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Observation of the Slip Bands and Glide Planes in Aluminium/Alumina Alloys (SAP)

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SAP specimens, strained between room temperature and 440° C, show wavy slip bands having complex indices. These features probably result from double slip occurring on $\{111\}$ and $\{211\}$ planes, with a common $<01\bar{1}>$ direction. At room temperature slip is very fine. It is noticed that, at constant temperature, increasing the strain-rate results in finer bands more closely spaced, while at constant strain rate, spacing between bands increases markedly with temperature. This behaviour is more pronounced in SAP than in aluminium. Experiments suggest that dislocation recovery should be important in determining the density of bands.

1. Introduction

A large number of studies has been made in recent years on the mechanisms of deformation of dispersion-strengthened alloys, and in particular of SAP [1, 2]. Several theories and hypotheses have been proposed to explain the work-hardening and to account for the decrease in ductility with decreasing strain-rate and with increasing temperature [3-7]. On the other hand it is well known that observation of the slip bands has given important information on these problems in precipitation-hardened aluminium alloys [8-12]. The present research makes use of this classical technique, unattempted so far in SAP, and aims to determine (i) whether slip bands are observable in these alloys; (ii) the crystallographic planes for slip; and (iii) the features of the bands as a function of the main parameters, temperature and strain rate, which influence the ductility of SAP.

This work is based on the possibility, brought about by our previous works on recrystallisation, of obtaining SAP specimens with large crystals by suitable heat-treatments after cold-rolling [13, 14].

2. Experimental

Our study has been carried out on a SAP alloy (Puroxal) with 2.3 wt % oxide, produced by ISML*. The detailed composition is reported in table I.

TABLE I Impurities (ppm) in the alloy

Fe	Si	Mg	Cr	Sb	Cu	Mn
400	960	510	110	20	16	13
Pb	B	Zn	Sn	Mo	Ni	
5	4	3	3	3	1,4	

Tensile specimens 1 mm thick, with a useful portion of 30 × 4 mm, were produced from rolled sheet obtained by a 93 % rolling reduction. This large degree of reduction was chosen because it gives rise to a more uniform dispersion of the oxide particles [15]. The microstructure of these alloys has already been described in detail [16, 17]. We merely report here that the mean side of our platelets was ~ 800 Å and the mean planar interparticle spacing about 2000 Å.

Tensile specimens were mechanically polished; subsequent recrystallisation, carried out after suitable recovery treatments, produced grains about 1 cm across; their thickness was sometimes equal to that of the specimen. For comparison also aluminium (99.99 %) samples were prepared. All specimens were standardised by vacuum-annealing 2h at 500° C followed by slow cooling in the furnace.

3. Techniques

Tensile tests were carried out at different temperatures in the range between room temperature and 440° C. Strain-rates ranged between

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2.77×10^{-5}/sec and 1.1×10^{-2}/sec. An Instron-TTCML machine, with a furnace stabilised to ± 4° C, has been used. Before straining, the samples were electrolytically polished in perchloric acid solution [17], in order to allow subsequent examination of the surface.

The crystallographic plane for slip was determined in the following way: specimens were prepared with two planar faces at right angles. They were etched in order to display the grain-structure [13] and regions where a single grain extended on both faces were noted. The sample was then electrolytically polished. After straining, the orientation of slip bands in any selected area was carefully determined under the microscope. The orientation was determined by the classical Laue X-ray back-reflection method, on the strained specimen in order to avoid angular errors due to the rotation of the lattice. The errors in the determination of the orientation of the slip bands and those due to the asterism of the Laue pattern led to an experimental imprecision of about 3° on the glide plane orientation.

4. Results

It is noticed that strained specimens present slip bands whose features depend markedly on temperature and strain-rate. At room temperature slip was very fine, much more than in aluminium, and the bands were closely spaced; fig. 1 represents slip bands on two adjacent crystals after 22% strain at a rate of 2.77×10^{-5}/sec. With increasing strain-rate slip became still finer and bands were difficult to observe. Obviously the steps became less marked with decreasing strain, at our lowest strain-rate, slip lines could be detected, under the optical microscope, only after strains exceeding about 5%. Fig. 2 shows, at higher magnification, slip bands after 6% strain. As a general rule the bands appear rather "fragmented" and wavy.

