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Deformation and recrystallization in cross-rolled Al–Cu precipitation alloys

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The deformation and recrystallization behaviour of single-phase f.c.c. metals have been studied mostly after conventional, uniaxial rolling. In this paper, the effect of both the presence of a second phase and the deformation path (i.e. straight rolling versus cross-rolling) on the evolution of microstructures and textures of an Al–3% Cu alloy are presented. The changes in the deformation and recrystallization texture are found to be complex, and it is not the deformation path nor solely the type of precipitate alone which produces the changes.

1. Introduction

Among all heat-treatable alloys, the properties and structures of Al–Cu alloys have been most intensively studied. The formation of Guinier–Preston (GP) zones (or θ'') leads to a well-known strength enhancement in these alloys, which leads to their widespread application as the basis for important structural materials. The effect of the various stages of precipitation (i.e. θ'' and θ') on the development of rolling textures has been investigated [1, 2]. The rolling texture at high strain is regarded as the copper type, irrespective of the kind of precipitate present, and the presence of second-phase precipitates (GP zones + θ') is said to correlate with the occurrence of shear bands [3].

The role of shear bands in deformation and recrystallization textures in low stacking-fault energy materials has received much attention [4–6]. Nevertheless, controversy still exists as to whether the brass-type rolling texture originates from the small and fine crystallites in shear band materials, or whether shear band formation is only a transient phenomenon in the development of rolling textures in f.c.c. materials [7]. During recrystallization, shear bands are found to be active nucleation sites. The $\{111\}\langle112\rangle$ textures in a steel which possesses a high normal anisotropy have been shown to arise from the shear band sites [8]. The correlation between shear bands and the recrystallization texture in low stacking-fault energy f.c.c. metals is, however, less certain, although there is some evidence that shear banding may destroy the sites for the nucleation of the cube grains in copper [9]. Recrystallization at shear bands in an Al–Mg alloy has been reported by Koken and Embury [10] but a textural investigation was not included in their work.

All the above-mentioned studies were performed on specimens which had been straight-rolled (i.e. rolled conventionally in a uniaxial manner). In this paper, the effect of two different heat treatments (i.e. natural ageing and over-ageing) and two different modes of rolling (i.e. straight and cross-rolling) on the deformation and recrystallization behaviour of an Al–3% Cu alloy have been investigated, and some preliminary findings are presented with the aim of exploring some of the above unsettled issues.

2. Experimental procedure

A hot-rolled slab of Al–3% Cu alloy was used as the starting material. Samples from this alloy were solution-treated at 500 °C for 1 h. Some specimens from this sample were naturally aged at room temperature for a few days, whilst others were over-aged at 300 °C for 5 h. These samples were then cold-rolled to a reduction of 82% at room temperature by either straight rolling or cross-rolling on a laboratory 2 high rolling mill with 127 mm roll diameter. In straight rolling, the samples were rolled in the same direction for each pass. The cross-rolled samples were rotated 90° around the rolling plane normal after each pass. Between 8 and 12 passes were used to achieve the required deformation. Over-aged specimens which had subsequently been straight-rolled and cross-rolled are designated in this paper as OS and OC, respectively, whereas the designations for the naturally aged specimens are NS and NC. After rolling, these materials were annealed in a fluidized-bed furnace at different temperatures (200, 250, 300, 350 and 400 °C) for various times from 5 to 300 min.

Hardness tests were performed on a Vicker hardness tester with a load of 5 kg. Optical metallography was performed on specimens prepared by mechanical polishing followed by chemical etching. Three pole figures (i.e. $\{111\}$, $\{200\}$, $\{220\}$) were determined by the Schultz reflection method. To remove any surface effect, 10% of the surface of the specimen was removed by chemical etching in a dilute NaOH solution. The percentage of texture components was obtained from automatic quantitative texture analysis software developed by Cai and Lee [11]. The intensity peaks from

