Part VII. Miscellaneous topics
Module 2 : Grain growth

2 Grain growth

2.1 Motivation

Consider a cold worked material which had undergone complete recovery and recrystallisation. It it is annealed for longer times, as shown in Fig. **??**, the properties keep changing. Why?

2.2 Grain growth

The interfaces in a material cost the system energy: the excess free energy associated with the interfaces is the interfacial free energy.

Grain boundaries are the interfaces between two crystallites which are differently oriented in space; the excess free energy associated with the grain boundary is the grain boundary energy.

The grain boundary energy acts as the driving force for the movement of grain boundaries. Hence, if a recrystallised material is further annealed, then grains growth takes place; bigger grains grow at the cost of smaller ones. This process is known as grain growth.

Since the driving force for grain growth is the interfacial energy, and since the excess energy associated with a system due to interfaces is related to the curvature of the interface, the grain growth is curvature driven. In Fig. 5 we show the direction of movement of grain boundaries and their relationship to curvature (in 2D systems).

If v is the velocity of the interface, then, $v \propto \kappa$, where κ is the curvature $(\frac{1}{r})$. More specifically,

$$v = M\frac{2\gamma}{r} \tag{1}$$

where M is the mobility, and γ is the grain boundary energy. In terms of the diameter (D) of the grains,

$$\frac{dD}{dt} = \frac{4M\gamma}{D} \tag{2}$$

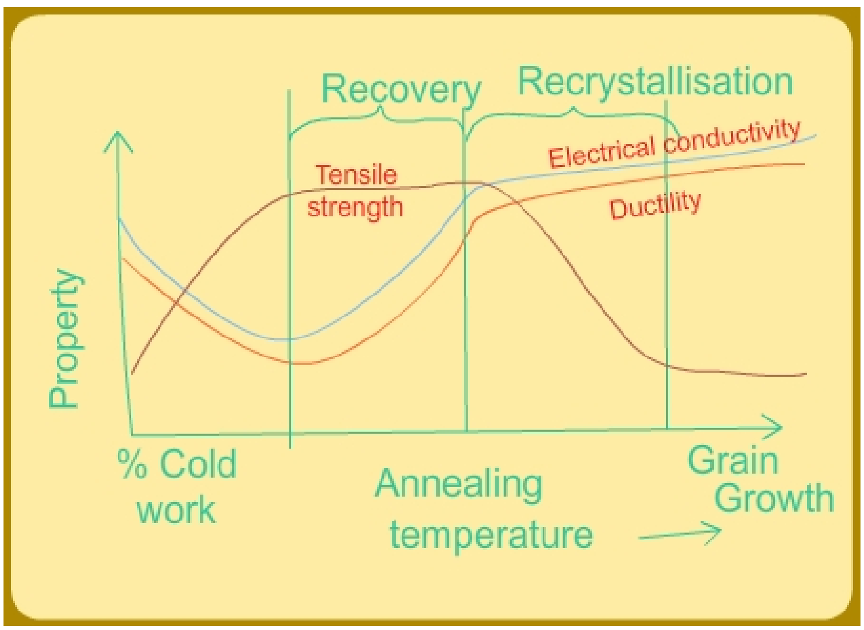

Figure 4: Change of properties with increased annealing temperature of a cold worked sample. Note that there are changes in properties beyond recrystallisation temperatures too (due to grain growth, as we discuss below).

