Lesson 06: Plastic deformation and strengthening

Exercise 06.1 Cupronickel

Sketch (qualitatively) the flow curves of the following materials in a common stress strain diagram.

a) Pure annealed copper
b) Cupronickel with 25 wt.% Ni
c) Cupronickel with 44 wt.% Ni (Konstantan)

Compare the three flow curves with respect to their Young's modulus, yield strength, tensile strength and ductility (can be found in presentations). Why do the curves look different?

Material	Young's modulus	Yield strength	Tensile strength	Ductility (fracture strain)
Pure kobber	115 GPa	70 MPa	220 MPa	56%
Cupronickel with 25 wt% nickel	145 GPa	135 MPa	350 MPa	37%
Cupronickel with 44 wt% nickel	165 GPa	160 MPa	410 MPa	32%

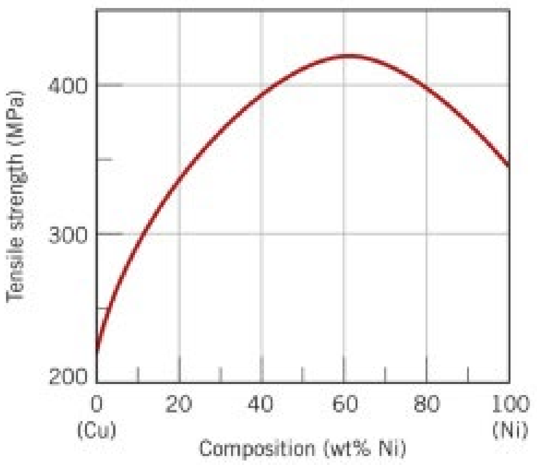
The data are collected from the presentations and one can sketch flow curves from it (see lecture slides). Young's modulus is different for the alloys as the bonding forces between the atoms of the two elements are different. The plastic behavior is changed due to solid solution strengthening.

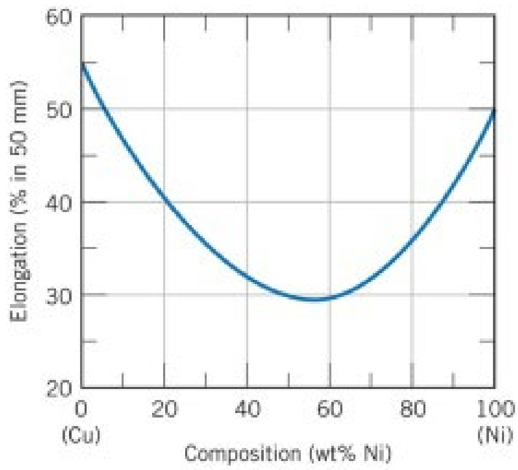
Exercise 06.2 Copper Nickel alloys with high Ni content

The dependence of yield strength and ductility of cupronickel is shown below for compositions with maximum nickel content of 50 wt.%. How do the curves continue to higher nickel contents and to pure nickel? Sketch the dependence of the electrical conductivity of the alloys in dependence on the nickel content.

The yield strength shows a maximum, the ductility a minimum for intermediate nickel content, as the yield strength of pure nickel is smaller than the yield strength of nickel with foreign copper atoms in the nickel lattice (copper is slightly larger than nickel) due to solid solution strengthening. For the same reason, the ductility of pure nickel is higher than that of a nickel alloy with a few wt% Cu.
The electrical conductivity of copper is higher than that of nickel. Impurity atoms increase the resistivity and hence lower the conductivity. The conductivity has a minimum for intermediate nickel content.

The following pictures show tensile strength (not yield strength) and elongation for the entire composition range. The graph for the yield strength resembles the one for tensile strength with different numerical values.



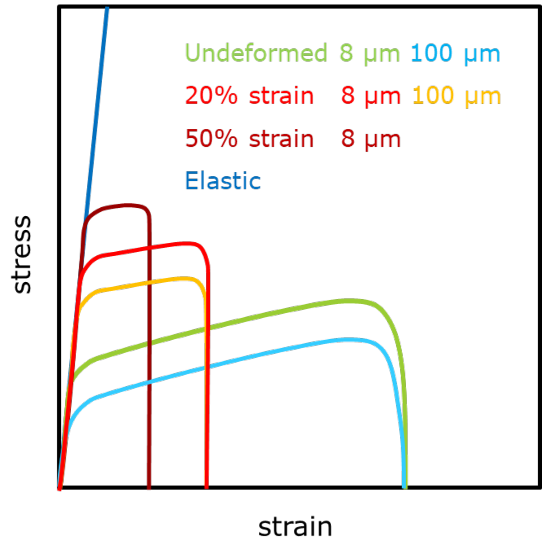


Exercise 06.3 Brass
Sketch the flow curve of (alpha) brass (copper with 30 wt.% zinc) after five different treatments in one and the same stress strain diagram:

a) Undeformed brass with grain size 8 µm
b) Brass with grain size 8 µm deformed to 20 % strain
c) Brass with grain size 8 µm deformed to 50 % strain
d) Undeformed brass with grain size 100 µm
e) Brass with grain size 100 µm deformed to 20 % strain

Compare the flow curves with respect to their Young's modulus, yield strength, tensile strength and ductility. Why do the curves look different?

