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TEXTURE DEVELOPMENT IN EXTRUDED Al–Cu COMPOSITES

H. GERTEL, H. G. BROKMEIER and H. J. BUNGE

Department of Physical Metallurgy, Technical University Clausthal, Großer Bruch 23, D-3392 Clausthal-Zellerfeld, FRG and GKSS Research Center, Max-Planck-Str., D-2054 Geesthacht, FRG

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Extensive neutron texture analysis of extruded Al–Cu composites was conducted in order to investigate the influence of material composition as well as various processing conditions (extrusion temperature, heat treatment) on the texture development in both phases. Texture changes in cold extruded and subsequently heat treated samples were investigated up to 400°C. Moreover, the texture of a series of cold extruded samples was compared with that of warm extruded samples. It was found that the recrystallization behaviour of the two metals differs and that the stacking fault energy has a large influence on the recrystallization texture.

KEY WORDS Neutron diffraction, fibre texture, composites, aluminium, copper, recrystallization.

INTRODUCTION

In cold extruded pure aluminium the deformation texture is already well known (Merz and Wassermann, 1965; Wassermann and Grewen, 1969). It develops a double fibre texture $\langle 111 \rangle$ and $\langle 100 \rangle$ which is typical for fcc metals. To obtain information about the deformation behaviour in two-phase materials Brokmeier, Böcker and Bunge (1988) investigated the texture development in cold extruded Al–Pb composites. Additionally Böcker and Bunge (1988) determined the degree of internal deformation in the harder Al phase by quantitative SEM measurements. It was found that texture as well as the degree of internal deformation in the aluminium decreases with an increase in the amount of the softer Pb phase. For cold extruded Al–Cu composites the deformation texture was studied by Ratke, Seifert and Wassermann (1984) and Brokmeier *et al.* (1988). The measurements were restricted to composites with a maximum Cu content of 60 vol.%. In the present work composites with larger Cu amounts were investigated including pure copper which is the harder phase in this system.

EXPERIMENTAL PROCEDURE

For the production of the Al–Cu composites commercial purity aluminium and copper powders were used with a purity of 99.5% and 99.9% respectively. The powder was sieved to a fraction of 45–315 μm and a mean grain size of about 100 μm. Homogenous powder mixtures were then compacted by uniaxial pressure of 100 MPa. The composition of the mixtures varied between pure aluminium and pure copper in steps of 10 vol.% Cu. In the case of cold extrusion, the precompacted material was extruded at room temperature to rods of 8 mm diameter (93% reduction in area). In the case of warm extrusion, which took place at 500°C, the degree of deformation was nearly the same (90% reduction in area). From the cold extruded material additional samples were prepared by different heat treatments (1 hour at 200, 300 and 400°C).

The neutron measurements were carried out using the texture diffractometer TEX-2 at the GKSS Research Center. The wavelengths used were 1.167 Å and 1.336 Å. Because of the high penetration depth of neutrons compared with X-rays it is possible to measure the global texture of a sample instead of the surface texture. Consequently, neutrons are appropriate for texture determinations in two phase composites even if the volume fraction of one phase is low (Brokmeier and Bunge, 1988).

In order to determine the texture of the Al–Cu composites, three pole figures (111) (200) and (220) were measured for aluminium and copper whereby a partial overlap between the Cu(111) and Al(200) Bragg reflections occurs. In spite of this overlap it was possible to calculate the ODF with a modified program (Dahms *et al.*, 1988). Because of the fibre texture of the composites only a χ-scan from 0°–90° in steps of 5° was measured to obtain a complete pole figure. Afterwards, the orientation distribution function (ODF) was calculated by the series expansion method (Bunge, 1982) up to a degree of series expansion of $l_{even} = 22$.

RESULTS

Cold Extruded Al–Cu Composites

Figure 1 shows the texture development of aluminium in cold extruded composites represented by inverse pole figures. Compared with the inverse pole figures of copper (Figure 2) it can be seen that the double fibre texture in pure copper is essentially sharper than in pure aluminium. In both phases the ⟨111⟩ direction forms the main texture component and the ⟨100⟩ direction the minor component. Therefore, these components are used for the description of textural changes within a sample series. Figure 3 shows the texture development within the cold extruded sample series as a function of the material composition for both aluminium and copper. Between pure aluminium and Al–10%Cu the degree of orientation of the Al⟨111⟩ component decreases from 10.66 mrd to 7.86 mrd. Thus, the deformation texture of the aluminium is slightly disturbed by the presence of copper. Apart from the slight increase at Al-70%Cu, which cannot be understood at present, the Al texture remains nearly constant with increasing Cu content. At low amounts of copper the Al phase has to flow turbulently around the harder Cu particles, and the Al texture becomes considerably weaker in these regions. With increasing volume fraction of copper the turbulent regions also increase. On the other hand the degree of deformation of the aluminium increases, since the distance between the Cu particles decrease.