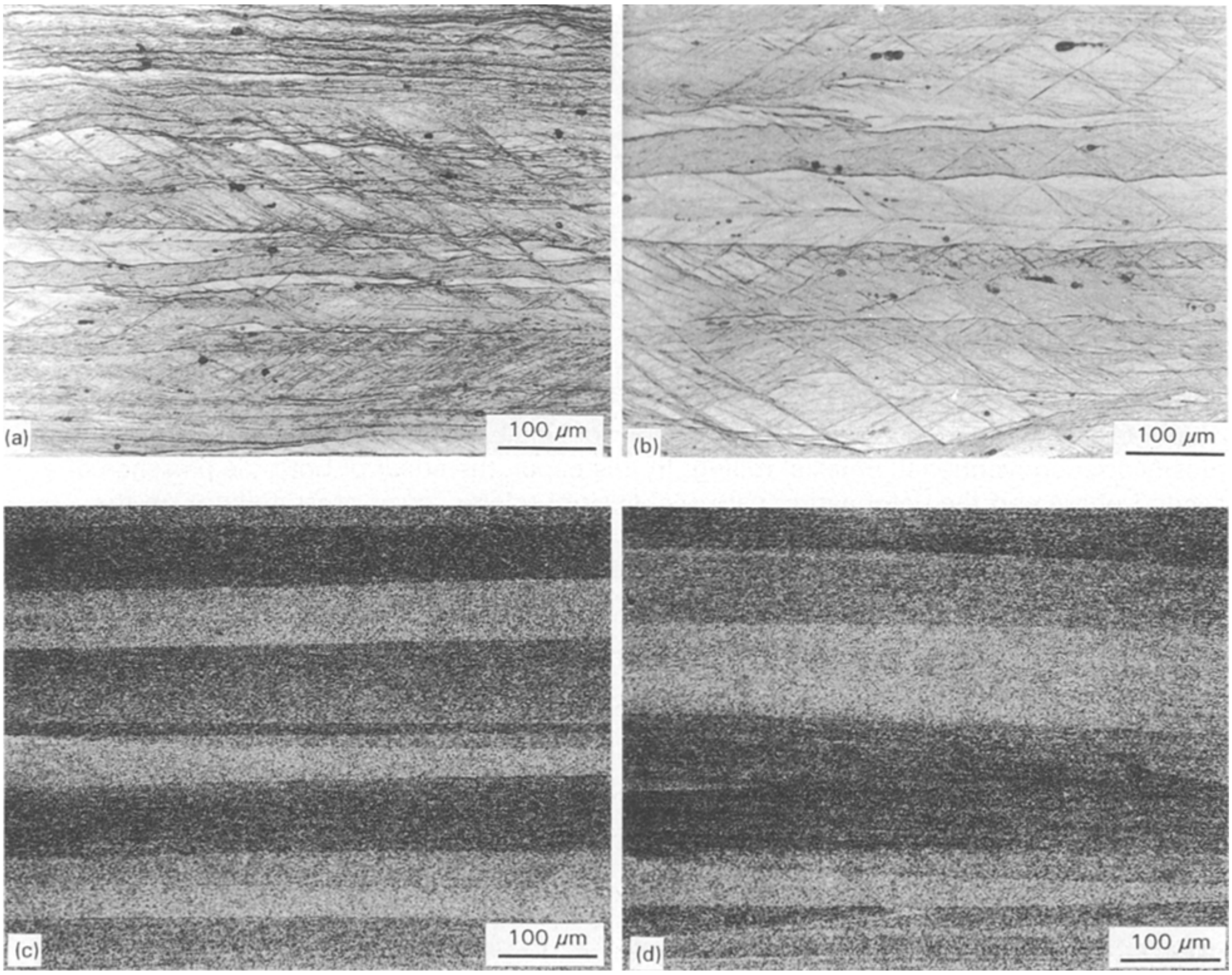

Figure 1 Optical micrographs showing longitudinal section of specimens in (a) naturally aged and straight-rolled (NS), (b) naturally aged and cross-rolled (NC), (c) over-aged and straight-rolled (OS) and (d) over-aged and cross-rolled (OC) condition; cold-rolled reduction – 82%.

the orientation distribution functions (ODFs) were automatically located and an angular spread of 20° from the intensity peaks of each ideal orientation position was included in the calculation of the volume fraction. When two peak intensities overlapped, their intersecting points were taken as the dividing line between the space occupied by the two ideal orientations.

