enhance student learning and generate interest among the students?
4. Was the background material sufficient for the students? The instructors?
5. Please provide your input on how this module can be improved, including comments or suggestions concerning the approach, focus and effectiveness of this activity in your context.

Student evaluation questions:

1. Was the laboratory procedure defined clearly?
2. Were the objectives well defined? Was the relevance to your course of study explained?
3. Was the instructor able to explain the objectives and outcomes clearly?
4. Was the instructor able to answer student questions?