Part VII. Miscellaneous topics
Module 1 : Recovery and recrystallisation

# Part VII. Miscellaneous topics

In this part, we discuss the recovery, recrystallisation and grain growth processes; though these are not strictly phase transformations, they do have characteristics that are very similar to phase transformations and hence are discussed here. In the last module of this part we discuss coarsening.

# 1 Recovery and recrystallisation

## 1.1 Motivation

Why is it not possible to use work hardened structural materials in high temperature applications?

## 1.2 Cold working

There are many ways in which materials can be strengthened; work or strain hardening is one of the strengthening mechanisms. To work harden a material, it is cold worked: that is, it is deformed at low temperatures – typically at the ambient temperature, but any temperature which is below 0.3 to 0.5 of the melting temperature of the material will qualify as low temperature. Cold working introduces defects in the material (typically point defects and dislocations) which act as impediments to the movement of dislocations and hence the material is strengthened. The defects generated during cold working can store about 1 to 10 % of the energy of plastic deformation.

A cold worked material, however, cannot be used at high temperatures; typically, 0.3 to 0.5 of the melting temperature of the material is considered as high service temperature. In this temperature range, the microstructure of a cold worked material undergoes changes which reduce the strength of the material. In this module we study these microstructural changes, namely, recovery and recrystallisation.

## 1.3 Recovery

Recovery is a process that kicks in at low temperatures; in this stage, the excess defects are annealed out, dislocations of opposite signs annihilate each other, and dislocations align to form low energy configurations, namely tilt and twist boundaries. In Fig. 1 for example, we show how a wall of edge dislocations form a tilt boundary. In the recovery stage, however, the energy released through the annihilation and rearrangment of dislocations is not considerable.

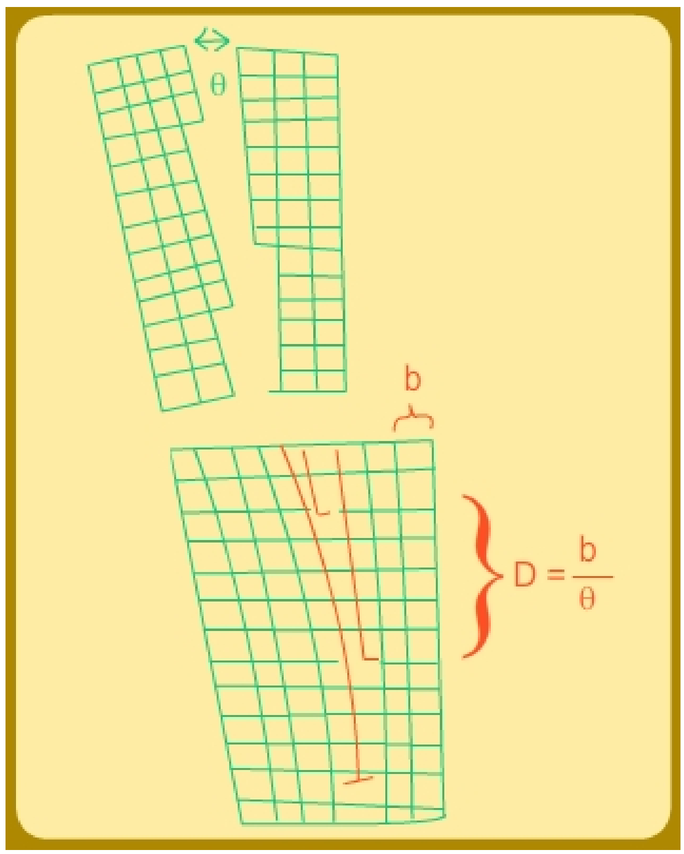


Figure 1: A wall of edge dislocations form a tilt grain boundary; it is a small angle grain boundary; the inter-dilocation separation in the grain boundary is decided by the misorientation between the two grains and the Burgers vector.

## 1.4 Recrystallisation

Recrystallisation is the process in which deformed grains are replaced by strain-free grains. It is generally observed that higher cold work and smaller initial grain size lead to finer recrystallized grains.

The driving force for recrystallisation is the stored strain energy in the material. For recrystallisation to take place, a minimum of cold working is needed; if the deformation is very low, recrystallisation does not occur.

During recrystallisation, the stress-free grains nucleate and grow. In a recrystallised system (after more than about 90% deformation) the resultant microstructure is textured; that is, most of the grains have similar orientation.

In Fig. 2 we (schematically) show the fraction recrystallised in cold worked copper as a function of annealing time at different temperatures. From the figure it is clear that the dynamics of recrystallisation can be described by JMAK kinetics. It is also observed that the recrystallisation rate increases with temperature in an expotential manner.

The temperature at which a given material completely recrystallises in an hour is defined as the recrystallisation temperature. The recrystallisation temperature is low if the degree of deformation is high and/or if the temperature of deformation is low and/or if the initial grain size is small. The recrystallisation temperature is also very sensitive to the purity of the material; an addition of 0.01 at.% of Te to pure copper, for example, can increase the recrystallisation temperature by about 240°C.