3. Results

3.1. Optical metallography

The as-cold-rolled microstructures of the four samples are shown in Fig. 1. No shear bands were found in the samples which had been over-aged. Shear bands typical of those found in α-brass were found in the samples which had been naturally aged. The most frequently observed shear band angle was 35 °C, although deviations from this angle were also found. In the straight-rolled sample, shear bands were usually confined within individual grains (Fig. 1a), whereas sample-scale shear bands (shear bands traversing the entire thickness of the specimen) were common in cross-rolled specimens (Fig. 1b). These intersecting sample-scale shear bands divided the cross-rolled material into regular rhomboids similar to those in cross-rolled α-brass, as reported by Yeung *et al.* [12].

The recrystallization behaviour was investigated in the temperature range 200–400 °C. At the optical level, nucleation of new grains was detected first in the over-aged samples in both OS and OC conditions after annealing at 300 °C for 10 min. Although recrystallization was rapid in the shear bands in the naturally aged samples, the grains nucleated in the shear bands were very small compared to the much larger grains nucleated at prior grain boundaries. The naturally aged samples just started to give rise to visible new grains after a longer annealing period (i.e. 1 h) at the same annealing temperature of 300 °C (Fig. 2), although extensive recovery had already occurred, as shown by the changes in the hardness curves (Figs 3 and 4). The shear bands with very fine recrystallized grains in the naturally-aged samples (NC, NS) were still discernible at this stage and were found to disappear after the samples had been annealed at 350 °C for 30 min, while the long but recovered grains in the NS sample were still retained compared with the cross-rolled samples in the same naturally aged condition (NC). The cross-rolled samples showed a more rapid consumption of the elongated but recovered grains under the same annealing conditions. The partially recrystallized structure of all four samples exhibited a mix of small grains dispersed in the large grains. The difference in the sizes of the

