Textures and Microstructures, 1991, Vols 14–18, pp. 703–708
Reprints available from the publisher
Photocopying permitted by license only

THE DEVELOPMENT OF MICROSTRUCTURE AND TEXTURE DURING THE DEFORMATION AND ANNEALING OF PARTICLE-CONTAINING POLYCRYSTALS

F.J. HUMPHREYS and P.N. KALU
Materials Department, Imperial College, London, England.

INTRODUCTION

When an alloy containing non-deformable second-phase particles is deformed, then the incompatibility of the particles and the deforming matrix may result in what is essentially "turbulent flow" of the matrix adjacent to the particles, and at particles larger than around 0.5μm, highly rotated deformation zones may form. If the volume fraction of particles is large, then these zones may influence the deformation texture. Particles may also have an effect on the long range heterogeneity of deformation, e.g. deformation and shear bands. On subsequent recrystallisation, the deformation zones may act as sites for recrystallisation (PSN). The orientation of the deformation zones may thus have an influence on the recrystallisation texture even if the volume fraction of particles is quite small.

This paper will briefly review some recent theoretical and experimental work on the plasticity of particle-containing polycrystals [1] and will extend this to the annealing behaviour of these materials.

MATERIAL

Polycrystalline Al-0.8wt% Si alloys were heat treated to produce large equiaxed particles (2μm < d < 9μm, average diameter 5.6μm) or smaller particles (0.1μm < d < 1μm, average diameter 0.55μm). In both cases the volume fraction of particles is ~1%. Details of the heat treatments are given elsewhere [1]. Cylindrical specimens were deformed in uniaxial compression to reductions of 25%, 50% and 70% at temperatures of up to 300°C.

MICROTEXTURE INVESTIGATION OF DEFORMATION

If polycrystalline aluminium is deformed in compression, then the grains deform and rotate in a manner which may be described approximately by the Taylor theory of plasticity. The regions adjacent to the particle are predicted to rotate in an opposite sense by amounts which depend on the activity of the operating slip systems [1]. Thus, in a grain of orientation **M** a large particle will be associated

with a deformation zone within which the orientation extends from **M** to **P**. We can define the misorientation between the matrix and the most highly rotated part of the deformation zone as shown in figure 1. The direction of the misorientation is defined by the angle α and the extent of the misorientation by the angle **MP**. The direction of misorientation depends on the active slip systems and is not very sensitive to strain, whereas the extent of the misorientation is approximately proportional to strain. It is expected that several deformation zones will be formed at a single particle. The predicted distribution of misorientations is shown in figure 2. There are three strong peaks (A,B,C) predicted, corresponding to zones formed by the $(1\bar{1}1)[011]$, $(11\bar{1})[101]$ and $(111)[10\bar{1}]$ slip systems respectively. Other distributions are possible if there is interaction between different deformation zones. The predictions have been tested experimentally by measuring the orientations of matrix and deformation zones using a TEM microtexture technique [1]. Figure 3 shows the measured distribution of misorientations for the large particle containing alloy deformed 50%. It can be seen that the experimental distribution peaks strongly near the theoretical peak B, with smaller peaks near A and C. Details of the model and experimental results may be found in a recent paper [1].

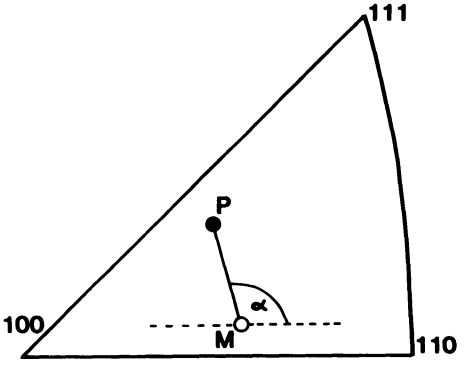

Figure 1. Definition of angle α

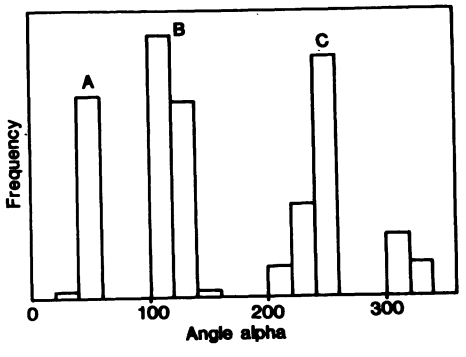

Figure 2. Predicted distribution of deformation zone orientations.

