THE INFLUENCE OF MICROSTRUCTURE ON TEXTURE EVOLUTION DURING HOT DEFORMATION AND ANNEALING OF COMMERCIAL PURITY ALUMINIUM

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Abstract

The recrystallization textures produced after annealing following commercial hot rolling of aluminium alloys are known to be important in controlling anisotropy of properties in the final product. Of particular interest is the generation of cube orientated crystallites, which compete with those grains nucleated at large intermetallic particles and elsewhere in the deformed microstructure in determining the texture balance in the recrystallized microstructure.

The annealed texture is believed to be influenced by both the hot deformation conditions and the microstructure prior to deformation. Both have been assessed in this study, with the initial microstructure altered in terms of the strength of the cube orientation. Samples have been deformed by Plane Strain Compression (PSC) followed by either a water quench, to preserve the deformed structure, or immediately fully annealed. The textures and grain structures are discussed with regard to the current understanding of the nucleation of recrystallized grains with these important crystallographic orientations.

Introduction

In the aluminium industry considerable effort is directed into reducing anisotropy of mechanical properties and crystallographic texture in order to produce a product with the required properties for the customer. For the vast majority of alloys the latter are controlled by careful regulation of the rolling processes and thermal treatments. In the case of hard rolled products for example, crystallographic anisotropy, in the form of earing, is reduced by balancing the textures. The cold rolling textures are balanced by the strong cube component developed during annealing at the end of hot rolling. It is the latter that is the focus of the present study.

The evolution of the cube orientation has been the subject of much debate in the field of texture research with, broadly speaking, two differing views being argued: those of orientated nucleation and orientated growth during recrystallization. Historically, most of the work on aluminium alloys has been carried out on samples in the cold rolled condition(1,2) and it is only more recently that the experimental equipment required to deform the samples at elevated temperatures in a controlled manner and to analyse the microstructures on a fine scale have been readily available. These contemporary studies(3,4), using TEM and the Electron Backscattered Pattern (EBSP) technique respectively, have identified recovered cube orientated subgrains in the hot deformed microstructure as possible sites for nucleation of recrystallized grains with the cube texture. This is despite the fact that this orientation is believed to be unstable during deformation, especially cold deformation, during which the crystallites rotate towards the stable brass, S and copper rolling components(1). This concept of a stable cube texture has been experimentally verified by channel die compression (CDC) experiments on single crystals(5,6) where, under certain thermomechanical conditions (high temperatures and very low strain rates), the cube component was observed to remain intact. These studies, together with other recent data[7,8], appear to support the orientated nucleation theory with the cube subgrains, or bands of subgrains, that are capable of "surviving" the deformation, able to form a viable nucleation site in the initial stages of annealing.

Clearly, from the theories discussed above, both the state of the initial, predeformed microstructure and the deformation conditions are expected to strongly influence the generation of the cube component during subsequent recrystallization. In an earlier paper[9] some of these aspects were assessed in AA1050, with various grain sizes and levels of cube in the starting microstructure, subjected to deformation to a range of thermomechanical conditions. The work concluded that the cube component was promoted after recrystallization both by the deformation conditions (higher strain and lower Zener-Hollomon parameter) and by the level of preserved cube in the deformed structure. The present study is an extension of this work in which additional microstructures have been developed to assess the influence of the remaining cube orientation in the deformed microstructure.

Experimental

The study has been based on the hot deformation of AA1050 by Plane Strain Compression (PSC) testing and the measurement of bulk textures and grain structures in the as quenched and fully annealed conditions. Prior to deformation a number of annealed microstructures were developed, by either industrial or laboratory thermomechanical processing, to obtain a range of materials with varying levels of cube texture. The grain sizes of these materials were also quantified. However, an earlier study[9] showed an insignificant effect of initial grain size on the strength of the cube component after deformation and annealing and, as such, this aspect has not been included in the present work. The microstructural parameters are given in Table I. These microstructures provided a wide range of initial cube texture strengths, ranging from ~2% for the #5 rotated structure to over 34% for #6, and these were expected to produce a variety of microstructures in the deformed state depending on the deformation conditions. The #5 rotated samples came from the same starting stock as material #5, however, instead of deformation being imposed in the rolling plane, samples were machined from the rolled slab rotated by 45° around the transverse direction (TD) and 45° around the normal direction (ND). Thus the cube orientation was effectively removed from the starting microstructure or, rather, the compression axis was no longer along the axes of the cubic crystal.