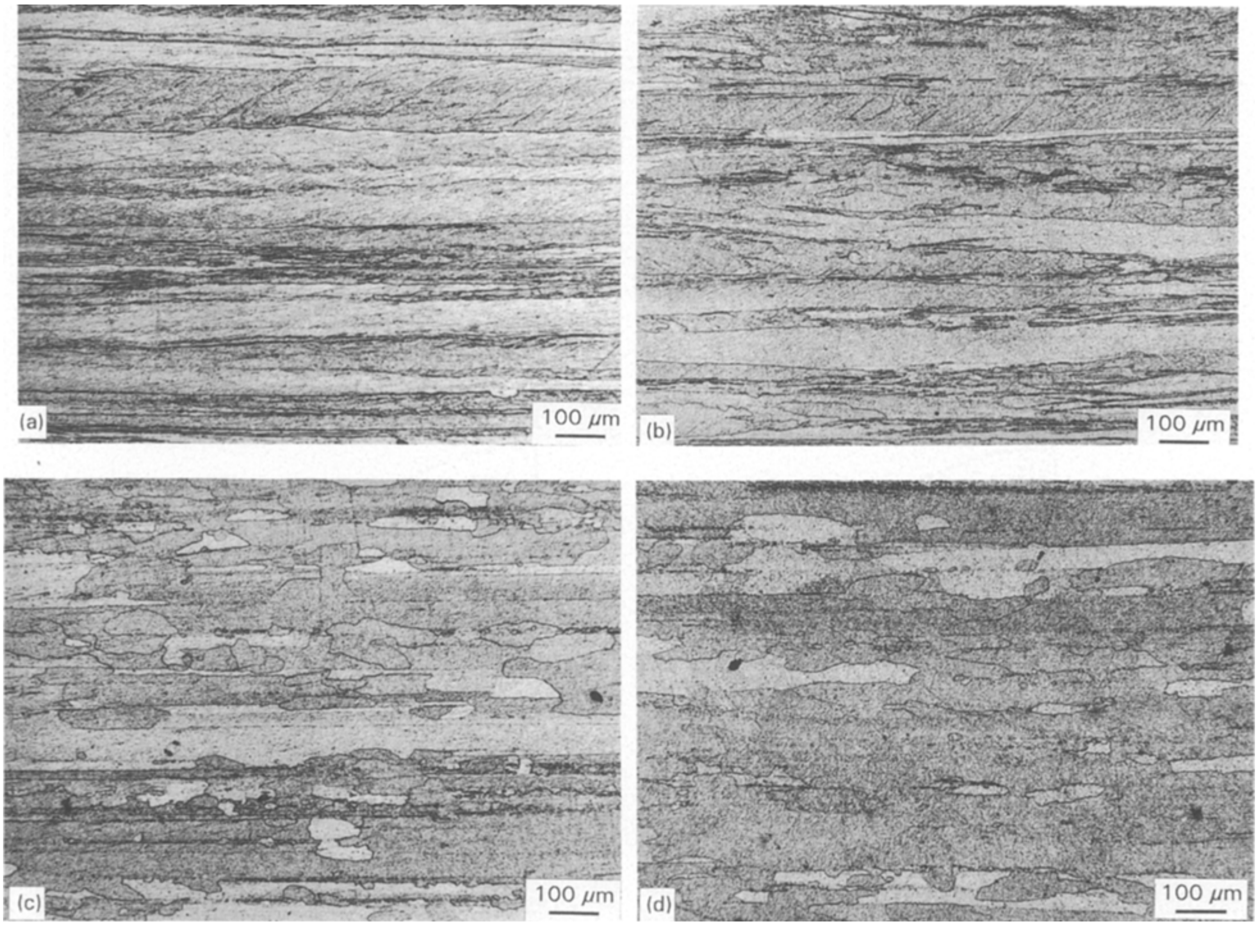

Figure 2 Same specimens as Fig. 1 but annealed at 300 °C for 1 h.

small and large grains appeared to be greater in the naturally-aged samples. Recrystallization was well advanced in all the samples annealed for 2 h at 350 °C, although occasional elongated and recovered grains could still be detected in the straight-rolled samples. The average recrystallized grain size was found to be largest in the over-aged and cross-rolled samples (OC).

3.2. Recrystallization kinetics

The changes in the annealed hardness of the four samples with annealing time at 300 °C are shown in Fig. 3. The hardness curves for samples with the same heat treatment (i.e. over-aged or naturally aged) are close to each other. The hardness values of the naturally aged ones are higher than those of the over-aged ones. However, the rate of change in the annealed hardness is just the opposite. The hardness decreased more rapidly in the samples which had been naturally aged, although an appreciable drop in the annealed hardness (i.e. more than 50% reduction in hardness) occurred in all samples annealed at 300 °C for 1 h. At 300 °C, recovery still dominated over recrystallization in the samples which had been naturally aged, whereas

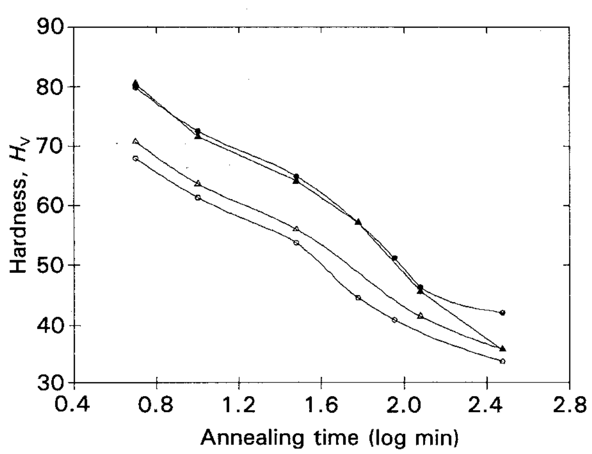

Figure 3 Hardness against annealing times at 300 °C for the four specimens: (●) NS, (▲) NC, (○) OS, (△) OC.