Spacing between bands increases markedly with increasing temperature: fig. 3 shows bands after 5% strain at 440° C at a strain-rate of 2.77×10^{-5}/sec. The occurrence of slip on several systems is more readily resolvable in these conditions; in some instances three distinct intersecting families of bands have also been noticed. The occurrence of wavy bands, as shown at higher magnification in fig. 4, seems related to this behaviour.

At any temperature in the range of our observations, it was noticed that increasing the strain-rate results in finer bands, more closely

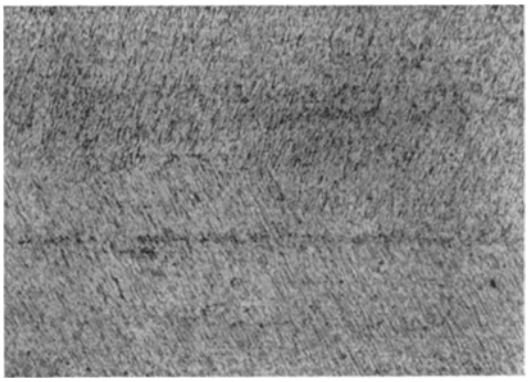

Figure 1 Slip bands in two adjacent crystals of SAP with 2.3% oxide strained 22% at room temperature. Strain rate: 2.77×10^{-5}/sec (× 130).

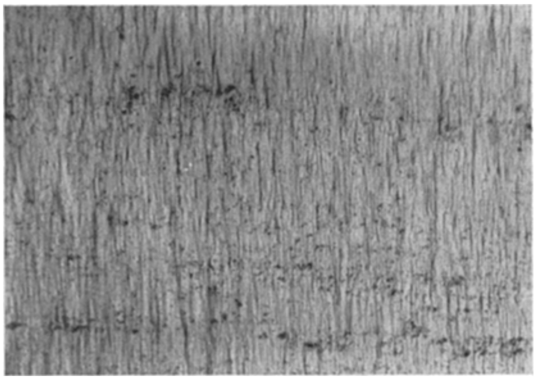

Figure 2 Features of the slip bands in SAP with 2.3% oxide, strained 6% at room temperature. Strain rate: 2.77×10^{-5}/sec (× 320).

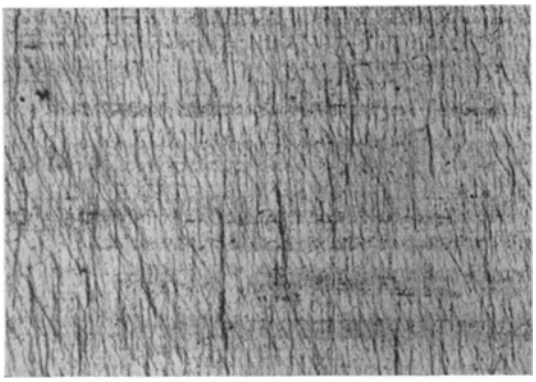

Figure 3 Slip bands on two intersecting planes in SAP with 2.3% oxide, strained 5% at 440° C. Strain rate: 2.77×10^{-5}/sec (× 140).

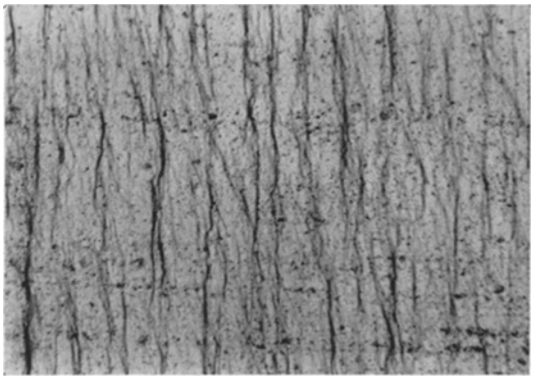

Figure 4 SAP with 2.3% oxide, strained 5% at 440° C. Strain rate: 2.77×10^{-5}/sec. Wavy bands resulting from slip on two systems (× 360).

spaced. Determinations after 5% strain at 440° C have shown that increasing the strain-rate from 2.77×10^{-5} to 2.77×10^{-3}/sec results in a decrease in band spacing by a factor of 2 to 3. The dependence of the spacing of the slip bands in SAP on temperature and strain-rate is thus qualitatively similar to that observed for pure aluminium [18, 19], although more pronounced (as we were able to establish by comparison with our specimens of Raffinal).

