

## Question Sheet 3, Solid State Transformations

### Recommended reading

- Chapter 3, pp 110-184, Chapter 5, pp 263-381 in Porter D. A. and Easterling K. E., *Phase Transformations in Metals and Alloys*, 2nd edition. Chapman & Hall, 1992. [Dept. library Ln30]
- Chapter 16, pp 515-537 in Reed-Hill R.E. and Abbaschian R., *Physical Metallurgy Principles*, 3rd edition. PWS Publishing, (1994) [Dept. library A160]

### Matter software

- Choose Dislocations module, especially third section "Interactions of dislocations".

### Web resources

- [www.aluminium.matter.org.uk](http://www.aluminium.matter.org.uk)  
*Strongly recommended. Especially useful with many modules of direct relevance*
- [www.doitpoms.ac.uk/tlplib/dislocations/index.php](http://www.doitpoms.ac.uk/tlplib/dislocations/index.php)  
*Background to dislocations, as Part IA.*
- [www.msm.cam.ac.uk/phase-trans/abstracts/recryst.html](http://www.msm.cam.ac.uk/phase-trans/abstracts/recryst.html)  
*Recrystallisation microstructures*
- [www.msm.cam.ac.uk/phase-trans/abstracts/recrystallise.grain.size.html](http://www.msm.cam.ac.uk/phase-trans/abstracts/recrystallise.grain.size.html)  
*Recrystallisation*
- [www.msm.cam.ac.uk/phase-trans/abstracts/annealing.twin.html](http://www.msm.cam.ac.uk/phase-trans/abstracts/annealing.twin.html)  
*Annealing twins*
- [www.msm.cam.ac.uk/phase-trans/abstracts/grain.movies.html](http://www.msm.cam.ac.uk/phase-trans/abstracts/grain.movies.html)  
*Grain growth simulations*

### Questions

1. A metal yields at a stress of 0.1 GPa and the subsequent work hardening during continued plastic deformation is negligible. If 5% of the plastic work is stored in the metal, estimate the increase in stored energy per unit volume for a true strain of 0.4.

The grain boundary energy in this metal is  $0.5 \text{ J m}^{-2}$ . Estimate the size of a critical nucleus for the homogeneous formation of a strain-free grain, and the activation energy for nucleation.

*[For a reminder of homogeneous nucleation theory, see Part IA Materials and Mineral Sciences Course D.]*

Comment on both of your answers by imagining the chance of a random fluctuation of the critical size, and by comparing the activation energy versus the energy available from thermal vibrations.

Describe briefly whether or not recrystallisation does occur by nucleation in deformed metals?

2. Estimate the stored energy due to a change in dislocation density of  $10^{15} \text{ m}^{-2}$  in a deformed aluminium alloy (ccp) which has a shear modulus  $G$  of 30 GPa and a lattice parameter of 0.424 nm.

The alloy contains a fraction  $f = 0.012$  of spherical oxide particles, each of radius  $r = 50 \text{ nm}$ . Hence decide whether or not the particles can hinder the motion of grain boundaries if the force driving the boundaries comes entirely from the elimination of dislocations. The grain boundary energy is  $0.3 \text{ J m}^{-2}$ .

3. Complete exercises 4 and 5 in your Metallography Booklet on samples M9 to M11, ( $\alpha$ -brass specimens) and transmission electron micrographs.

In addition, look at specimen M24 which is an Al-4Cu wt.% alloy aged at  $220^\circ\text{C}$  for 10 days. Comment on the precipitate distribution (in the matrix and in the vicinity of grain boundaries). How can such non-uniform distributions be prevented in practice?

4. The properties at room temperature of various aluminium alloys (all polycrystalline) are tabulated below.

	Yield strength (MPa)	Failure stress (MPa)	Strain to fracture (%)
Annealed pure aluminium	34	90	45
Deformed pure aluminium	82	89	9
Annealed Al-Mg alloy (4 wt.% Mg)	138	165	27
Annealed Al-Cu alloy (4 wt.% Cu)	97	186	18

Sketch, on one diagram, the stress-strain curve for each of the alloys and account for the differences between them. Comment, with reasons, on their relative toughness.

[Note that the Al-Mg alloy is a solid-solution strengthened alloy while Al-Cu is precipitation strengthened.]

Samples of the annealed Al - 4wt.% Cu alloy were heated to  $530^\circ\text{C}$  for 1 hour and then quenched in cold water. The yield strength was found to have increased to 230 MPa. The samples were then aged at  $145^\circ\text{C}$  for various times before being tested at room temperature. The results are shown on the next page.

Time at 145°C (hours)	Yield Strength (MPa)
1	250
10	370
10 <sup>2</sup>	420
10 <sup>3</sup>	315
10 <sup>4</sup>	205

Explain the changes in yield strength resulting from the quenching and ageing. Suggest, with reasons, differences in the ageing response if the copper content was halved.

[Note that the web resource [www.aluminium.matter.org.uk](http://www.aluminium.matter.org.uk) gives useful insights into the precipitation and strengthening mechanisms in aluminium alloys.]

**Numerical answers to BQ3; full answers will be distributed with BQ4.**

1.  $r^* = 5.7 \times 10^{-7} \text{ m}$ .       $G^* = 0.52 \times 10^{-12} \text{ J}$

2. The stored energy per unit volume is 1.35 MPa, the pinning stress is 0.108 MPa.