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Effect of internal oxidation on the mechanical properties of a Cu–Co–Si alloy

L. S. TÓTH, I. KOVÁCS, J. LENDVAI
Institute for General Physics, Loránd Eötvös University, Budapest, Hungary

B. ALBERT
Csepel Metal Works, Budapest, Hungary

The mechanical properties of an internally oxidized Cu–Co–Si alloy of wire form was studied by torsional deformation. It is found that as a result of the internal oxidation the ageing heat-treatments lead to the formation of regions with cylindrical symmetry which have significantly different mechanical properties.

1. Introduction

It is well-known that in Si-containing copper alloys, SiO_2 particles are formed in internal oxidation [1, 2]. The structure of these spherical particles is amorphous and they strongly influence the plastic behaviour of the material by obstructing the motion of dislocations [3]. In the present paper we report on the investigation of the mechanical properties of an internally oxidized Cu–Co–Si alloy. It will be shown that as a consequence of the internal oxidation in wire samples, regions with cylindrical symmetry are formed with significantly different plastic properties.

2. Experimental details

The specimens used in the investigations were 150 mm long wires of 1.5 mm diameter with composition of Cu–0.63 at% Co–0.27 at% Si. For solution-treatment the samples were kept for 1 h at 960° C in a protecting atmosphere. During the ageing heat-treatments at 400, 500 and 600° C the specimens were encapsulated in hermetically sealed copper tubes of 2 mm i.d.

After heat-treatment, the specimens were tested by simultaneous torsion and extension. The torsion tests were performed at 78 K in liquid nitrogen. The tensile force was produced by calibrated springs. Other details of the method have been described elsewhere [4]. On the specimens deformed by torsion up to failure, microhardness measurements and metallographic investigations by both optical and scanning electron microscopy were carried out.

3. Results

After solution heat-treatment, the specimens contained 100 to 200 μm large grains. On the metallographic picture of the cross-section of the specimens deformed by torsion, etch lines characteristic of the torsional deformation could be observed. The etch lines of roughly radial direction appeared most pronounced near the surface of the specimen.

Fig. 1 shows the metallographic picture of a sample heat-treated for 1 h at 400° C and then deformed by torsion up to failure ($\gamma = 2.5$).

After the 500° C heat-treatment, a hetero-

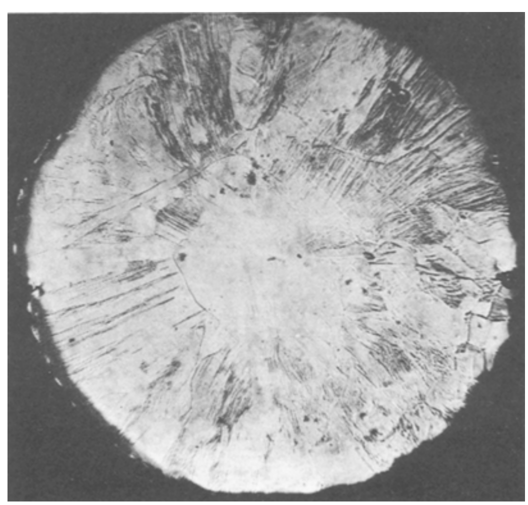

Figure 1 Metallographic picture of the cross-section of a sample deformed by torsion up to failure after ageing at 400° C for 1 h (X 46).

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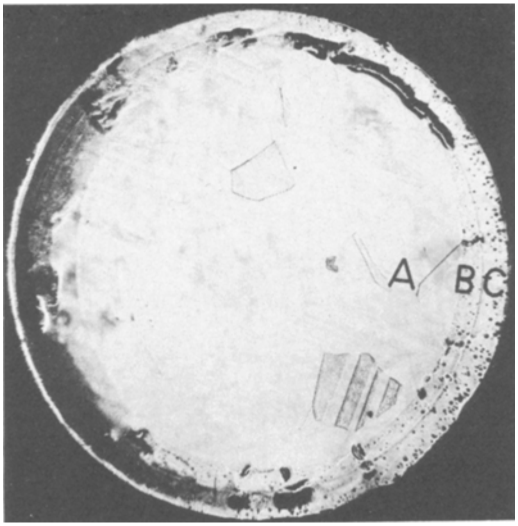

Figure 2 Metallographic picture of the cross-section of a sample after ageing at 500° C for 30 min (X 46).

geneous structure was observed in the cross-section of the specimens. Fig. 2 shows the metallographic picture after 30 min heat-treatment at 500° C. In the photograph three zones can be clearly distinguished, which are designated A, B and C in the figure. In Fig. 3 microhardness indentations obtained by applying 0.5 N load are shown in the same cross-section. It can be seen that the hard-