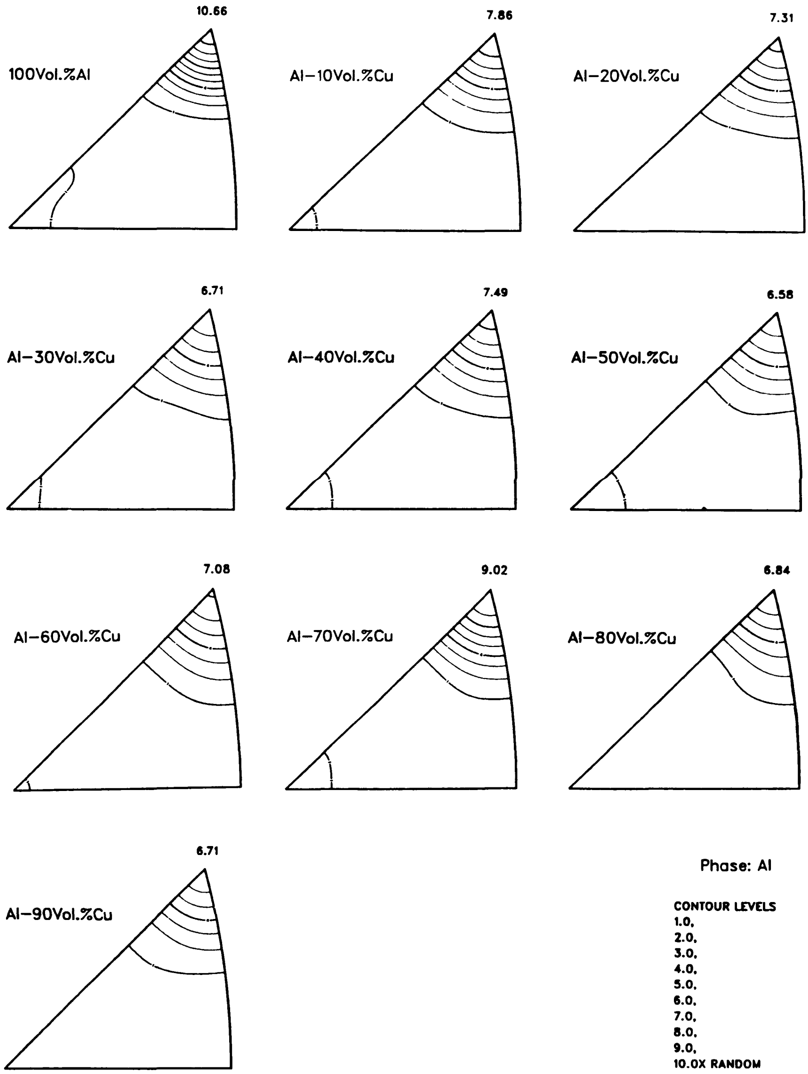


Figure 1 Inverse pole figures of aluminium in Al–Cu composites extruded 93% at room temperature.

In contrast to aluminium, the Cu texture becomes continuously sharper with increasing Cu content. It rises from 6.48 mrd in Al–10%Cu to 18.19 mrd in pure copper. In samples with low Cu amounts the deformation of the Cu particles is rather small, because of the low shear force of the soft Al matrix (Figure 4). With increasing Cu content the decrease in the distance between the Cu particles leads to an additional strengthening of the Al Phase (Figure 5). This effect and the increase in Cu-Cu boundary surfaces results in a larger deformation of the Cu phase and consequently to sharper Cu texture.

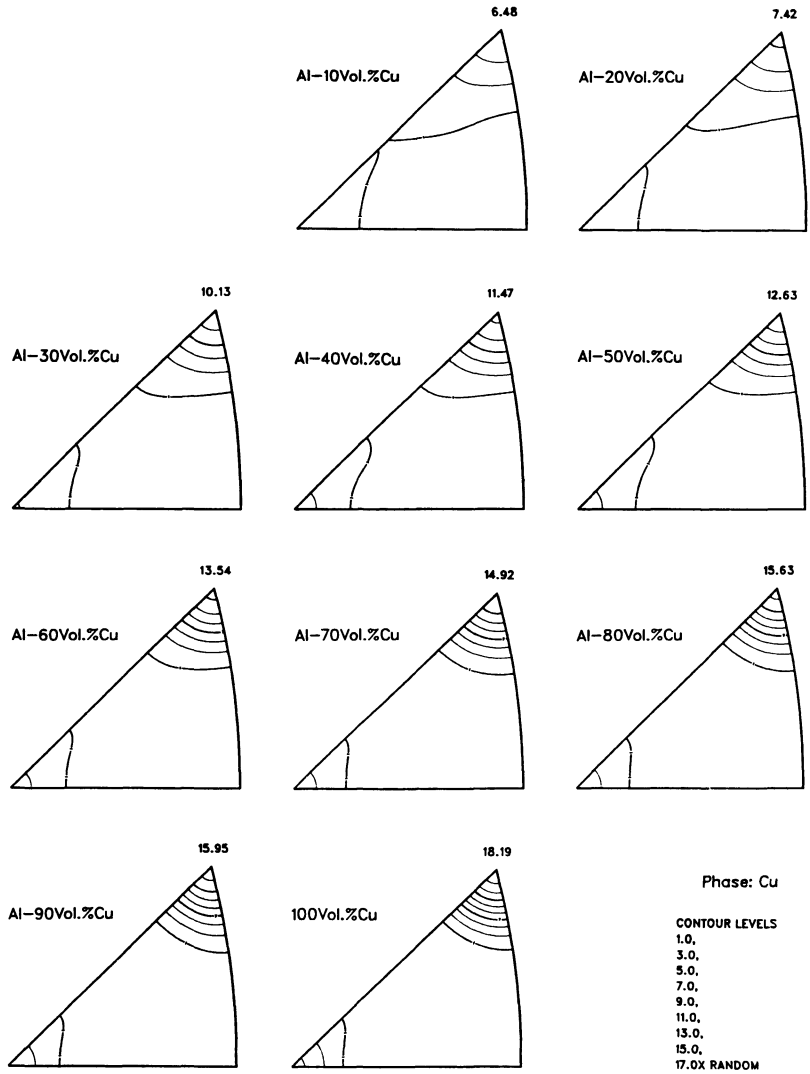
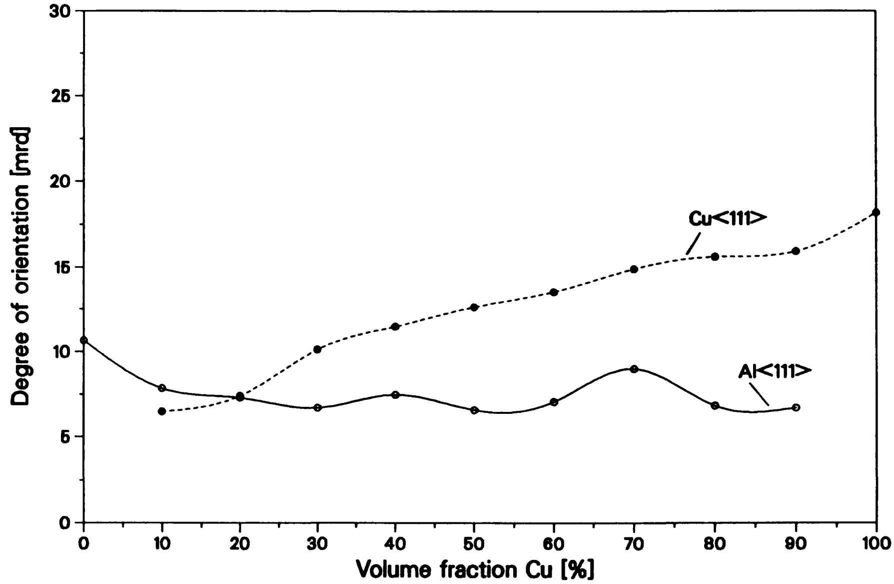
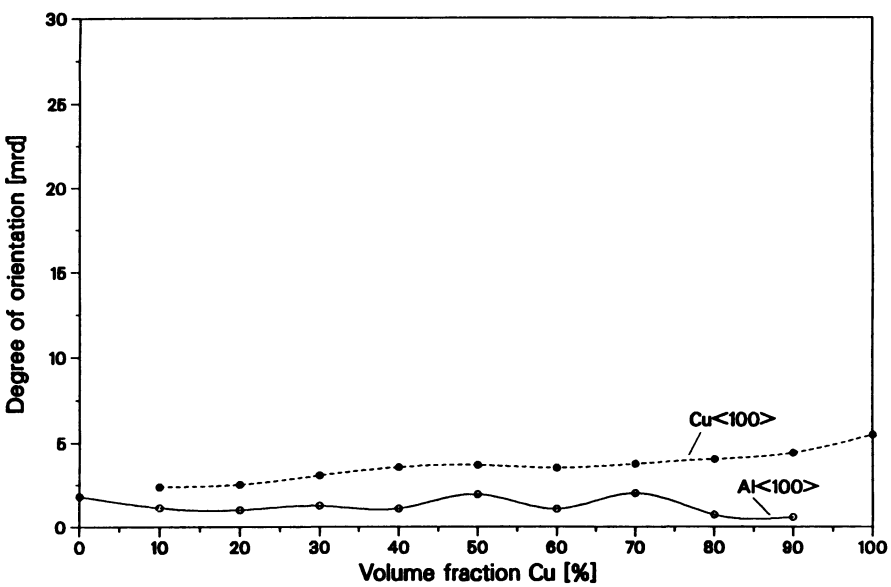