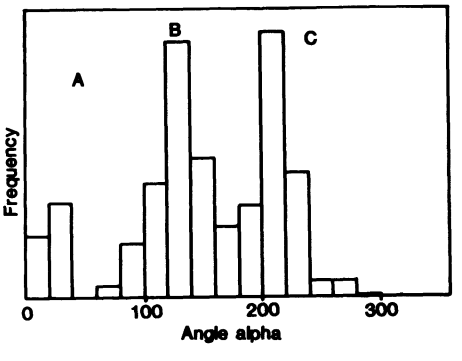

Figure 3. Measured orientation of deformation zones ($\epsilon = 50\%$)

MICROTEXTURE INVESTIGATION OF RECRYSTALLISATION

In-situ annealing experiments. The TEM microtexture method was used to measure the texture at large particles in the higher strained samples discussed above. The TEM specimens were then annealed in an HVEM at 250C until recrystallisation nucleation occurred. The microtextures of the same areas which now contained nuclei and the remnants of the deformation zone, were then remeasured. In this way, the relationship between the deformation structure at the particles and the orientation of the nuclei could be determined unambiguously. Figure 4 is an inverse polefigure in which the orientations of the matrix area (o), the deformation zones (•) and the recrystallisation nuclei (*) are shown for specimens deformed 50%.

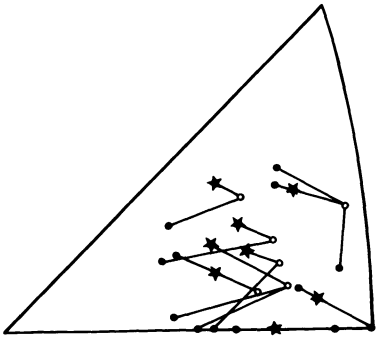

Figure 4. Orientations of matrix, deformation zones and nuclei.

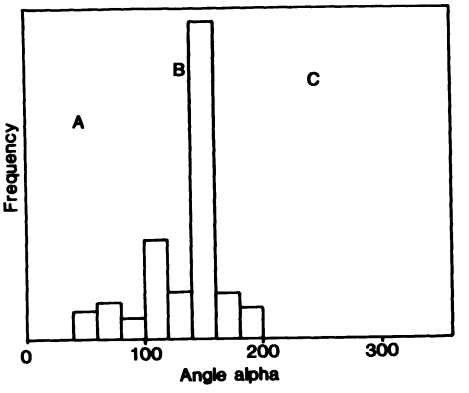

Figure 5. Distribution of nuclei orientations.

It may be seen that the orientation of the nuclei are within the spread of the deformation zones, in agreement with earlier work [2] and also that the nucleus does not always have the maximum misorientation present in the deformation zone. If, as is usually the case, there are several deformation zones formed at a particle, then it can be seen that the nucleus tends to form preferentially in the primary $(11\bar{1})$ [101]. A detailed study of the deformation structures [1] has shown that this zone is generally the most active.

Bulk annealing experiments. Similar microtexture experiments on specimens which were annealed in bulk allowed similar data to be obtained more rapidly, although the one to one correlation of the nuclei and deformation zones could not of course be studied.

The distribution of the orientations of the deformation zones for specimens deformed 50% is shown in figure 3. The distribution of nuclei orientations for the same material when annealed, is shown in figure 5. It can be seen that the distribution of nuclei orientations is much narrower than that of the deformation zones, and is strongly peaked at the $(11\bar{1})$ [101] zone direction, in agreement with the in-situ results discussed above.

The extent of the misorientation between matrix and nuclei has been measured, and for the large particles and a strain of 50% is a mean of 11.5°. This compares with a mean misorientation of 13.5° for the deformation zones. This again confirms the in-situ result that the nucleus is not necessarily formed in the most highly misoriented region of the deformation zone.