## 1.5 Cold work, recovery, recrystallisation and material properties

The processes of cold work, recovery and recrystallisation, because of the changes they produce in the microstructure of the material, also affect the properties of the materials. In Fig. 4, we show, schematically, variations in tensile strength, electrical conductivity and ductility with these processes.

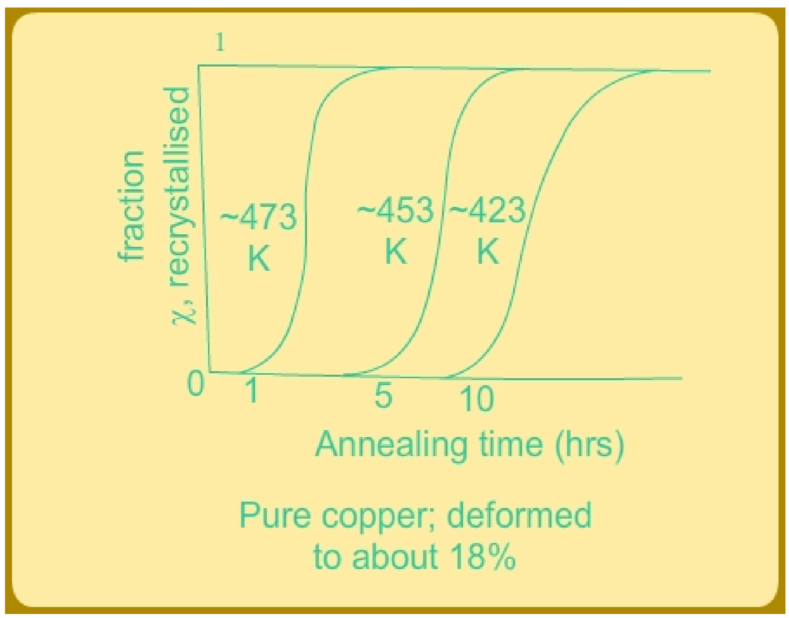


Figure 2: Annealing time versus fraction of recrystallised copper as a function of temperature. Note that the time changes from 1 to 5 to 10 hours with a decrease of about 20 K in temperature indicating the strong influence of temperature on recrystallisation kinetics.

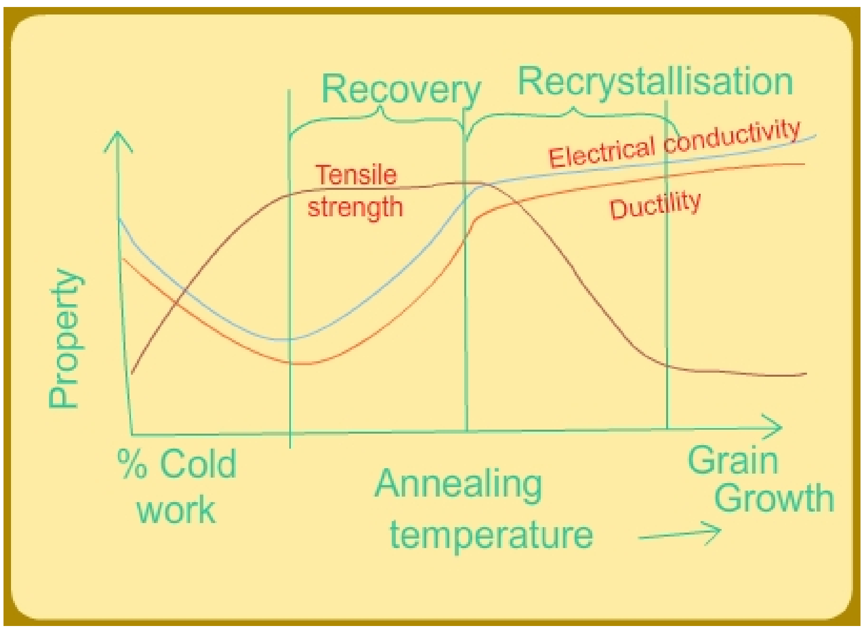


Figure 3: Changes in properties with % cold work and annealing temperature; increasing annealing temperatures leads to recovery and recrystallisation. Note that still higher annealing temperatures leads to grain growth.

## 1.6 Tutorial problems and questions

- Consider cold worked aluminium in which the dislocation density is increased from $10^{10}$ to $10^{14}$ per $m^2$. Calcualte the driving force for recrystallisation.

## 1.7 Solutions to the tutorial

- The shear modulus of aluminium is about 26 G Pa. Hence, the energy associated with $10^{14}$ per $m^2$ of dislocations is (since the Burgers vector is 2.86 Å)

  $\frac{1}{2} \times 26 \times 10^9 \times 2.86^2 \times 10^{-20} \times 10^{14}$;

  that is, the driving force is about 1 MJ per $m^3$.

## 1.8 Supplementary information

If the temperature of deformation is high, the recovery process can occur simultaneously with cold working. Such a process is known as dynamic recovery. Similarly, dynamic recrystallization is one in which recrystallisation processes take place along with deformation; again, dynamic recrystallization is possible if the temperature of deformation is high (during hot working, for example).