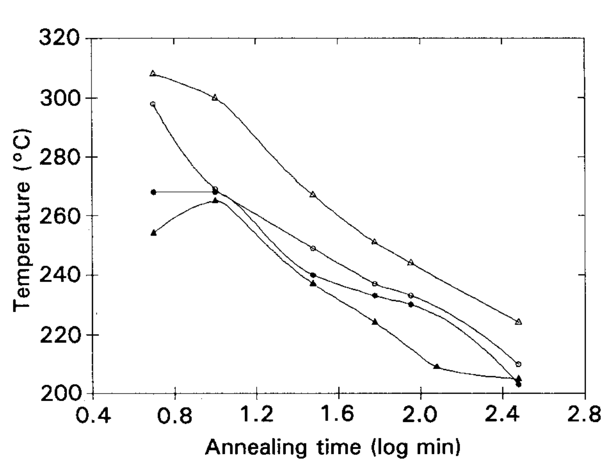

Figure 4 Rate of hardness change as shown by the time–temperature plot for 50% reduction in the annealed hardness: (●) NS, (▲) NC, (○) OS, (△) OC.

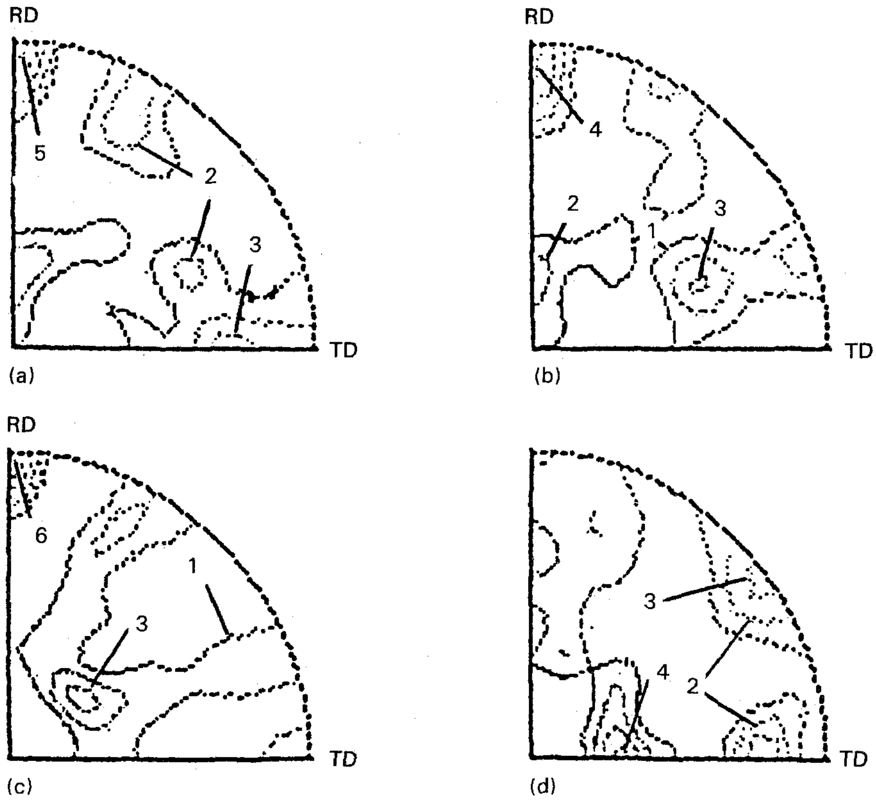

Figure 5 {1 1 1} pole figures of as-cold-rolled specimens: (a) NS, (b) OS, (c) NC, (d) OC.

in the over-aged samples there was more recrystallization.

The rate of hardness change is shown in the time–temperature plot for 50% reduction in the annealed hardness in Fig. 4. The time taken to soften the material by 50% was shortest for the NC samples, while the OC sample took a longer time to soften. The recovery and recrystallization rates for the OS and NS samples are intermediate between these two. There is a difference of 4.5 times in the time taken between the OC and NC samples to soften at 240 °C to the same percentage of their original hardness. The 50% change in hardness does not correspond to 50% recrystallization, as is evident from the optical metallography results.

