

Influence of degree of deformation in rolling on anneal hardening effect of a cast copper alloy

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Abstract. This paper reports results of investigations carried out on a cast copper alloy containing 8 at.% Al. The alloy, and pure copper for the sake of comparison, were subjected to cold rolling with a final reduction of 30, 50 or 70%.

The cold rolled copper and copper alloy samples were isochronally and isothermally annealed up to the recrystallization temperature. The hardness, strength and electrical conductivity were measured and X-ray and DSC analyses performed.

Anneal hardening effect was observed in the alloy in the temperature range 180–300°C, followed by an increase in the electrical conductivity. The amount of strengthening increases with increasing degree of prior cold work. The X-ray analysis shows a change in the lattice parameter during annealing when anneal hardening effect was observed. The DSC analysis shows the exothermic character of this effect.

Keywords. Degree of deformation; anneal hardening; cast copper alloy.

1. Introduction

The strength properties of cold-worked substitutional solid solutions increased upon annealing up to the recrystallization temperature in several Cu based alloy systems. This strengthening effect is termed anneal hardening and is mainly applied to copper alloys when producing spring materials for electro-mechanical devices. Three general trends can be noted which characterize the phenomenon in all alloy systems. The amount of strengthening, which accompanies ageing, increases with increasing degree of prior cold work; the strengthening increases with increasing substitutional solute concentration; the strengthening due to ageing is a decreasing function of the plastic strain at which the strength is measured (Bader *et al* 1976; Vitek and Warlimont 1979).

The mechanism responsible for this hardening effect is investigated in several copper based alloys after cold rolling and annealing at 150–300°C. The effect has been investigated mainly in cast copper base alloys and some observations have been interpreted as indicating that atomic ordering is primarily responsible for the hardening effect (Zehtebauer 1976). On the other hand, in a detailed investigation of anneal hardening in Cu–Al alloys (Bader *et al* 1976), it was concluded that solute segregation to dislocations is the predominant hardening mechanism. However, the mechanism responsible for this hardening effect is not fully understood (Vitek and Warlimont 1979).

This anneal strengthening effect is also observed in several sintered copper based alloys (Nestorovic *et al* 1997, 2002; Nestorovic and Markovic 1999, 2001).

2. Experimental

A cast copper alloy containing 8% Al is selected for the present study. For comparison, parallel investigation has been carried out on specimens made from cast pure copper.

Copper and copper alloy weighing ~ 2 kg, were melted in a furnace and cast in copper molds with dimensions 80 × 80 × 30 mm. The cast alloys were homogenized at 850°C for 24 h. Samples with dimension 80 × 30 × 7 mm were cut from the homogenized material. Cold rolling was carried out on these samples with intermediate anneals at 500°C for 1 h, a heat treatment of 500°C for 2 h, followed by an ice-water quench. After that the copper and copper alloy were subjected to cold rolling with different final reduction of 30, 50 and 70%.

The cold rolled copper and copper alloy samples were isochronally and isothermally annealed up to recrystallization temperature, during which the values of hardness, strength and electrical conductivity were measured. X-ray analysis was also performed.

3. Results and discussion

3.1 Cold rolled cast samples

The hardness of the samples during cold rolling increases with deformation due to strain hardening (figure 1).

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Higher hardness values were obtained for alloy due to solid solution hardening. Maximum value of hardness for copper is 126 HV and for alloy, 207 HV (deformation degree, 70%).

Figure 2 shows the changes of electrical conductivity during cold rolling. It can be seen that the electrical conductivity for pure copper is higher than in the alloy. Also figure 2 shows that the electrical conductivity of the alloy slowly decreases with the deformation degree. However, it is known that the increase in cold working results in a decrease in electrical conductivity.

3.2 Annealed cold rolled cast samples

Figure 3 shows the dependence of hardness on annealing temperature for the copper and copper alloy samples with deformation degree—30, 50, 70%. It can be seen that the recrystallization temperature for copper for all applied deformation degrees is above 200°C, but for the alloy, it is above 350°C for all deformation degrees; i.e. the alloying element Al cause an increase in the recrystallization temperature of pure copper.