Table I. Grain sizes and crystallographic textures of the materials used in the study.

material	grain size (μm)	volume fraction (%)				
		cube	Goss	brass	Cu	S
#2	330	9.4	4.6	8.7	4.9	12.1
#5	250	25.1	4.0	5.9	3.8	12.2
#6	50	34.8	5.5	3.3	2.3	15.4
#5 rotated	250	2.1	2.3	25.2	7.9	24.9

PSC testing was carried out on a specially designed machine capable of accurate control of the deformation parameters strain, strain rate and temperature. A matrix of deformation conditions was studied to assess these effects on deformed and recrystallized textures and is described in Table II. Following deformation, samples were water quenched within 2 seconds of the end of the test to preserve the deformed microstructure. Where necessary, samples were annealed in a fluidised bed at the deformation temperature for times long enough to allow full

Table II. Matrix of PSC test conditions used in the study

deformation temperature (°C)	strain rate (s^{-1})	Z (s^{-1})	equivalent strain			
			0.5	1.0	2.0	3.0
400	2.5	3.3×10^{12}	*	*	*	*
400	77.0	10^{14}			*	
300	0.6	10^{14}			*	
300	25.0	4.2×10^{15}			*	

recrystallization to occur.

Deformed and recrystallized textures from the ½ thickness position were quantified by a bulk x-ray technique using Mo Kα x-rays. Four incomplete pole figures ((111), (200), (220) and (113)) were measured from which the ODF was derived using the series expansion method up to L=22[10]. The volume fractions of each of the major crystallographic components found in aluminium alloys were calculated allowing for a 15° spread around the ideal orientations.

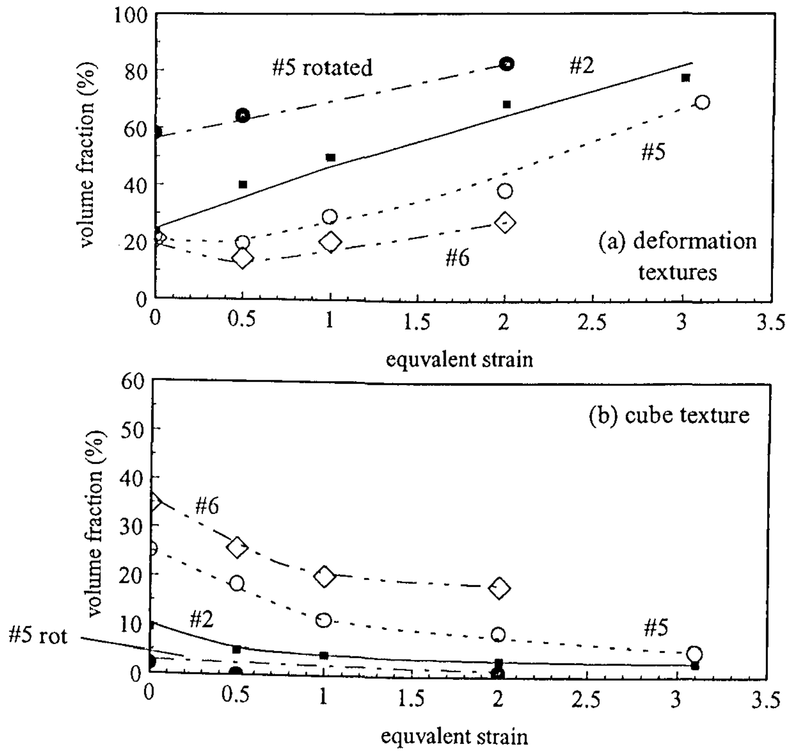
Results

Figure 1 displays data describing the effect of strain on the deformation textures of all 4 materials deformed at 400°C and a strain rate of 2.5s^{-1}. In all cases the texture consists of a combination of the rolling components, brass, Cu and S (Figure 1a) and the cube orientation (Figure 1b). The rolling textures gradually strengthen with increasing reduction, at approximately the same rate for all the materials when considered as a total of the 3 orientations, while the cube component weakens. Both the rolling textures and the cube appear to depend strongly on the initial, predeformed texture, especially in the case of the latter. Figure 1b clearly demonstrates that a significant level of this orientation can remain in the structure after deformation to a high reduction under these deformation conditions, if a substantial amount of cube is present in the starting stock.