3.3. Texture

In uniaxial rolling, the cold-rolled textures (i.e. copper-type rolling texture) of the naturally aged and over-aged samples are basically of the same type (i.e. the {1 1 2}⟨1 1 1⟩ texture component predominates). However, the deformation texture became very different when the samples were cross-rolled. The cross-rolling textures of the age-hardened samples could be represented by {1 0 1}⟨1 1 1⟩(24.2%) + {0 0 1}⟨3 1 0⟩ (23%) + {0 1 2}⟨4 2 1⟩(11.8%), whilst those of the over-aged ones were represented by {1 1 0}⟨1 1 1⟩ (26.1%) + {0 1 1}⟨1 2 2⟩(16.6%) + {1 1 4}⟨1 1 0⟩ (15.7%). In the naturally aged samples there was a small percentage of cube grains which was absent in the over-aged samples. The pole figures of the four as-deformed samples are given in Fig. 5.

Extensive recovery, as indicated by the hardness change, had occurred in all four samples after annealing at 300 °C for 1 h. There were very few changes in the textures of these samples (Fig. 6) which confirmed that in this case very little recrystallization had taken place. The four samples had all recrystallized after annealing for 1 h at 400 °C. This is supported by the changes in the annealing textures (Fig. 7). In general, the recrystallization textures are all weakened regardless of whether they had been straight-rolled or cross-rolled. Table I gives a breakdown of the major recrystallization components as calculated from the ODFs. The pole figures of the texture of the four samples annealed at 400 °C for 1 h are shown in Fig. 7. Both the R and cube texture components are very

TABLE I Volume fractions of major texture components of samples annealed at 400 °C for 1 h

Sample	Major recrystallized components
NS	{0 0 1}⟨6 1 0⟩ (22.3%) + {3 2 1}⟨1 2 1⟩ (14.8%) + {1 0 1}⟨5 4 5⟩ (10.8%) + {1 1 2}⟨0 2 1⟩ (6.1%) + others
NC	{3 0 1}⟨1 1 3⟩ (35.8%) + {0 1 2}⟨3 2 1⟩ (7.8%) + {1 0 0}⟨0 1 1⟩ (7.4%) + {3 1 7}⟨3 5 2⟩ (5.1%) + others
OS	{1 0 0}⟨0 3 2⟩ (20.1%) + {2 0 1}⟨2 3 4⟩ (17.0%) + {1 1 0}⟨0 0 1⟩ (10.5%) + {6 3 4}⟨3 2 6⟩(9.5%) + others
OC	{1 1 0}⟨1 1 2⟩ (18.9%) + {3 5 7}⟨1 2 1⟩ (11.6%) + {0 0 1}⟨6 1 0⟩ (9.3%) + {3 1 9}⟨2 3 1⟩ (9.2%) + others