Figure 3 shows that in the temperature range of 180–300°C, for the alloy, the hardness value increases at all deformations (30, 50, 70%). At 240°C the hardness values increase by about 9 HV for deformation degree of 30%, by 19 HV for deformation degree of 50% and by 30 HV for deformation degree of 70%. The hardness values increase remarkably for 70% deformation in the alloy. This can be explained by the fact that the amount of strengthening effect i.e. anneal hardening effect increases with increasing degree of prior cold work (Nestorovic *et al* 1997; Nestorovic and Markovic 1999, 2001).

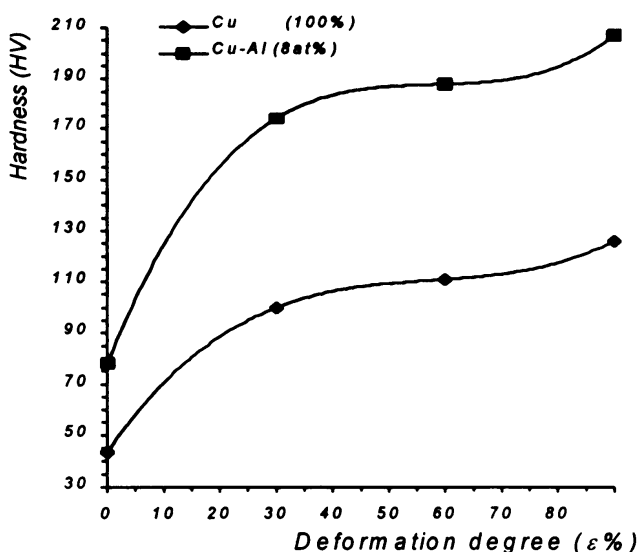


Figure 1. Dependence of hardness of cold rolled samples on deformation degree.

This effect has been investigated mainly in the cast copper-base alloys containing Al, Ni, Au, Ga, Pd, Rh and Zn. The results would tend to support the hypothesis that solute segregation to dislocation, analogous to the formation of Cottrell atmospheres in interstitial solid solutions, is primarily responsible for anneal hardening phenomenon (Vitek and Warlimont 1979).

During annealing the samples after cold rolling, the electrical conductivity of copper slowly increases with annealing temperature due to recovery and recrystalliza-

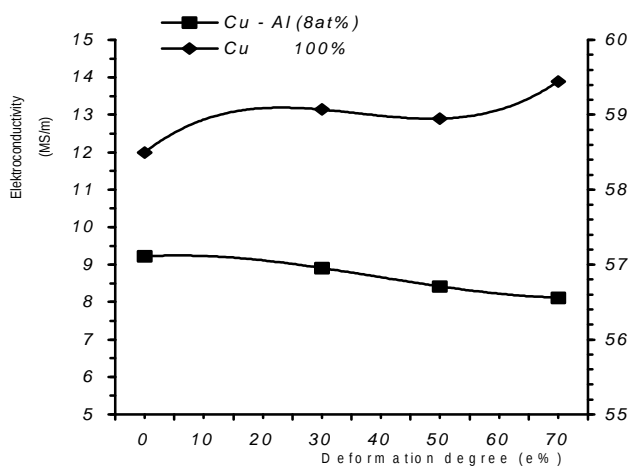


Figure 2. Dependence of electrical conductivity of cold rolled samples on deformation degree.

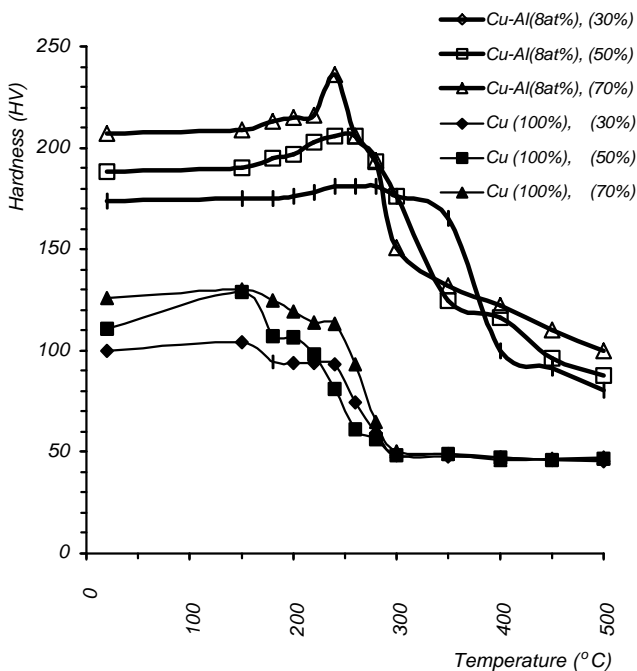


Figure 3. Hardness of cold-rolled samples of copper and copper alloy with annealing temperature.