After annealing to produce a fully recrystallized microstructure (1 hour at 400°C), two features are clearly apparent regarding the strength of the cube texture (Figure 2). Firstly, the influence of strain is considerable, with an augmented cube component being generated with increasing reduction. Furthermore, for three of the materials, #2, #5 and #5 rotated, the level of cube in the recrystallized microstructure reflects that remaining in the deformed structure (Figure 1b). In the case of material #5 rotated, where the cube texture strength was lower than random even before deformation, only very low levels were generated during annealing. For the fourth material, #6, the remaining cube strength after deformation was not reflected in the annealed texture with a fairly weak cube orientation produced at all strain levels. Indeed, for this material deformed at low strains (0.5 and 1.0) the usual recrystallization texture, consisting substantially of the cube component, did not evolve. Instead, the texture consisted of a combination of the cube component and the (103)<113> orientation. Orientation Distribution Functions (ODF) of the phi2 = 0° sections for the #6 material deformed to strains of 0.5, 1.0 and 2.0 and annealed are shown in Figure 3.

The influence of deformation temperature and strain rate on the level of cube and the recrystallized grain size in the annealed microstructure is shown in Figure 4, in terms of the temperature compensated strain rate or Zener-Hollomon parameter (Z). Generally, an increase in Z, by deforming at a lower temperature and/or a higher strain rate, results in a weakening of the

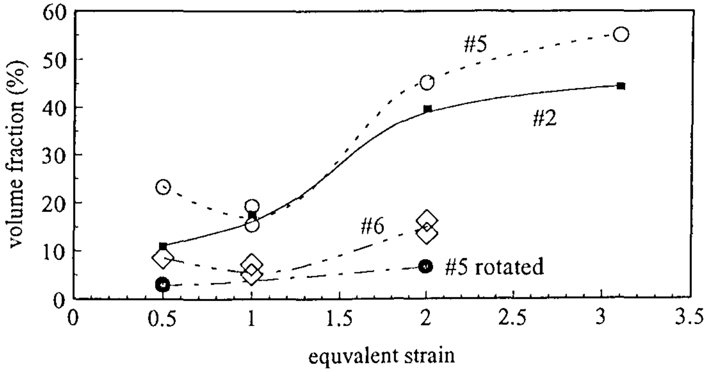
Figure 1. The effect of strain and initial cube texture on (a) the strength of the rolling textures (bs + S + Cu) and (b) the level of cube texture afterdeformation at 400°C and 2.5/s.



cube component (Figure 4a) and a refinement in the recrystallized grain size (Figure 4b). However, where Z was kept constant ($Z = 10^{14}s^{-1}$) but the deformation carried out at different temperatures with the appropriate strain rate compensation, a consistently higher level of cube was measured in those samples deformed at the higher temperature. Similarly there is a disparity in the grain sizes of the samples deformed at $Z = 10^{14}s^{-1}$ reflecting a change in the number of available nucleation sites depending on the imposed deformation temperature and strain rate.

Comparing the influence of initial cube strength there once again appears to be an effect on the annealed texture. Material #5, which has a prominent initial cube orientation, preserves this feature across the range of deformation conditions studied, while the cube component in the rotated sample (#5 rotated) remains very weak. It is interesting to note the behaviour of the #6 material which had an extremely strong cube orientation in the predeformed structure. At low Z values only a fairly weak cube component was produced, as reported above, however, as the deformation temperature was decreased and the strain rate increased the strength of the cube was also enhanced, and at the highest Z values evaluated the #6 material actually exhibited the strongest level of cube of all the materials.

Figure 2. The effect of strain and initial cube texture on the level of cube texture after deformation by PSC at 400°C and 2.5/s and annealing



Discussion

The data presented above clearly show the level to which the cube texture strength can be modified in this dilute alloy by control of the deformation conditions and the initial, predeformed texture. Altogether, a range from less than 5% to almost 55% volume fraction of cube has been produced in the recrystallized microstructure. The two most influential parameters were found to be that of reduction and the degree of retained cube in the deformed microstructure. The data in Figure 1a show that, although the cube orientation is not stable under these deformation conditions, it is at least metastable and significant levels can be retained at relatively high strains. A number of studies[1,8,11] have now shown that the cube orientation can be nucleated, during a subsequent anneal, at subgrains with the cube orientation in the deformed structure. The mechanism accounting for this behaviour is not totally understood, however, it is proposed that "surviving" cube subgrains are able to recover faster, either statically or dynamically, than subgrains of other orientations due to the limited dislocation types present after deformation. Studies by Ridha and Hutchinson[12] in pure copper have shown that only two sets of orthogonal dislocations need be active to accommodate plane strain in a cube orientated crystallite. This orthogonality inhibits interaction between the two types of dislocations and, hence, annihilation

Figure 3. phi2 = 0 sections from ODFs showing the annealed textures of material #6 after deformation to strains of (a) 0.5, (b) 1.0 and (c) 2.0. Contour lines 1, 2, 2, 4, ...