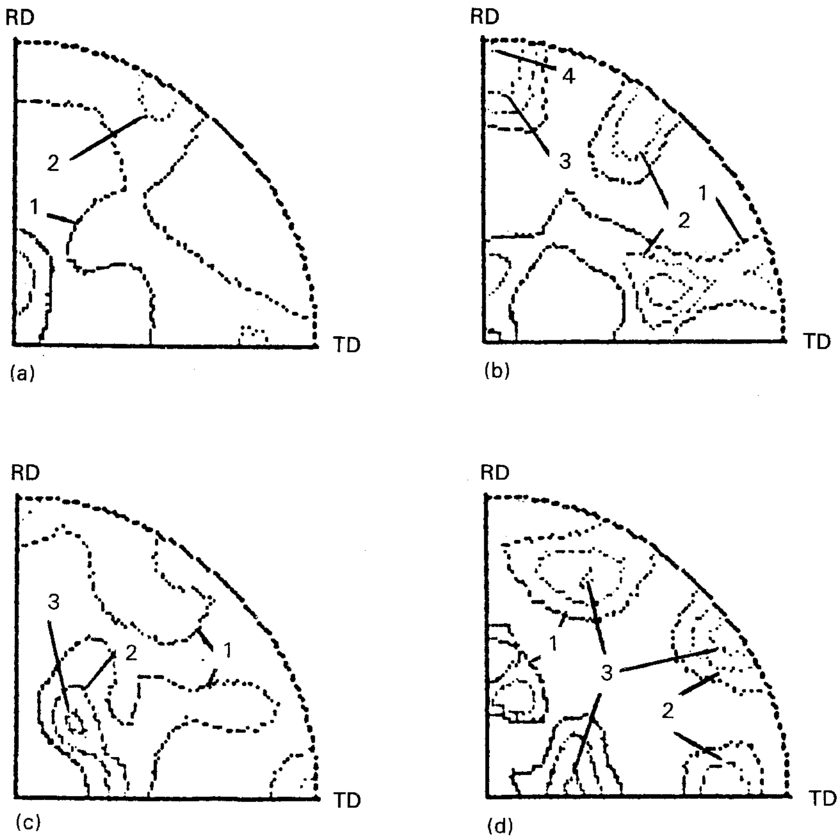

Figure 6 {1 1 1} pole figures of specimens rolled and annealed at 300 °C for 1 h: (a) NS, (b) OS, (c) NC, (d) OC.

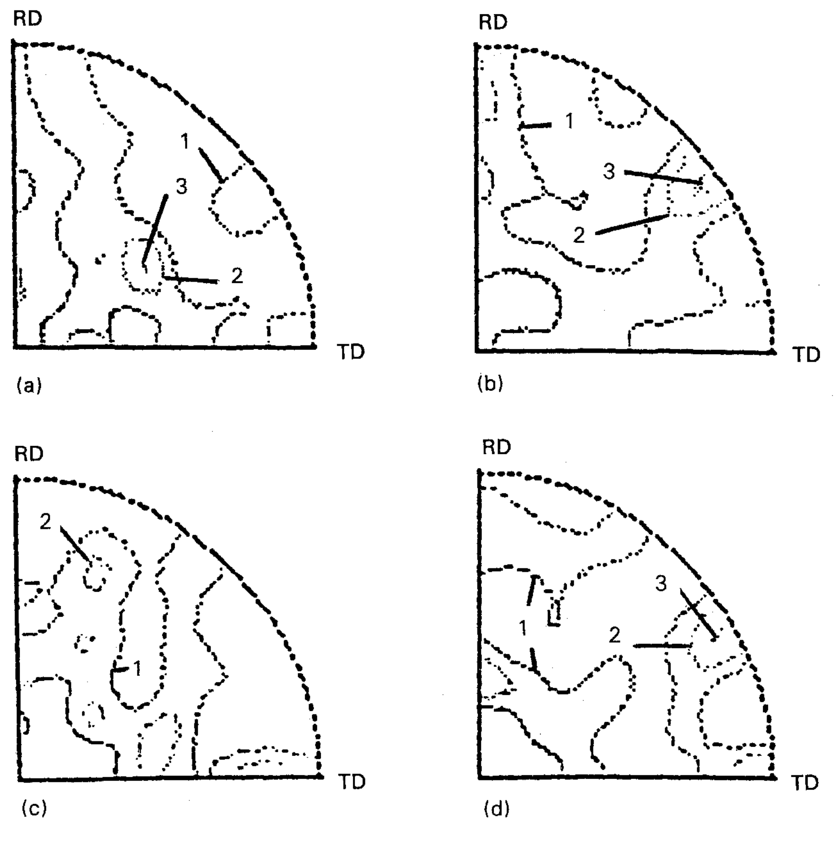

Figure 7 {1 1 1} pole figures of specimens rolled and annealed at 400 °C for 1 h: (a) NS, (b) OS, (c) NC, (d) OC.

weak in the straight-rolled samples compared with those found in commercially pure aluminium.

One interesting observation is that the cube components are completely destroyed. However, there are relatively strong {0 0 1} rolling plane components in the aged-hardened (> 30%) and over-aged specimens (~ 25%) which had been straight-rolled and annealed at 400 °C. In the naturally aged specimens, the spread of the {0 0 1} rolling plane component is towards the ⟨0 0 1⟩ direction. If an angular deviation of 9° is allowed, there are about 22% cube-aligned grains in the naturally aged specimens. In the crossed-rolled specimens in either heat-treated condition, there are fewer {0 0 1} rolling plane components. The major recrystallized component in the aged-hardened specimen was {3 0 1} ⟨1 1 3⟩, whereas a {1 1 0} fibre texture appeared in the over-aged specimen with 18.9% of grain orientation, clustered around the {1 1 0}⟨1 1 2⟩ orientations.