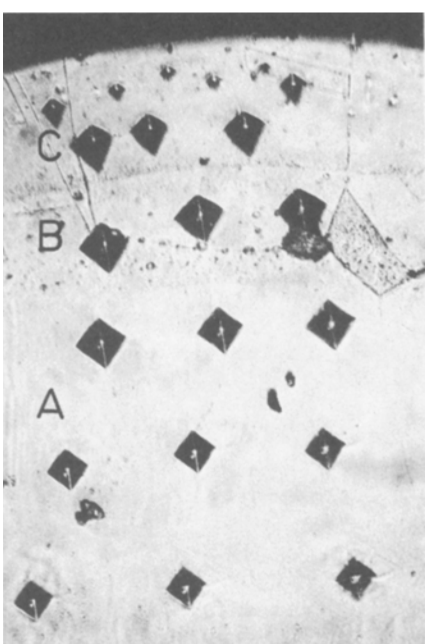

Figure 3 Microhardness indentations obtained by 0.5 N on the sample shown in Fig. 2.

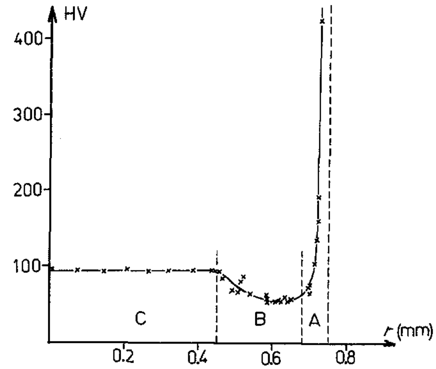

Figure 4 Microhardness as a function of the radius of the sample shown in Fig. 2.

ness is greatest in zone A, while it is smallest in zone B. The changes in the Vickers hardness along the radius of the specimen are shown in Fig. 4. The heterogeneous character of the specimens remains unchanged during torsional deformation, which is clearly demonstrated by the metallographic picture of a specimen deformed by torsion up to fracture (Fig. 5).

The formation of the different regions is a consequence of the internal oxidation taking place during the solution heat-treatment. By comparing Figs 1 and 5 it is clear that there is no significant effect of the previous internal oxidation on the precipitation process taking place during the 400° C ageing heat-treatment. In the following paragraphs we shall characterize in more detail the specimen aged at 500° C for 15 min and then deformed by torsion up to fracture. The hetero-

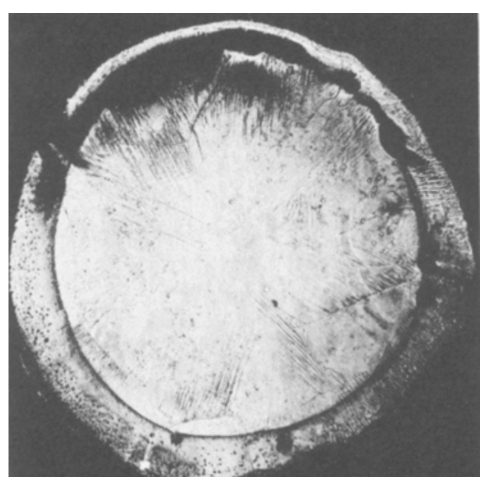

Figure 5 Metallographic picture of the cross-section of a sample deformed by torsion up to fracture after ageing at 500° C for 30 min.

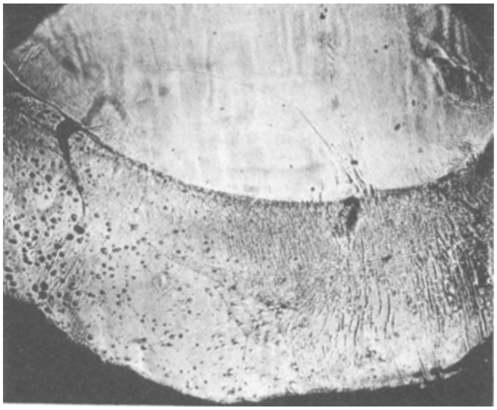

Figure 6 The heterogeneous structure of a sample aged for 15 min at 500° C (X 93).

geneous structure can be observed in this case too (Fig. 6). It can be seen in the figure that the failure of the specimen takes place along the boundary of zones B and C and along grain boundaries in zone A. The scanning electron micrograph taken from the same fracture surface clearly supports this statement (Fig. 7).

Fig. 8 shows the metallographic picture taken from a longitudinal section of the same specimen. The heterogeneity of the material is also shown in this figure; it can also be observed that the boundary of zones B and C cuts through the grains.