Figure 2 Inverse pole figures of copper in Al–Cu composites extruded 93% at room temperature.

Ratke, Seifert and Wassermann (1984) have found that the Cu texture in samples with 20, 40 and 60 vol.% Cu and a degree of deformation of 93% is always the same. This would mean that the Cu content has no influence on the Cu texture. However, such behaviour of the Cu phase cannot be confirmed by the present work. This may be due to the higher accuracy of neutron diffraction as compared to X-ray diffraction used in these former measurements.



(a)



(b)

Figure 3 Texture development of Al⟨111⟩ and Cu⟨111⟩ (a) as well as Al⟨100⟩ and Cu⟨100⟩ (b) as a function of the composition of the cold extruded samples.

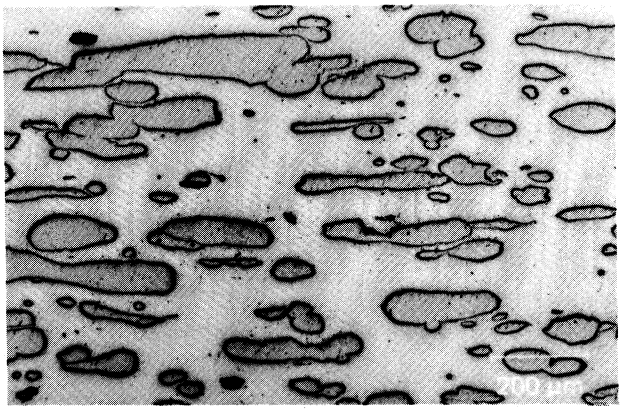


Figure 4 Longitudinal section of cold extruded Al-20%Cu; dark phase: Cu.

Influence of Heat Treatment

Figure 6 shows the degree of orientation of Al⟨111⟩ plotted versus the material composition for different annealing temperatures. The label "deformed" signifies the cold extruded sample series which is the original material of the annealed series. At low Cu volume fractions the shape of the curves is similiar, but owing to measuring inaccuracy at low Al volume fractions a slight divergence occurs at higher Cu concentrations. There is no doubt that the Al texture remains stable after annealing. Neither the Al⟨111⟩ nor the Al⟨100⟩ component exhibit a change in their spread about the ideal orientation. Moreover, new texture components were not observed. Although the microstructure of pure aluminium annealed for 1h at 400°C does not show recrystallization, samples containing copper showed recrystallized areas which grow with increasing Cu amount. In Al-50%Cu the whole Al phase is recrystallized (Figure 7). It can be concluded that aluminium recrystallizes and retains the deformation texture.