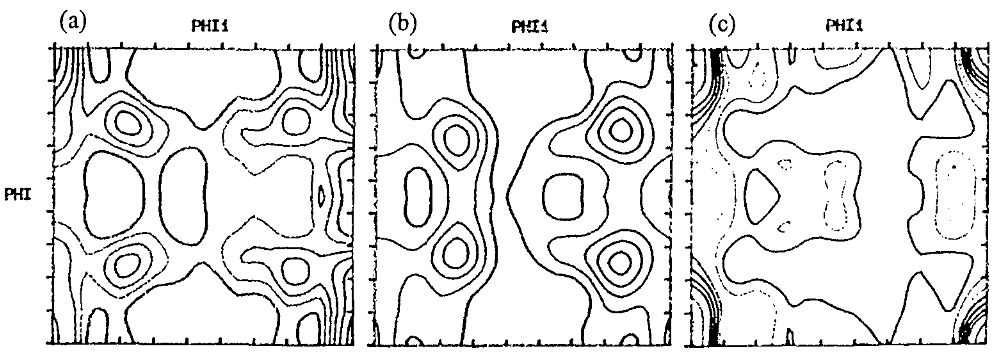
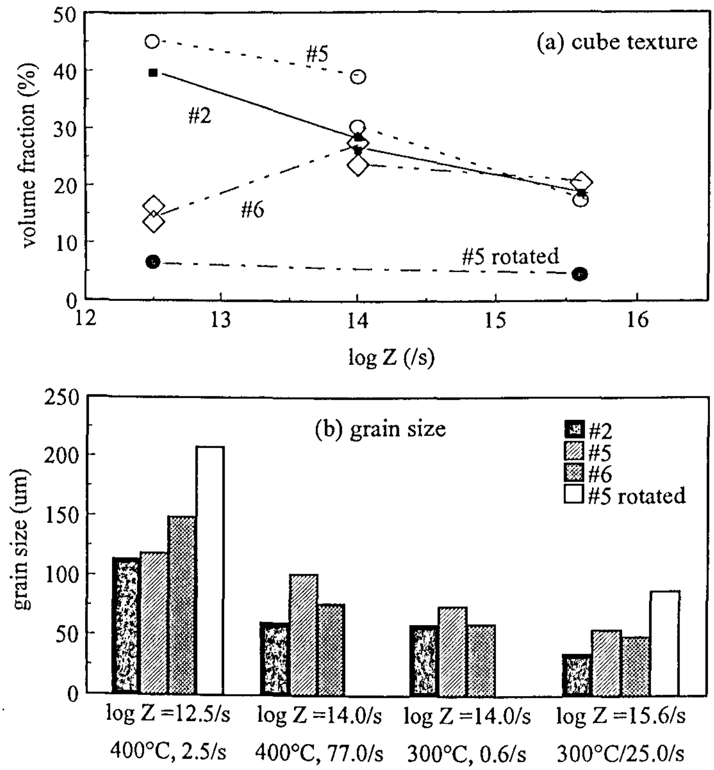


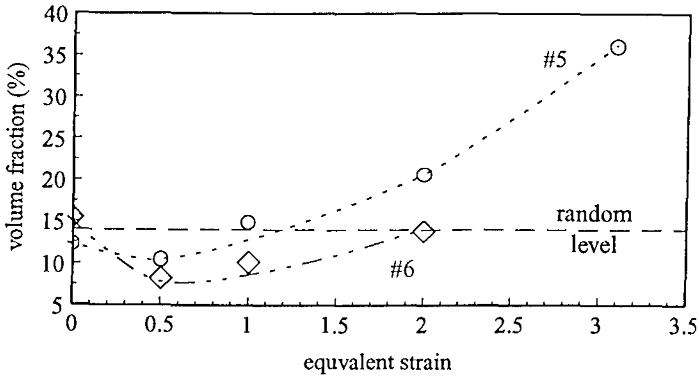
Figure 4. The effect of Z and initial cube texture on (a) the strength of the cube texture and (b) the grain size after deformation to a strain of 2.0 and annealing



leading to recovery is enhanced. This effectively results in orientated nucleation of the cube grains and is reflected in the texture of the fully recrystallized structure. Certainly comparing materials #5, #2 and #5 rotated in Figure 1b there is a tendency for more cube to be generated in the annealed microstructure at any particular strain if there is a higher level retained in the deformed structure. Furthermore, the annealed grain sizes in Figure 4b reveal the #5 rotated samples deformed to a strain of 2.0 at this temperature and strain rate (log Z = $12.5s^{-1}$) are significantly coarser than for the other two materials, suggesting that fewer nucleation sites, presumably from cube orientated subgrains, are available.