tion. The electrical conductivity of the alloy increases above 220°C, due to the anneal hardening effect. Bader *et al* (1976) obtained similar results by electrical resistivity measurements.

Figure 5 shows the change in hardness with annealing time at 240°C for 70% deformation. It can be seen that the hardness increases for 30, 60, 120, 150 min, due to anneal hardening effect and after that decreases slowly with annealing time. After 5 h the hardness values are somewhat higher than for cold rolled state. It can be explained by the fact that anneal hardening effect has

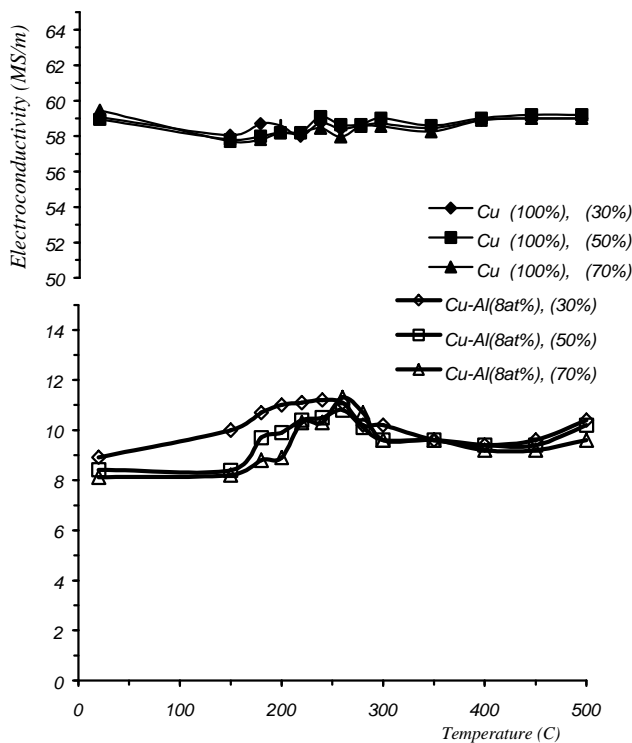


Figure 4. Electrical conductivity of cold-rolled samples of copper and copper alloy with annealing temperature.

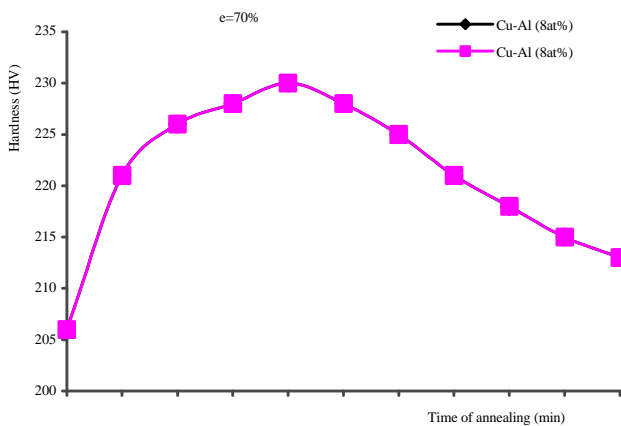


Figure 5. Hardness of cold-rolled samples as a function of time of annealing at 240°C.

influence on recrystallization temperature. After 120 min of annealing the maximum hardness values increase due to anneal hardening effect by about 30 HV. After 300 min of annealing, recrystallization still does not seem to have occurred, because the value of hardness is higher than for cold rolled state.

Figure 6 shows the change of electrical conductivity up to an annealing time of 300 min at 240°C, for the alloy. It can be seen that electrical conductivity increases for the first 30 min due to anneal hardening effect and after that, it only slowly increases.