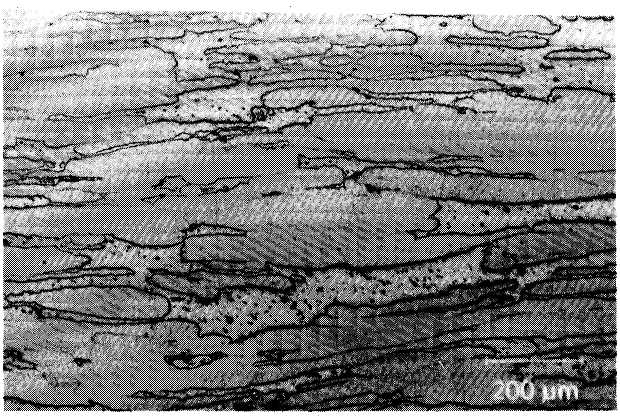
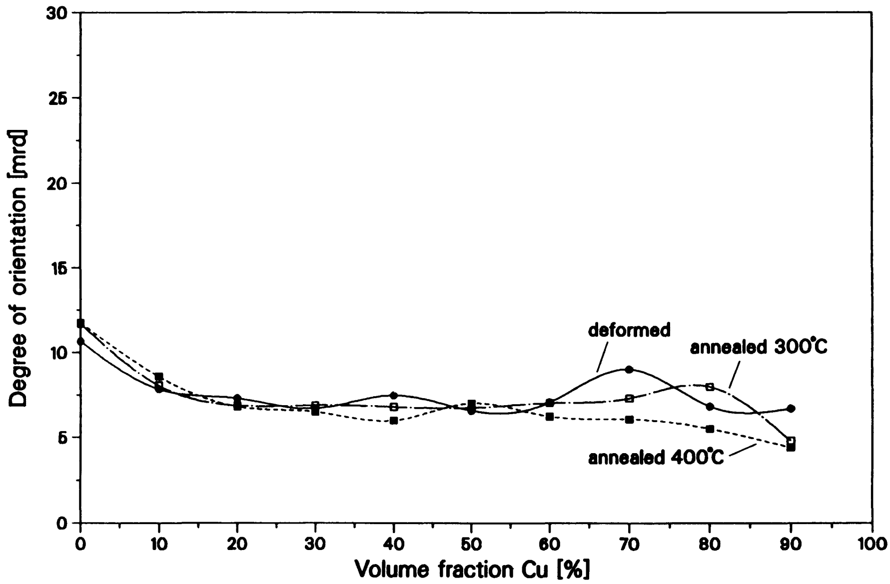
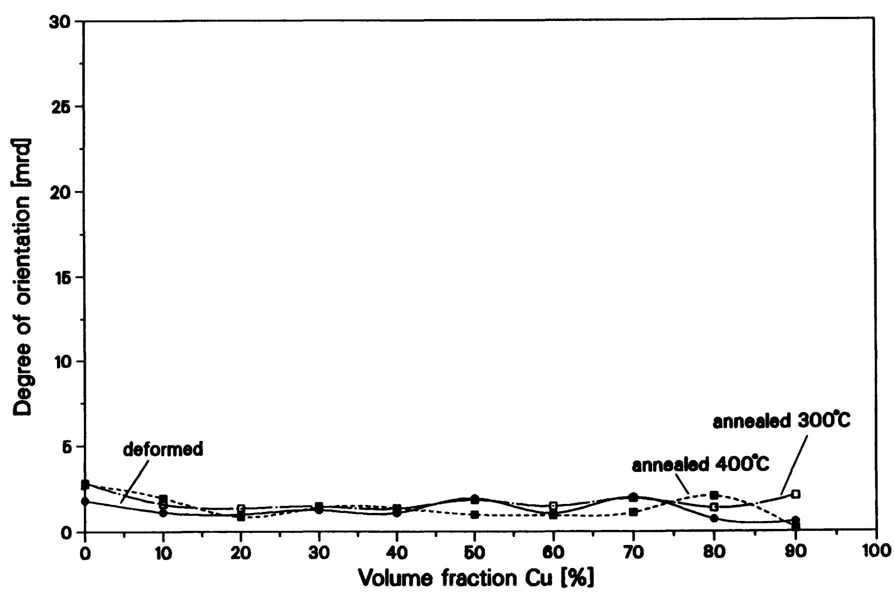


Figure 5 Longitudinal section of cold extruded Al-50%Cu; dark phase: Cu.



(a)



(b)

Figure 6 Texture development of Al⟨111⟩ (a) and Al⟨100⟩ (b) as a function of heat treatment and sample composition.

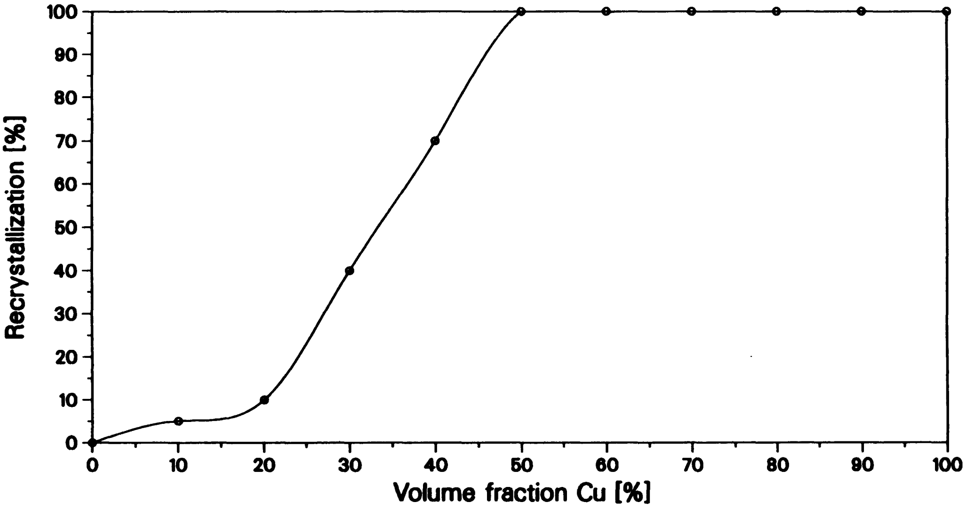


Figure 7 Degree of recrystallization of aluminium in Al-Cu composites annealed for 1h at 400°C after cold extrusion; as estimated from the microstructure.

An additional texture analysis of pure aluminium annealed for 1 h at 500°C has also shown that the deformation texture remains unchanged. From texture investigations on rolled single crystals and polycrystalline material it is known that for fcc metals a 40° ⟨111⟩ orientation relationship between the deformation and recrystalization texture exists (Lücke, 1984). Obviously the texture behaviour of extruded aluminium can be explained by such a growth selection, because the ⟨111⟩ texture component lies parallel to the fibre axis and a 40° rotation consequently effects no change of texture.

Figure 8 shows the texture development of the Cu phase as a function of the annealing temperature. During annealing at 300°C and 400°C the Cu texture becomes very much weaker. The degree of orientation is almost constant with increasing Cu concentration. In pure copper annealed at 400°C the degree of orientation of the ⟨111⟩ component decreases from 18.19 mrd to 3.10 mrd. In Figure 9 the microstructure of pure copper annealed for 5 h at 400°C is shown. The sample was etched with nitric acid in order to make the grain boundaries visible. Because of the low stacking fault energy of copper ($\gamma_{ST} = 0.07\ \mathrm{Jm}^{-2}$), the microstructure exhibits to a large extent recrystallization twins. Probably, the weakening in texture can be explained by the subsequent formation of recrystallization twins to higher generations (Gottstein, 1984). This mechanism leads to the formation of new orientations with all possible orientation relationship to the original position. From the sample series annealed at 300°C and 400°C it can be observed that the double fibre texture ⟨111⟩ and ⟨100⟩ only becomes weaker during annealing, but additional and with it new texture components are not formed. In other words, the recrystallization leads to a gradual reduction of the deformation texture while simultaniously the amount of randomly oriented crystallites increases. Especially in samples with high Cu concentrations the weakening in texture is considerable, as the internal deformation degree of