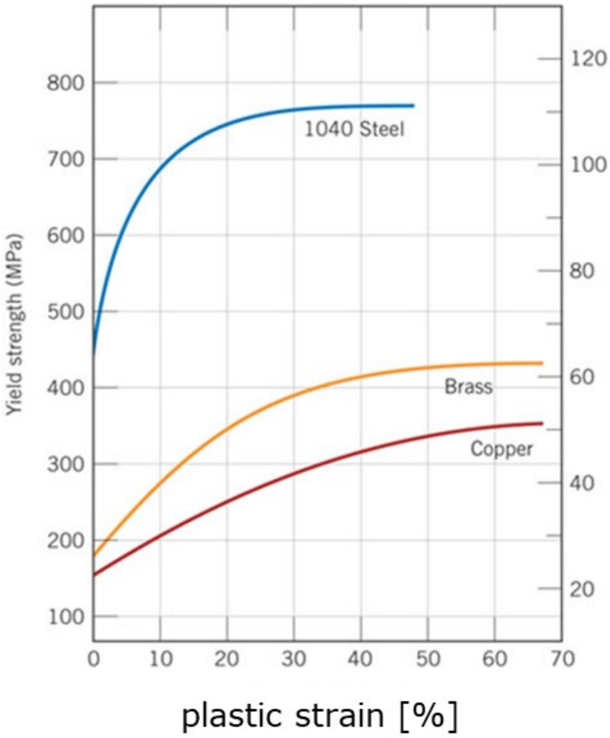
Qualitative flow curves



The curves look different due to strain hardening and grain refinement. The Young's modulus is always the same, yield and tensile strength increases by deformation. A larger grain size reduces yield and tensile strength. The ductility is lowered by deformation, but not much affected by grain refinement (in fact, a slight reduction occurs). The toughness (i.e. the area below the curve) is reduced by work-hardening but increased by grain refinement.

For a more quantitative analysis, yield strength, tensile strength and ductility night be taken from diagram 7.19. The Young's modulus of alpha-brass with 30 wt.% Zn is 97 MPa independent of any deformation or grain size (table 6.1). Diagram 7.15 shows brass with 8 µm grain size and a yield strength of 180 MPa and 60 MPa for a grain size of 100 µm. The table and the data in 7.19 must correspond to a small grain size!

Exercise 06.4 Pure copper
Pure copper with a relatively large grain size (500 µm) and a low dislocation density ($2 \cdot 10^{10}$ m^{-2}) is deformed at room temperature; its yield stress increases as shown in the figure. What is the dislocation density after 30 % and after 60 % plastic strain (M = 3, α = 0.5, $k_y = k_{HP}$ = 0.11 MPa m$^{1/2}$, G = 46 GPa, b = 0.255 nm)?



From the graph, several yield stresses are determined: 155 MPa in the undeformed state and 285 MPa and 345 MPa after 30 % and 60 % plastic strain, respectively. (Note, slightly different readouts will lead to slightly different values of the dislocation density.) The yield stress is given by

$$. \sigma = \sigma_0 + M\alpha G b \sqrt{\rho} + \frac{k_{HP}}{\sqrt{D}}$$

The parameter $\sigma_0 = 152$ MPa (for k_{HP} = 0.11 MPa $m^{1/2}$) is found from the undeformed condition, its grain size ($D = 500$ µm) and the initial dislocation density ($\rho = 2 \cdot 10^{10}$ m^{-2}). The dislocation density after 30 % cold deformation can be found from the yield stresses in the graph to be $\rho = 5.7 \cdot 10^{13}$ m^{-2} and increases to $\rho = 1.2 \cdot 10^{14}$ m^{-2} after 60 % cold deformation.

Exercise 06.5
Assess the yield strength of three specimens:
(A) Pure Cu.
(B) Pure Cu, which has been rolled at room temperature.
(C) A copper alloy with 50 wt.% Ni, which has been rolled at room temperature as (B).
Explain the mechanisms affecting the yield strength assume that all specimens have the same grain size. No quantitative values for the yield strength are required, just compare them using ”larger than” or ”smaller than”.

The yield strength of pure copper is lower than the yield strength of deformed copper due to work hardening during rolling. The yield strength of rolled copper is smaller than the yield strength of a rolled copper alloy with 50 wt.% nickel, as rolling leads to about the same amount of work-hardening and the alloy is additionally strengthened by solid solution strengthening caused by the foreign atoms.