Determinations of the slip planes were made after deformation of SAP at high temperature (440° C) and at room temperature. At high temperature, slip planes with complex crystallographic indices such as (755) and (744) were found. In all cases the experimental slip plane lies, within 0.5°, in the zone of axis $[01\bar{1}]$, between the (111) and (211) planes.

Calculations of resolved shear stress for the possible slip systems, assuming <110> as slip direction, showed that the active systems were those with highest resolved shear stress. Further, the resolved shear stresses on (111) and (211) were nearly equal.

The most reasonable interpretation of these observations appears to be the occurrence of double slip on the planes (111) and (211), with the common $[01\bar{1}]$ slip direction. Actually in a particular case slip bands appeared very wavy on one face and nearly straight on the other one. The former face made an angle of 48° with the $[01\bar{1}]$ direction, while the latter was only inclined 14°: these observations are thus consistent with the above interpretation.

After deformation at room temperature, the observed situation turned out to be the same, i.e. the glide plane again had complex indices between (111) and (211).

These observations are by no means exhaustive; the number of samples observed does not allow us to exclude the possibility of other slip systems. In particular, we notice that the {311}, more densely packed than the {211}, might also be expected to be a slip plane in keeping with our experimental results.

5. Discussion

The results reported indicate that {111} and {211} planes are active both at room and high temperature. The hypothesis of extensive double slip is in agreement with the observed larger waviness of slip bands in SAP, when compared to aluminium. As is well known, the interpretation of double slip occurring with a common <110> direction was proposed by Lacombe and Beaujard to explain the waviness of slip bands in aluminium deformed at high temperature [20].

Slip on {211} and {311} have been observed in aluminium by other authors, but only at high temperature [21, 22]. On the other hand *cross-slip* on {111} {212} as well as on {100} has been noticed even at room temperature in aluminium single crystals [23].

We can only guess at reasons to account for the fact that in SAP {211} is active even at room temperature; a possible reason could be that the flow stress in SAP is much higher than in pure aluminium [6, 7, 24].

The high density of bands observed at room temperature is consistent with the high rate of work-hardening in SAP resulting from mechanical tests [6, 24] and electron microscopy observations after tensile deformation [7]. Also, electrical resistivity determinations have shown that the density of dislocations, resulting from a given strain, is much higher in SAP than in aluminium, and increases with the oxide content [17, 25].

With increasing temperature the bands become fewer, probably because the applied stress decreases and fewer Frank-Read sources become active. Further, the dislocations can climb, thus decreasing the back-stress on the sources and the work-hardening in general. To test this interpretation we carried out observations of band density after straining at various temperatures in the range from room temperature to 440° C. Actually a remarkable decrease in band density is observed at about 300° C, that is, the tempera-

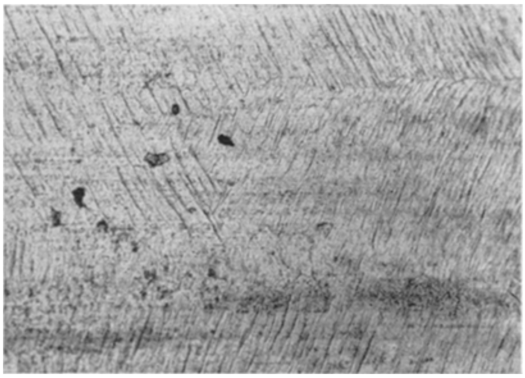

Figure 5 Slip bands in SAP with 2.3% oxide, strained 5% at 310° C. Strain rate: 2.77×10^{-5}/sec. Shows both fine and coarse slip bands (× 140).

ture at which we observed in SAP a recovery peak characterised by the activation energy for self-diffusion [26]. A typical micrograph of a sample deformed at this transition temperature is shown in fig. 5. The same arguments can account for the effect of strain-rate on the density of bands.

6. Conclusions

In the range between room temperature and 440° C, the slip bands in SAP show complex crystallographic indices. This is probably due to double slip occurring on {111} and {211} planes with a common $<01\bar{1}>$ direction. This interpretation is in keeping with the waviness presented by the bands. At room temperature slip is very fine, much more so than in aluminium. The dependence of band density on temperature and strain-rate in SAP is qualitatively the same as in pure aluminium, but more pronounced: the spacing between bands increases markedly with increasing temperature, while increasing the strain-rate, at constant temperature, results in finer bands more closely spaced.

A link has been noticed between band density and the process of dislocation recovery.

Research is under way on the problem of crack nucleation in these alloys.

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