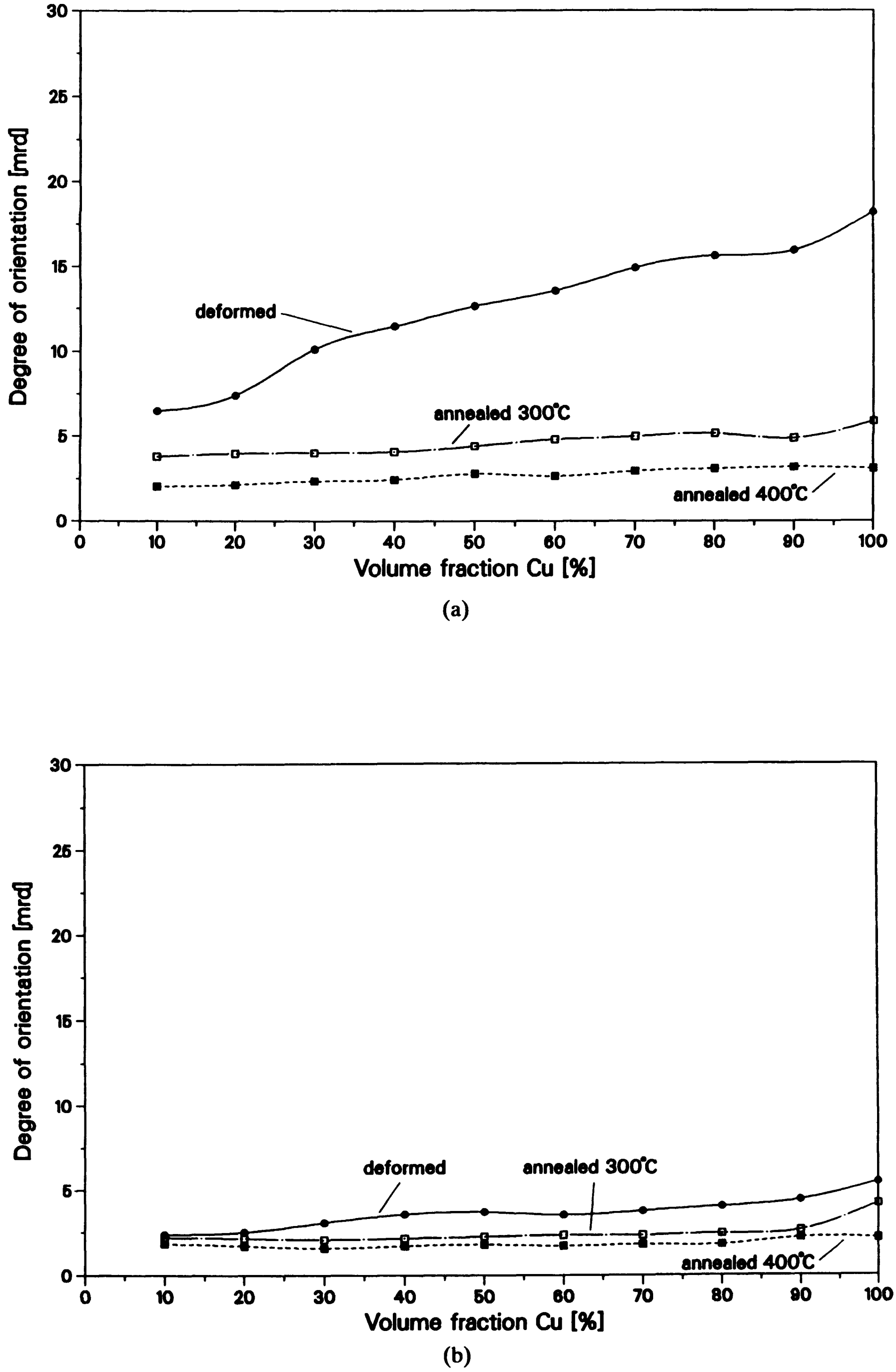


Figure 8 Texture development of Cu⟨111⟩ (a) and Cu⟨100⟩ (b) as a function of heat treatment and sample composition.

Figure 9 Longitudinal section of pure copper annealed for 5h at 400°C after cold extrusion; the extrusion direction lies horizontal.

copper rises with increasing Cu amount. Hence, the recrystallization is accelerated owing to the increase of energy in the Cu phase.

Warm Extruded Al–Cu Composites

The Al texture of Al–Cu composites produced by warm extrusion is essentially weaker than in cold extruded samples. The inverse pole figures of aluminium shown in Figure 10 are representative of the warm extruded samples series. Figure 11 shows the texture development of Al⟨111⟩ within the warm extruded sample series compared to the cold extruded one. It can be seen that the Al texture of the warm extruded sample series becomes weaker in the presence of copper and remains constant with increasing Cu content, i.e. the Al texture