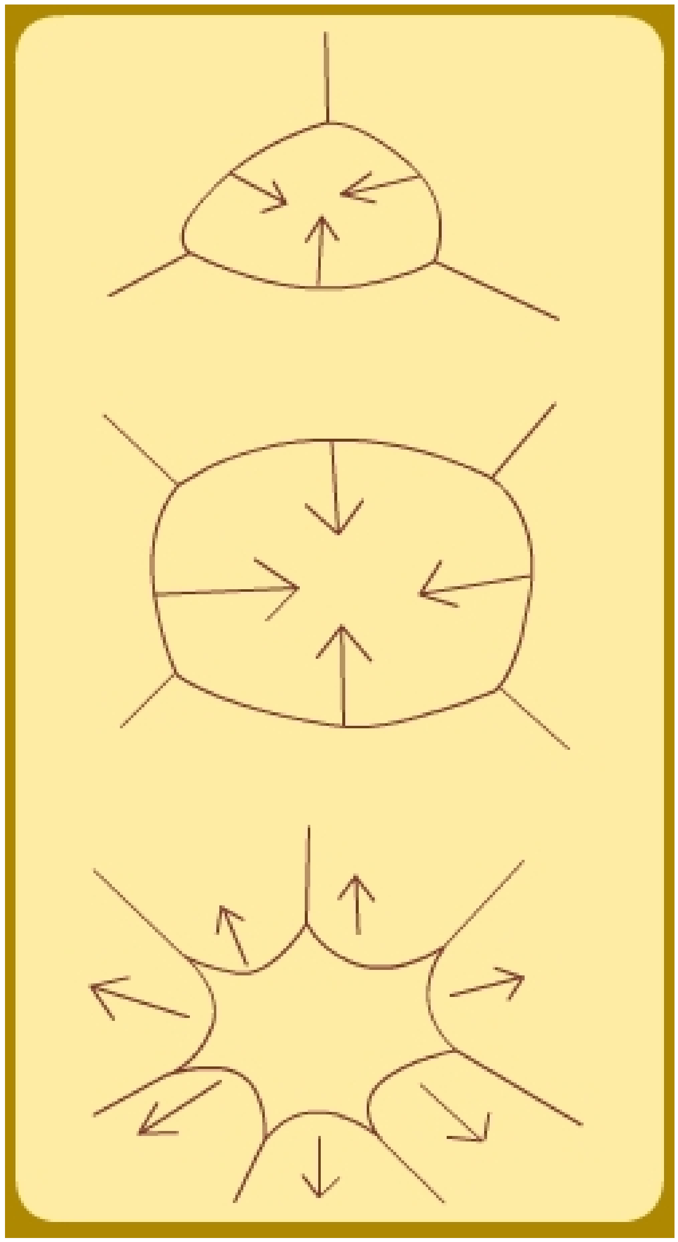

Figure 5: Curvature driven growth of grains (in 2D).

The solution to this equation is given by

$$D^2 = D_0^2 + 4M\gamma t \tag{3}$$

where D_0 is the mean size of the grain at time $t = 0$ and D is the mean diameter of the grains in the system.

Experimentally, it is found that the grain size as a function of time does follow an expression of the type $D = Kt^n$, where K is a temperature dependent proportionality constant and n is a number much less than 0.5. The deviation of the exponent from 0.5 is not yet clearly understood.

Due to the differences in the driving forces for recrystallisation and grain growth, as shown in Fig. 6, the movement of the interface in these two cases are different in character; recrystallisation, as long as the growing grain is free of strain and eats into the strained grain, will proceed irrespective of the curvature of the grain; however, during grain growth, the movement of the interface is dependent on the curvature of the grain.

2.3 Tutorial problems and questions

1. Most of the materials that we encounter in our daily lives are polycrystalline. If the grain boundary energy does increase the free energy of the system, why do they not disappear leaving behind a single crystal?

2. What happens if a grain boundary intersects a free surface as shown in Fig. 7?

2.4 Solutions to the tutorial

1. Polycrystalline materials are one of the best examples of systems in metastable equilibrium. The true equilibrium in a material can be reached only when all the grain boundaries disappear and the system becomes a single crystal. However, unless extreme care is taken, that