If a sufficient number of measurements is made, then the distribution of orientations in the deformed state, as measured by microtexture, should match the texture as measured by bulk x-ray techniques. Similarly, the distribution of orientations of the recrystallisation nuclei will determine the final bulk recrystallisation texture if all nuclei grow at a similar rate and if no other orientation components arise at a later stage of recrystallisation. The orientations of the matrix regions in the deformed material and of the recrystallisation nuclei are shown in figure 6 and 7. It may be seen that the matrix orientations after deformation are clustering towards [110] as expected [1]. The orientation of the recrystallisation nuclei is more random, although it should be noted that the nuclei are clustered towards the centre of the unit triangle, and away from the [100], [111] and [110] corners.

Figure 6. Matrix orientations ($\epsilon = 50\%$)

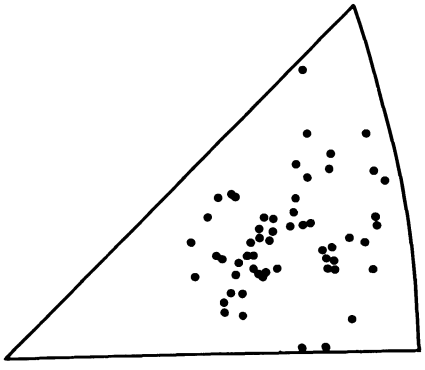

Figure 7. Nuclei orientations ($\epsilon = 50\%$)

BULK TEXTURE MEASUREMENTS

The textures of polycrystalline specimens containing large or small particles and of single phase alloys of the matrix composition have been determined after deformation by uniaxial compression at room temperature and elevated temperatures. The textures of fully recrystallised specimens have also been determined. Inverse pole figures were calculated from the experimental data.

The results may be summarised as follows:

a) Deformation. The deformation textures after room temperature deformation were similar for single-phase and both particle-containing alloys. As the volume fraction of particles is 1%, the volume of the highly rotated deformation zones is small, and little effect of particles is predicted. This contrasts with alloys

containing large volume fractions of non-deformable particles [3] in which texture weakening is found, and in alloys with deformable particles in which the texture may be strengthened [3,4].

Figure 8 shows the inverse polefigure of the large particle containing alloy deformed 70%. The similarity to fig 6 is expected.

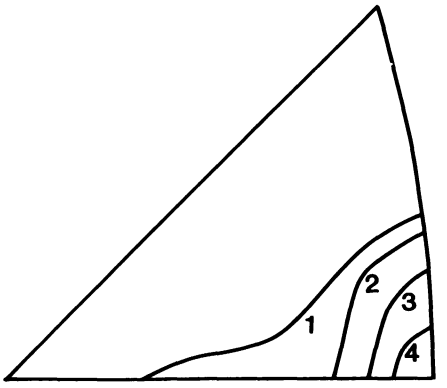

Figure 8. Texture after 70% compression at room temperature. (large particles)

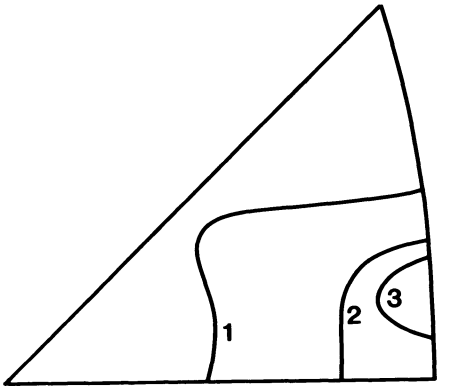

Figure 9. After recrystallisation.

b) Recrystallisation after cold deformation. On recrystallisation, the texture of the large particle containing alloy, in which PSN has occurred, weakens (fig 9). There is a significant increase in pole density in the middle of the unit triangle. comparison with the microtexture results of figure 7 suggests that these orientations correspond to the nuclei at particles. However, there is a significant pole density close to [110] in the recrystallised specimen, whereas no nuclei of this orientation were detected. This suggests that nuclei from other sources, possibly grain boundaries, are producing a recrystallisation component close to the deformed component.

c) High temperature deformation. It has been shown [5] that during deformation at lower temperatures and higher strain rates, similar deformation zones to those formed at low temperature occur and that these may lead to PSN on further annealing [6]. However below a critical strain rate, which depends on temperature and particle size, deformation zones are not formed, and hence PSN is not possible. For the aluminium alloys under consideration and for 6μm particles, the critical strain rates are 2×10^{-5} at 200°C and 9×10^{-3} at 300°C.