4. Discussion

The recrystallization texture of cross-rolled Al–3% Cu alloy in either the naturally aged or over-aged condition are different from those reported for other f.c.c. alloys, such as α-brass which has a lower stacking-fault energy [12]. In α-brass, the as-cross-rolled texture is a {1 1 0} fibre texture with {1 1 0}⟨2 2 3⟩ orientations as the major texture components, which agrees with the theoretical prediction based on the Talyor model of deformation in polycrystals. In the Al–3% Cu alloy the cross-rolled texture of the naturally aged alloy (i.e. sample NC) is close to that existing in α-brass. However, in the over-aged condition the peak intensity of the {1 1 0} fibre texture shifts to the {1 1 0}⟨1 2 2⟩ position. Straight rolling, on the other hand, produces qualitatively the same copper-type rolling texture in both the naturally aged and over-aged specimens. The presence of shear bands in the straight-rolled specimen strengthens rather than weakens the copper-type rolling texture. This finding agrees with the reported work of Morri and Nahayama [1] in that the stability of the {1 1 2}⟨1 1 1⟩ copper-type texture upon rolling is assisted by shear band formation. Such observations are interesting, since shear bands are thought to disrupt the development of the copper-type texture in low stacking-fault energy materials [4]. In short, neither the nature of the precipitates nor the presence of shear bands produces changes in the straight-rolling textures of aluminium alloys with different kinds of precipitates. It is not the deformation path *per se* (i.e. straight rolling or cross-rolling) which produces changes in the textures but the subtle effect of the interaction between the deformation path and the microstructural evolution. To look for a plausible explanation, the choice of the slip system and the associated hardening of the crystals should be dependent on the deformation path, a point which is worthy of further detailed investigation.

The role of shear bands, even though this is a minor aspect in the development of the rolling texture, affects significantly the recrystallization behaviour of the straight-rolled or cross-rolled samples. The recovery and recrystallization rate is highest in the alloys which had been naturally aged and contained shear bands. This can be explained by the coarsening of the precipitates upon heating and the rapid nucleation of recrystallization which is expected in the shear-banded materials.

There appears to be no systematic correlation between the rolling textures and the recrystallization textures in each of the four samples annealed at 400 °C. More significant amounts of {0 0 1} rolling plant recrystallized components are observed in the straight-rolled samples than in the cross-rolled samples. One interesting observation is the appearance of the recrystallized {1 1 0} fibre texture component in the over-aged and cross-rolled specimen (OC) with a peak intensity at {1 1 0}⟨1 1 2⟩ orientation, which is a major cold-rolling texture component in low-SFE materials. A similar {1 1 0} fibre texture component existed in recrystallized cross-rolled α-brass, but the strengths of the {1 1 0}⟨2 2 3⟩ cross-rolling texture components were retained in the recrystallization texture.

A major feature of the recrystallization behaviour of this aluminium alloy is that extensive recovery preceeds and accompanies the recrystallization process. The texture remained similar (Fig. 5) after annealing at 300 °C for 1 h although considerable softening had already occurred. The contribution of shear banding to the development of recrystallization textures in the Al–3% Cu alloy is negative, in the sense that it gave rise to a randomization of textures upon annealing. From Fig. 5 it can be seen that the peak intensity of the deformation texture (in either straight-rolled or cross-rolled samples) of the naturally aged specimens which contained the shear bands dropped more rapidly than in the specimens without shear bands. The {1 1 2}⟨1 1 1⟩ orientations are well known to give rise to shear banding in the naturally aged condition; the strength of this was found to decrease as the shear bands recrystallized to other orientations. On the other hand, the intensity of the major rolling-texture components of the over-aged specimens remained similar upon annealing, since recovery will normally strengthen rather than weaken the intensity of the major texture components.

The changes in the deformation texture and recrystallization texture in an Al–3% Cu alloy are found to be complex when the effects of both the heat-treated state and the deformation path are considered. To obtain a better physical understanding, more work on the details of the evolution of substructures and correlation with deformation paths will be needed.

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