Finally, some property changes other than hardening response during annealing may be considered in support of solute segregation to dislocations. In the previous investigation of anneal hardening of a CuAl alloy (Bader *et al* 1976), it was shown that the major decrease in electrical resistivity during annealing cannot be accounted for by short range ordering. It was concluded that segregation to dislocations is the only consistent interpretation for the major portion of the change in resistivity.

Figure 7 shows the exothermic effect of deformed specimens of Cu–Al upon heating, as revealed by DSC analysis. The exothermic heat effect is found in the temperature range 210–300°C where the anneal hardening effect is also observed.

The lattice parameter changes in the alloy during annealing, have also led to the conclusion that solute clustering at dislocations should be one of the major causes of the observed changes.

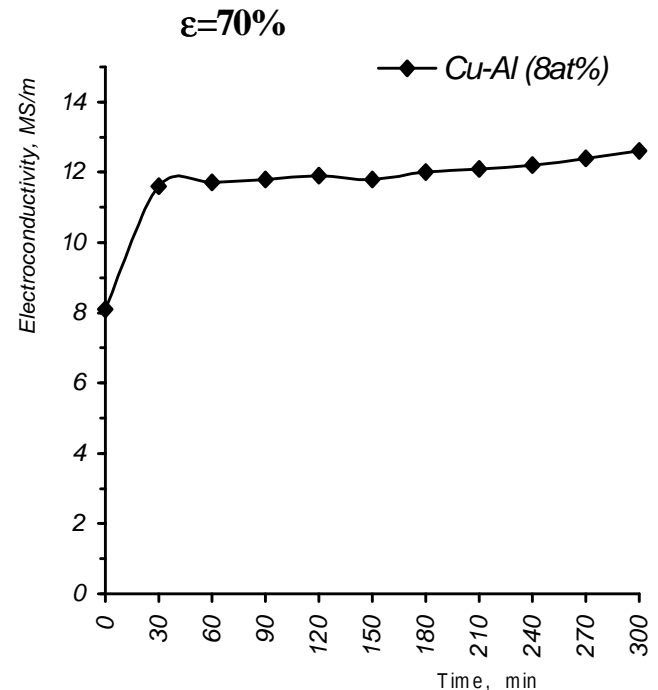


Figure 6. Electrical conductivity of cold-rolled samples of copper alloy as a function of time of annealing at 240°C.

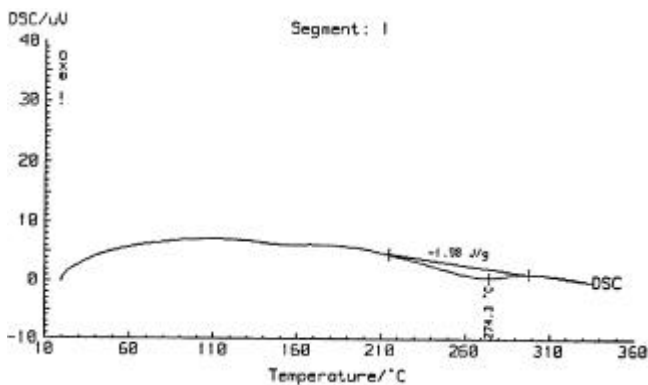


Figure 7. DSC for cold rolled samples of Cu–Al alloy deformed to 70%.

The anneal hardening effect is well known in Cu based solid solution alloys. This is due to the fact that these alloys are widely used as spring contact materials where strength in the elastic/plastic limit is of primary significance and has, therefore, been investigated extensively. Anneal hardening has also been found in the Al–Cr system where a size misfit of about 5 pct exists, similar to the magnitude of the misfit in the Cu–Rh system.

4. Conclusions

(I) The alloying element, aluminium, is found to have a pronounced effect on the increase in the recrystallization temperature of copper.

(II) The anneal hardening effect was observed in the Cu–Al alloy in the temperature range 180–300°C, and is accompanied by an increase in electrical conductivity.

(III) The amount of strengthening increases with increasing degree of prior cold work.

(IV) The maximum value of hardness was attained at 70% deformation.

(V) Anneal hardening may be considered as a genuine hardening mechanism in analogy with the other basic hardening mechanisms such as work, grain size, solid solution and dispersion hardening.

(VI) The results can be applied to derive the composition and processing variables which determine the strengthening effect of copper alloys.

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