Specimens were deformed 50% at these temperatures at strain rates above and below the critical values. Under conditions where rotations are formed, the deformation and recrystallisation textures are similar to those obtained at room temperature, although slightly weaker, and are shown in figures 10 & 11.

Under conditions where no rotations occur, the deformation textures are similar, but the particle containing material (fig 12) shows a rather different recrystallisation texture to that of the single phase material (fig. 13). In particular

significant amounts of [111] and [001] texture are formed in the particle-containing alloy. The explanation for this is not known, but may be due to the influence of the particles on formation of long range heterogeneities during deformation.

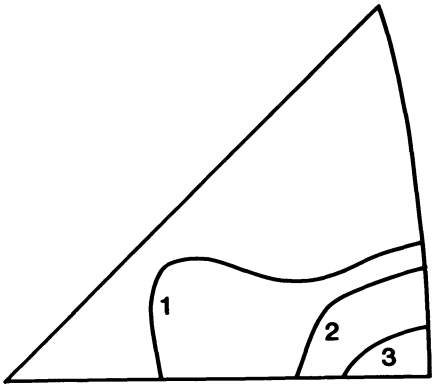

Figure 10. Deformed at 200°C, $\dot{\epsilon} = 8x10^{-4}$, $\epsilon = 50\%$. (large particles)

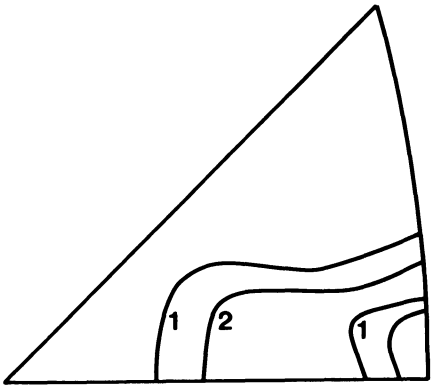

Figure 11. After recrystallisation

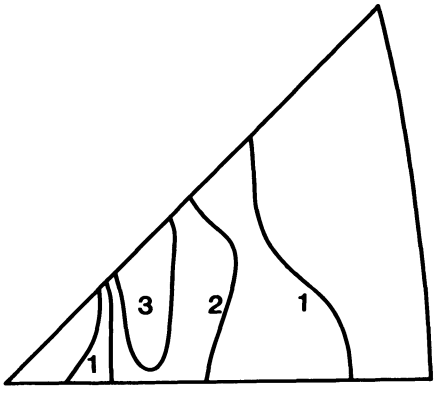

Figure 12. Single phase alloy. Recrystallised after 50% deformation at 300°C. $\dot{\epsilon} = 4x10^{-5}$.

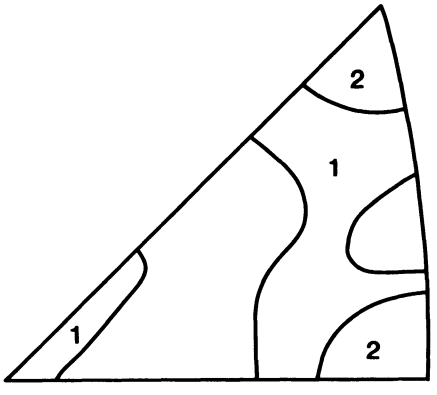

Figure 13. Large particle alloy. Recrystallised after 50% deformation at 300°C. $\dot{\epsilon} = 4x10^{-5}$.

REFERENCES

1. F.J. Humphreys and P.N. Kalu. *Acta Met.* **38**, 917 (1990)
2. F.J. Humphreys. *Proc. 1st Int. Riso Symp.* 35 (1980)
3. F.J. Humphreys and D.J. Jensen. *Proc. 7th Riso Int. Symp.* 93 (1986)
4. O. Engler, J. Hirsch and K. Lucke. *Acta Met.* **37**, 2743 (1989)
5. F.J. Humphreys and P.N. Kalu. *Acta Met.* **35**, 2815 (1987)
6. P.N. Kalu and F.J. Humphreys. *Proc. 7th Int. Riso Symp.* 385 (1987)