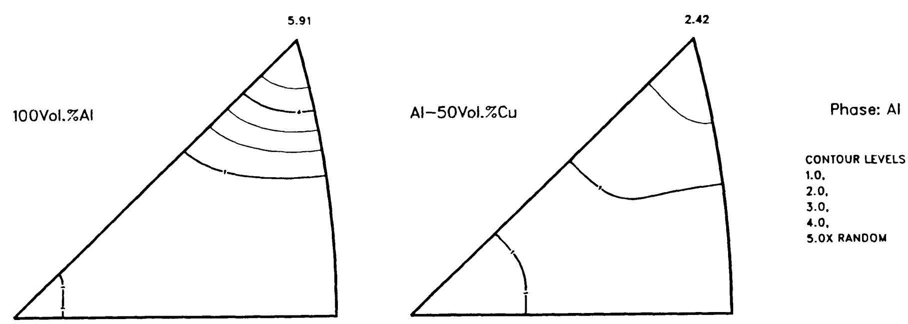
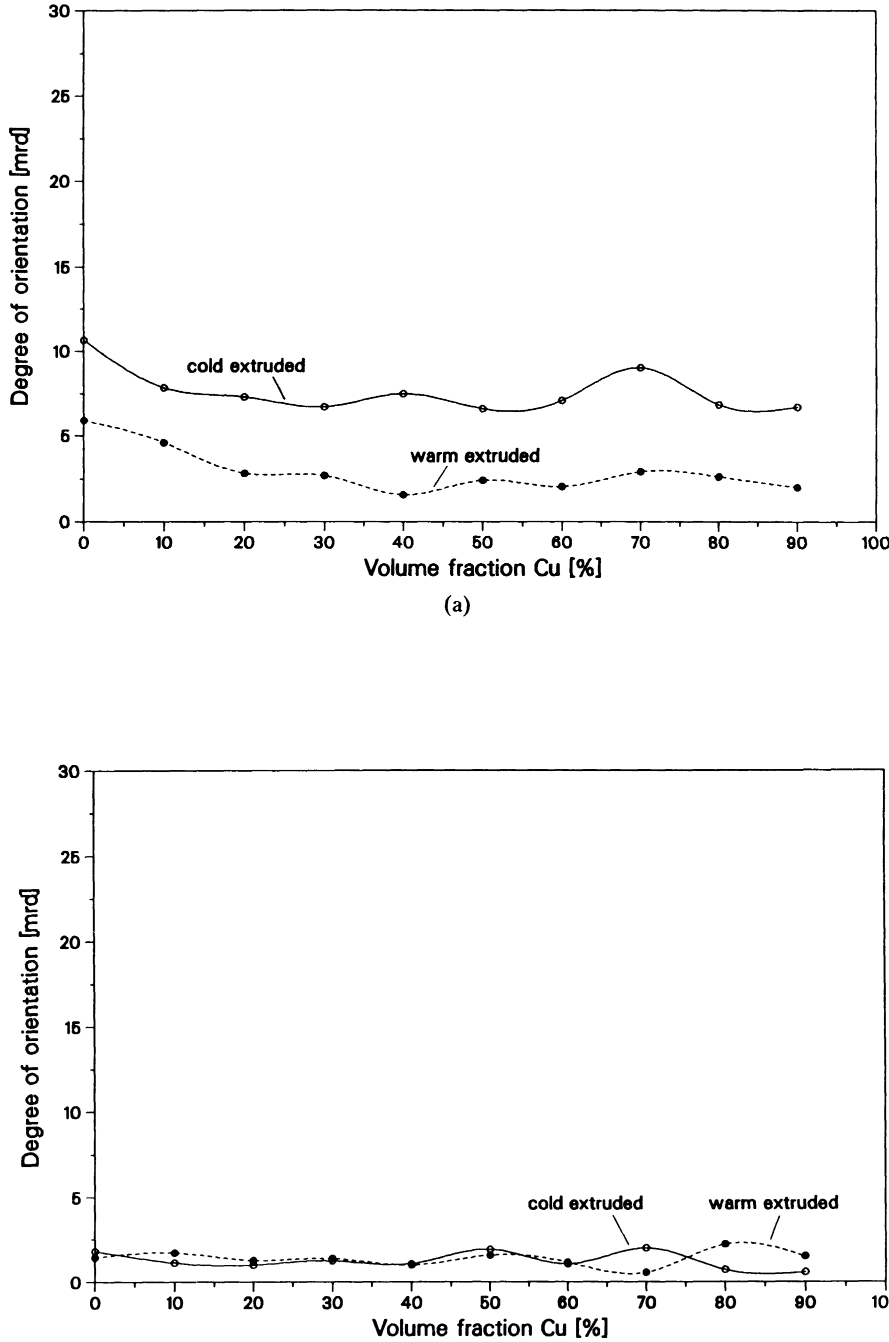


Figure 10 Inverse pole figures of aluminium in pure aluminium and Al-50%Cu extruded 90% at 500°C.



(a)

(b)

Figure 11 Texture development of Al⟨111⟩ (a) and Al⟨100⟩ (b) as a function of the composition of the cold and warm extruded samples.

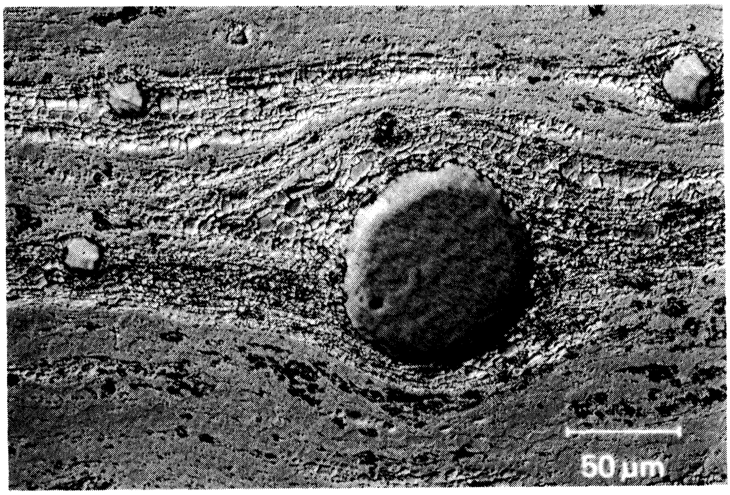


Figure 12 Recrystallized microstructure of aluminium in Al-20%Cu after warm extrusion; section parallel to the extrusion direction.

exhibits the same behaviour as in the cold extruded sample series. The degree of orientation in the warm extruded sample series is generally about 2.5 times lower than in the cold extruded one.

By etching the samples with NaOH, H_2SO_4 and HF, it was possible to observe the recrystallized microstructure of aluminium. The longitudinal section of warm extruded Al-20%Cu (Figure 12) reveals that the Al phase is only recystallized within the regions of turbulent flow, i.e. around the Cu particles. Between the Cu particles no recrystallization occurs because of the smaller deformation in these regions and the high stacking fault energy ($\gamma_{ST} = 0.2\,\mathrm{M\,m^{-2}}$) of aluminium. It is assumed that the dislocations formed during warm extrusion are subjected to