The surprising results, however, are for material #6. Here the deformed microstructure contains a very strong cube component even after a high reduction, though, on annealing, little cube is generated. An explanation may be sought from the recent work by Vatne and co-workers[8,13,14] who have studied, in some detail, the local orientations close to cube subgrains in deformed and partially annealed AA3004 and AA1050. They report that there is a propensity for the cube orientated subgrains to grow preferentially when the neighbouring substructure has the S texture component predominating. The cube and S orientations have nearly a 40°<111> relationship with each other and it has been argued that this gives the boundary a higher mobility than one which is randomly orientated[15]. Vatne and co workers have disputed this interpretation and have attributed the promotion of nucleation of the cube orientation at these sites to a reduction in the

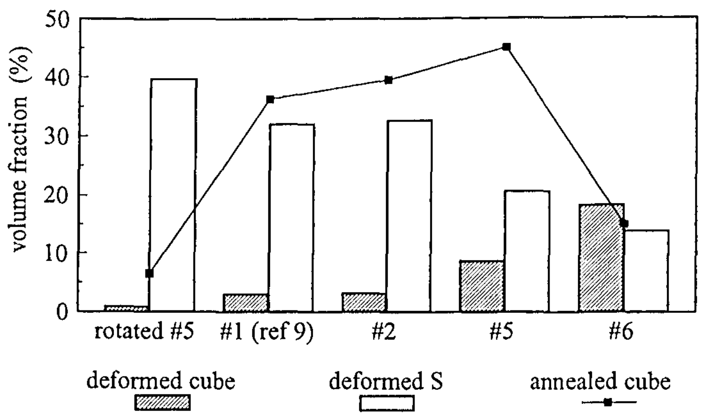
Figure 5. The effect of strain and initial cube texture on the level of S texture after deformation by PSC at 400°C and 2.5/s.



critical Gibbs-Thompson radius. This allows cube subgrains with a smaller radius to nucleate than would be expected for a random boundary orientation. The relevant data for materials #5 and #6 showing the change in the S component strength with strain are shown in Figure 5. For #6, and #5 at strains below 1.0, the S component is extremely weak, in fact below the level expected in a random aluminium sample. It is possible, therefore, that although there are sufficient cube subgrains to potentially act as nucleation sites in these deformed structures, few are adjacent to material with the S component, resulting in weak recrystallized textures.

To summarise the influence of the initial textures the relevant data for all the materials have been accumulated in Figure 6. This plot displays the strengths of the cube and S orientations in the deformed microstructure after hot deformation at 400°C, 2.5s^{-1} and to a strain of 2.0 as well as the level of cube in the annealed structure. The data indicate that a high cube component is promoted in the recrystallized microstructure if more is retained in the deformed state and a significant level of the S component is present.

Figure 6. Comparison between the deformation and recrystallization textures of various materials deformed by PSC at 400°C, 2.5/s to a strain of 2.0.



The other prominent influences on cube texture development are the deformation conditions and, in particular, strain. At high reductions substantial levels of the cube orientation can be generated after annealing (Figure 1b). This has been attributed to the development of a fine subgrain structure and high misorientations between neighbouring subgrains and grains in the deformed microstructure[1,11], both of which will increase the driving force for the recrystallization reaction, and an increase in the grain boundary area, which will maximise the efficiency of the available cube orientated nucleation sites. An even finer subgrain structure is developed at higher values of Z[11] though, as shown in Figure 4, the cube texture is weakened in the annealed state. As shown in a previous study[9] and observed by Driver et al[5,6], a reduction in the deformation temperature and an enhancement in the strain rate will lead to fewer metastable cube orientated subgrains during deformation. Coupled with an augmented contribution to the nucleation density from sites around coarse intermetallic particles[16], and as supported by the grain size data in Figure 4b, a further weakening of the cube component in the fully recrystallized microstructure would be expected.

Conclusions

1. The strength of the cube texture component in this dilute aluminium alloy after hot deformation and annealing is highly dependent on the condition of the deformed microstructure. It is enhanced by the retention of cube orientated subgrains, in conjunction with sufficient S texture. The data supports the opinion that cube grains are preferentially selected for growth when the neighbouring substructure is predominantly S texture.

2. The hot working, or deformation, conditions are also deemed important. The cube orientation after annealing is intensified when the deformation conditions help develop a fine and highly misorientated subgrain structure and maximise the efficiency of the potential cube nucleation sites relative to other sites producing non cube texture components.

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