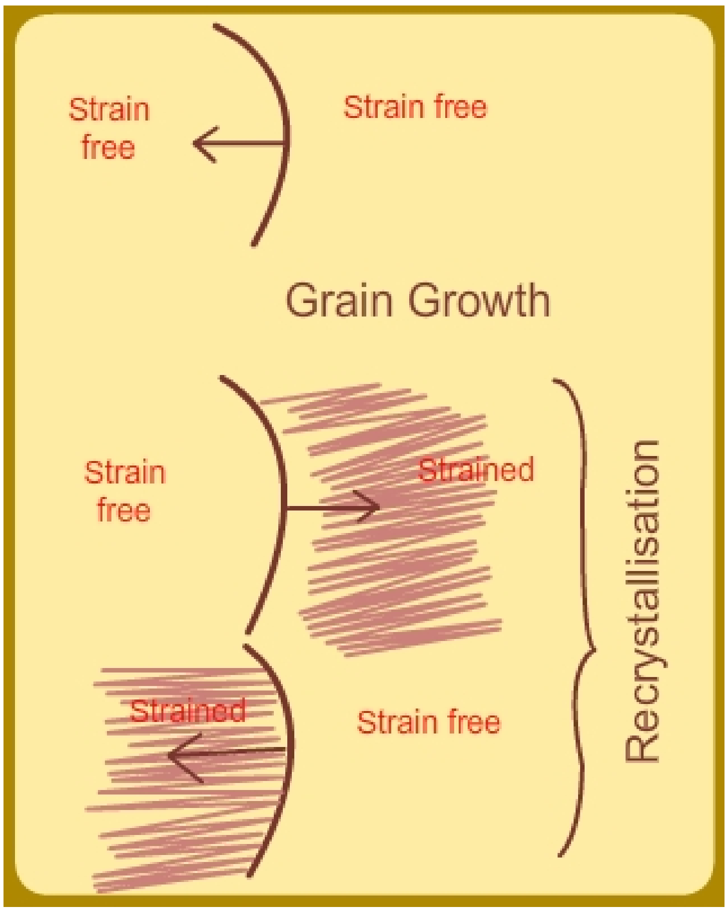

Figure 6: During grain growth, the direction of movement of the grain boundary is completely decided by curvature. On the other hand, during recrystallisation it is decided by the strains in the grains; the strained one is eaten up by the strain free crystal; hence, the growth can sometimes be such that the boundary moves away from its centre of curvature.

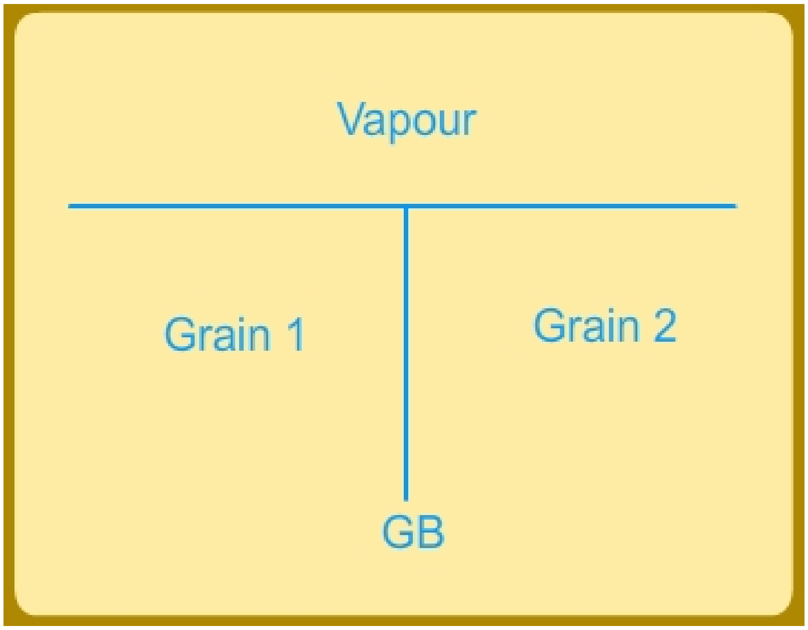

Figure 7: Grain boundary intersecting a free surface.

never happens. In most materials, the grain boundaries reach configurations in which the interfacial energies balance each other; in such scenarios, there is a barrier which must be overcome for the boundaries to move; the system is stable with respect to small changes in boundary shape and surface area. Hence, such metastable structures tend to stay.

2. We show in Fig. 8 what happens when a grain boundary intersects a free surface. The grain boundary region grooves; it grooves in such a way that the net surface-vapour surface tensions balance the grain boundary energy as shown in the figure. Grain boundary grooving is sometimes used to prepare microscopy samples because a grooved grain boundary gives rise to contrast which makes it clearly visible under a microscope.

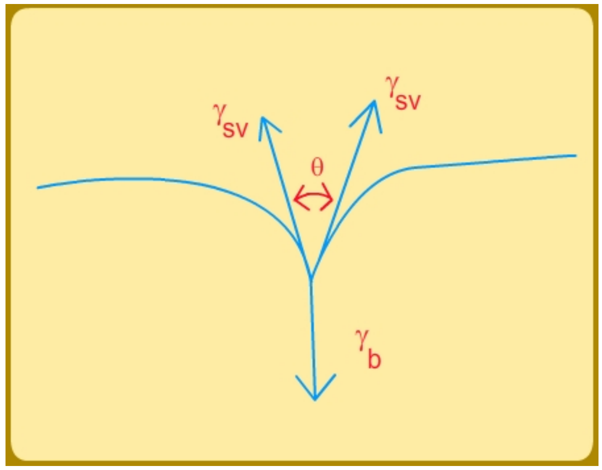

Figure 8: Grain boundary intersecting a free surface grooves to balance the forces.

2.5 Supplementary information

It is also possible for grains to rotate and hence decrease the orientation difference between them eventually leading to the removal of the grain boundary and hence an increase in the grain size. One of the mechanisms by which this can happen is that in the case of low angle boundaries, the dislocations that make up the grain boundary, if removed leading to an increase in the inter-dislocation distance in the grain boundary, will lead to reduction of misorientation between the grains. Such a process is sometimes seen in molecular dynamics simulations of grain growth.