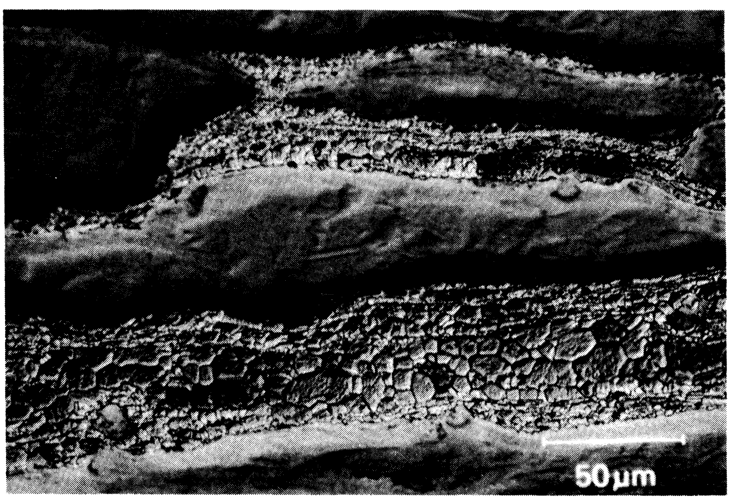


Figure 13 Recrystallized microstructure of aluminium in Al-70%Cu after warm extrusion; section parallel to the extrusion direction.

strong recovery processes so that the dislocation density necessary for recrystallization is not reached in the lower deformed regions. With increasing Cu amount the recrystallized regions increase up to Al-70%Cu where the Al phase is completely recrystallized (Figure 13). In Figure 14 the degree of recrystallization of aluminium is plotted against the composition. The high fraction of recrystallized regions in Al-10%Cu is remarkable and cannot be explained at the moment.

As the metallographic observations have shown that pure aluminium does not recrystallize during warm extrusion it can be excluded that recrystallization is the reason for the weaker texture after warm extrusion. Furthermore, it is evident from the heat treatments (cf previous section) that the deformation texture of aluminium is not influenced by recrystallization. Thus, the weaker Al texture in warm extruded Al-Cu composites can be only attributed to the weaker deformation, dependent on the processing conditions (warm extrusion, slightly lower deformation degree). The deformation forces needed for warm extrusion are lower than for cold extrusion since the yield stress decreases with increasing temperature.

The texture behaviour of copper within the warm extruded sample series is represented in Figure 15. It appears that the degree of orientation of Cu⟨111⟩ is very low and remains nearly constant with increasing Cu content. The average degree of orientation is approximately 2 mrd. Such a weak texture has been already observed in cold extruded samples annealed for 1 h at 400°C (cf previous section) and it can be concluded that in the case of warm extrusion recrystallization is also responsible for the texture behaviour of copper. Another possibility would be the weaker deformation of the warm extruded samples compared to the cold extruded material. But then the degree of orientation of Cu⟨111⟩ would be expect to increase with increasing Cu content, since the degree of deformation of the Cu phase also increases within the warm extruded sample series. Figure 16

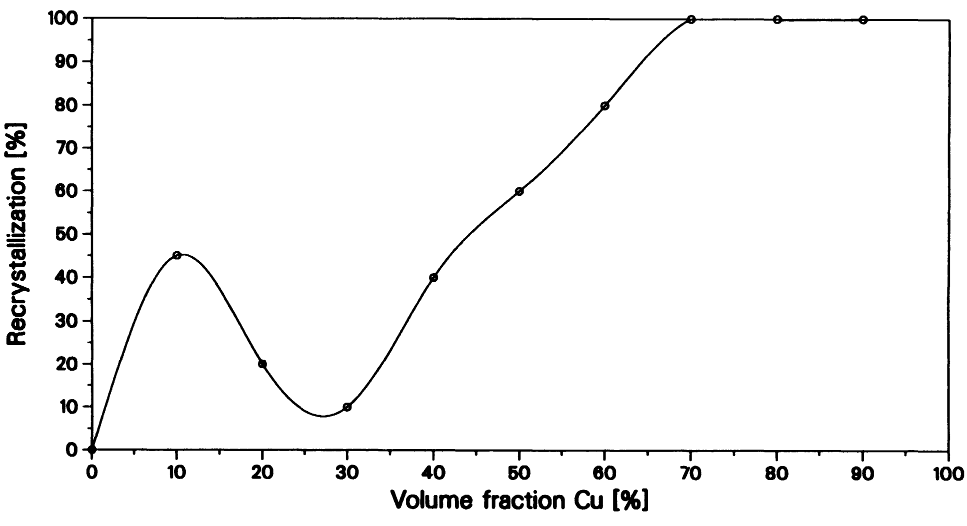
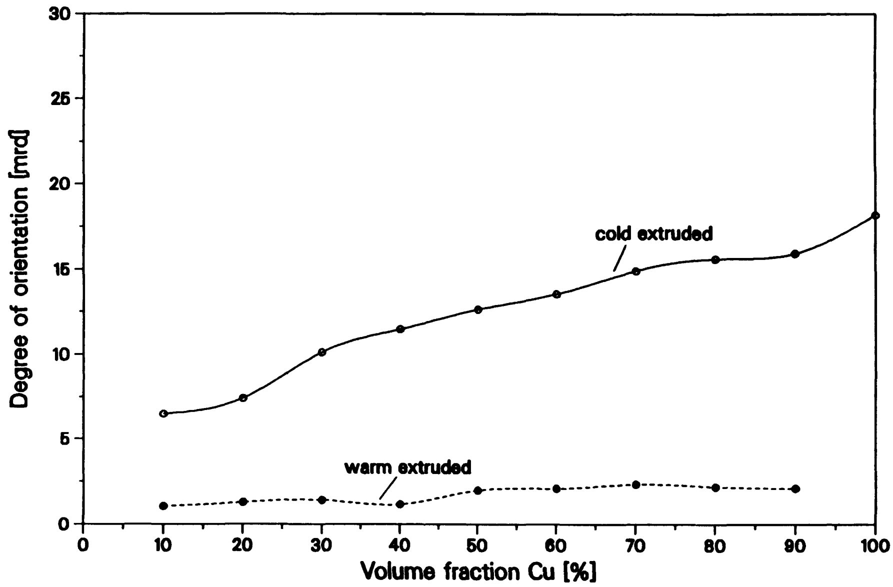
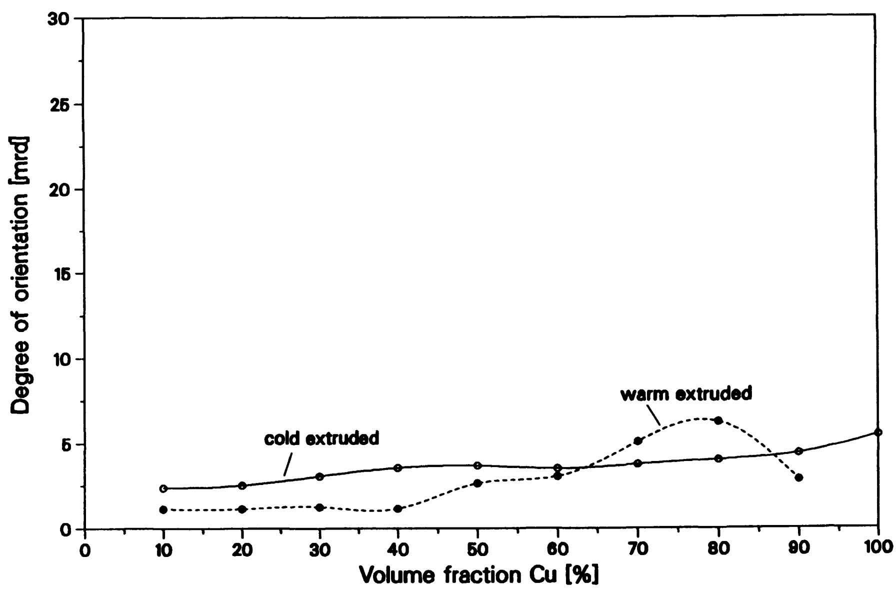