The heterogeneous structure also appears in the case of the specimen aged for 12 h at 500° C (Fig. 9), but the zones are somewhat eccentrically positioned. It is remarkable that both in Figs 7 and 9 a large number of second-phase particles can be observed in regions A and B, which indicates a compositional difference with respect to zone C. By comparing the metallographic pictures of the samples aged for different periods of time

Figure 7 Scanning electron micrograph taken from the fracture surface of the sample shown in Fig. 6 (X 46).

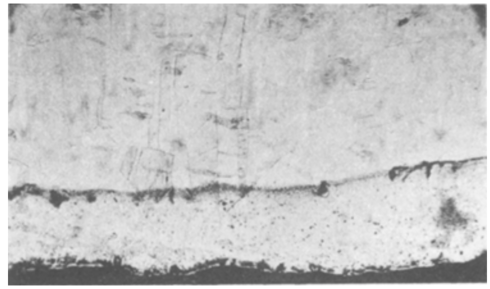

Figure 8 Longitudinal section of the specimen shown in Fig. 6 (X 185).

at 500° C (Figs 5, 6 and 9) it can be inferred that the size of the different regions is independent of ageing time, which shows clearly that the difference in the precipitation structure of the different zones is a consequence of the internal oxidation, taking place during the solution heat-treatment.

The same phenomena were observed in the course of the 600° C heat-treatment so we will not enter into the details of the results obtained on such samples.

The fracture of the samples deformed by torsion takes place generally in two steps. Failure first occurred at grain boundaries in the outer A and B regions and some excessive torsional deformation was required to induce rupture in region C. Failure also occurred at different sites along the length of the specimen. In such cases, zone C could be pulled out from the tubular A–B region (Fig. 10).

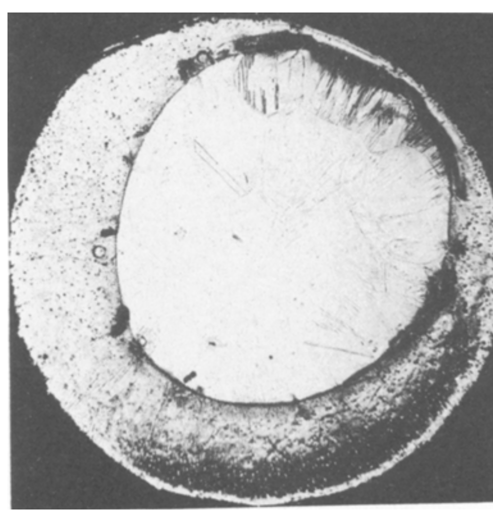

Figure 9 Heterogeneous structure along the cross-section of a sample aged at 500° C for 12 h.

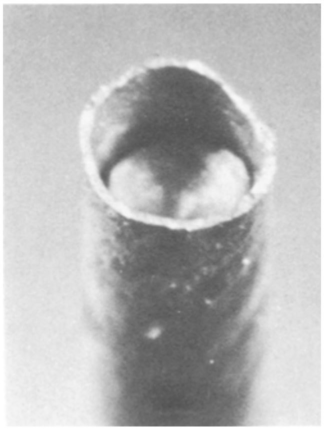

Figure 10 The shape of a sample fractured by torsional deformation.

4. Discussion and conclusions

On the basis of the experimental results we can conclude that in the internally oxidized zone of the specimen formed during the solution heat-treatment at 960° C, precipitation during the successive 500 or 600° C ageing heat-treatments takes place in a significantly different way from in the oxide-free region of the matrix. For this reason the strength and the hardness of the material vary considerably along the cross-section. The hardness is highest along the front of internal oxidation which is situated near to the surface of the sample. It seems probable that the oxide particles provide dispersely distributed preferred sites for the nucleation of precipitates and so most of the solute atoms in the internally oxidized zone (region A) precipitate within a relatively short period of time forming dispersely distributed precipitate particles. The number of nucleation sites in the inner region of the specimen is smaller, so during the same period of time only a smaller fraction of the solute atoms precipitates. The difference in the solute concentration results in a diffusional flow of solute atoms towards the outward region of the specimen. The reduction in solute concentration is strongest in the outer region of the unoxidized part of the specimen (zone B), therefore this zone is softer than zones A and C. In the innermost zone C the precipitation takes place by normal nucleation, therefore, on the boundary of zones B and C the changes in hardness are slower than on the boundary of zones A and B (Fig. 4), and in zone C the hardness is lower than in the internally oxidized zone A.

Torsional deformation is very suitable for investigating the mechanical properties of the heterogeneous structure produced by internal oxidation in wire samples since the symmetry of the deformation fits that of the internally oxidized structure. The yield stress of the material, however, is likely to change similar to the microhardness which makes the description of the torsional deformation process very difficult. For a more detailed description of the deformation process further investigations are needed.

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