Figure 14 Degree of recrystallization of aluminium in warm extruded Al–Cu composites; as estimated from the microstructure.

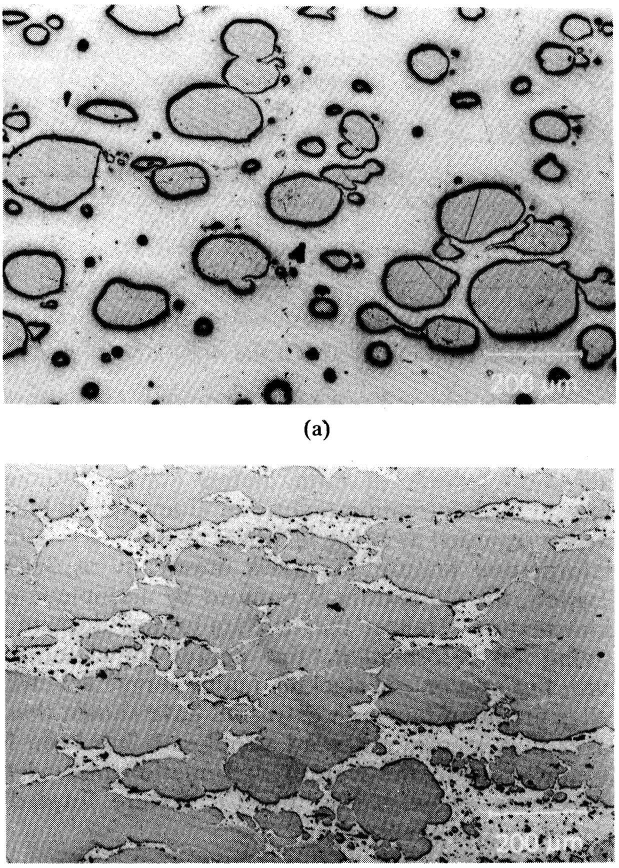


(a)



(b)

Figure 15 Texture development of Cu⟨111⟩ (a) and Cu⟨100⟩ (b) as a function of the composition of the cold and warm extruded samples.



(a)

(b)

Figure 16 Longitudinal sections of warm extruded Al-20%Cu (a) and Al-50%Cu (b) dark phase: Cu.

shows the microstructures of warm extruded Al–20%Cu and Al–50%Cu. In Al–20%Cu the shape of the Cu particles is approximately spherical i.e. they are nearly undeformed.

In all previously discussed cases the ⟨100⟩ direction forms the minor texture component. Only in this case does the CU⟨100⟩ component become stronger than Cu⟨111⟩ with a systematic increase between Al-40%CU and Al-80%Cu (Figures 15 and 17). In order to clarify the reason for this unexpected increase further investigations are necessary.

CONCLUSIONS

It has been found that in cold extruded Al–Cu composites prepared by powder metallurgy the deformation texture of both phases corresponds to a double fibre texture ⟨111⟩ and ⟨100⟩. In the presence of copper the Al texture becomes

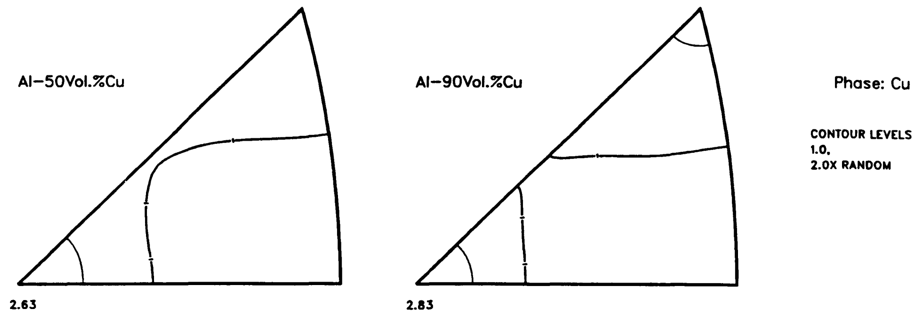


Figure 17 Inverse pole figures of copper in Al-50%Cu and Al-90%Cu extruded 90% at 500°C.

weaker and remains constant with increasing Cu content whereas the Cu texture increases continously. Heat treatments of cold extruded samples have revealed that the recrystallization texture of both metals differs, although the lattice structure is the same. The deformation texture of aluminium is stable for all heat treatments and can be regarded as being identical to the recrystallization texture. In copper the deformation texture decreases drastically at 300°C and 400°C. During recrystallisation, the Cu texture is reduced by multiple twin formation in favour of a random texture. Hence, the recrystallization texture does not only depend on the kind of deformation, the degree of deformation and the deformation texture, but also on the stacking fault energy. Texture investigations in Al–Cu composites prepared by warm extrusion have shown that the Al texure is very much weaker than in cold extruded samples. It has been found that this behaviour can be attributed to the weaker deformation instead of recovery or recrystallization processes. Nevertheless, the Cu texture formed during warm extrusion is influenced by recrystallization.

Acknowledgement

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