JOURNAL OF MATERIALS SCIENCE 5 (1970) 492-494

Mechanical Twinning in Copper-29.9 at.% Gold Single Crystals

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Three copper-gold single crystals containing 29.9 at. % gold and having the disordered, Cu_3Au I and Cu_3Au II structure respectively, were deformed in tension at room temperature, at dry ice temperature (just into the plastic region) and at liquid nitrogen temperature (until fracture) successively.

For Cu_3Au I and Cu_3Au II τ_{00} does not vary practically with composition, being four times that of stoichiometric Cu_3Au [6]. At 78° K twinning was observed in the elastic region for Cu_3Au II, whereas Cu_3Au I twinned only under the influence of complex stresses; the disordered alloy showed no twinning at all.

The strain-hardening θ_{II} at 78° K is almost the same for Cu_3Au I and Cu_3Au II at the 20.9 at. % composition.

Twinning in pure metals and metallic solid solutions during mechanical testing is normally accompanied by audible clicks and load drops on the stress-strain curve. On the other hand the occurrence of these phenomena does not necessarily imply that twinning has taken place, e.g. in ordered structures, in which the condition that the twinned portion of the crystal is a mirror image of the parent crystal cannot be fulfilled. The question as to whether the term twin may be used in this case has given rise to some discussion [1, 2]. In 1952 Laves [3] predicted that mechanical twinning in ordered cubic crystals is not possible and he proposed [1] that the word "pseudo-twin" should be used, e.g. for the stress-induced shear process occurring in Fe_3Be [4]. Despite the difference between the classical mechanical twins and the twin-like behaviour of superlattices the term twinning has been employed for treating twin-like phenomena in ordered structures [5]. No other word will be adopted here for describing the deformation characteristics in Cu_3Au I and Cu_3Au II structures of the copper-29.9 at. % gold alloy, resembling twinning.

A copper-gold single crystal containing 29.9 at. % gold (further indicated as $Cu_{70}Au_{30}$) of 4 mm diameter was prepared in a vacuum-sealed (10^{-5} torr) quartz tube by a modified Bridgman technique. The growth speed was 4 cm h^{-1} and the furnace temperature gradient amounted to about 50° C cm^{-1}. The crystal was easily removed from the mould, electropolished in a solution of chromic acetic acid and its singleness checked with Laue back-reflection photographs.

Subsequently the single crystal was spark-cut into three tensile specimens which had the disordered, the Cu_3Au I and the Cu_3Au II structure respectively.

TABLE I Heat-treatments required for obtaining the structures indicated

Structure	Heat-treatment
Disordered	water-quenched from 400° C
Cu_3Au I	16 days at 300° C; water quenched
Cu_3Au II	7 days at 340° C; water-quenched

The applied heat treatments are given in table I. The Cu_3Au II structure was checked by a rotating crystal X-ray diffraction photograph and the orientation of the single crystals determined by the back-reflection Laue technique.

Each specimen was then tested in tension at three different temperatures as follows: first, deformed until the end of the elastic region at room temperature, the load was removed and the sample was cooled in crushed dry ice; deformed again at this temperature just into the plastic region; finally the sample was deformed until fracture in liquid nitrogen.

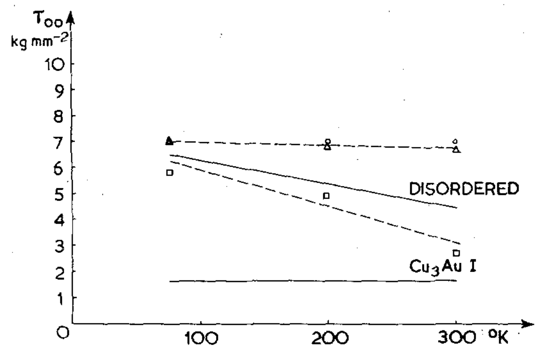

Figure 1 Variation of τ_{00}, determined at the first noticeable departure from the elastic slope, with temperature for a copper 29.9 at. % gold alloy having the disordered, the Cu_3Au I and Cu_3Au II structures. □, disordered; △, Cu_3Au I; ○, Cu_3Au II, present work, τ_{00}, $Cu_{70}Au_{30}$ composition. —, Davies and Stoloff [6], τ_0, Cu_3Au composition included for comparison.

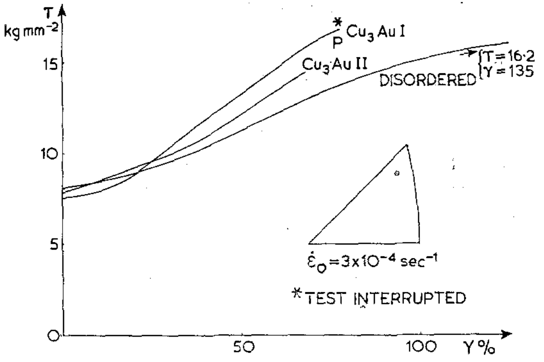

Figure 2 Shear stress-shear strain curves of copper-29.9 at. % gold crystals in the disordered condition and having the Cu_3Au I and Cu_3Au II structures.

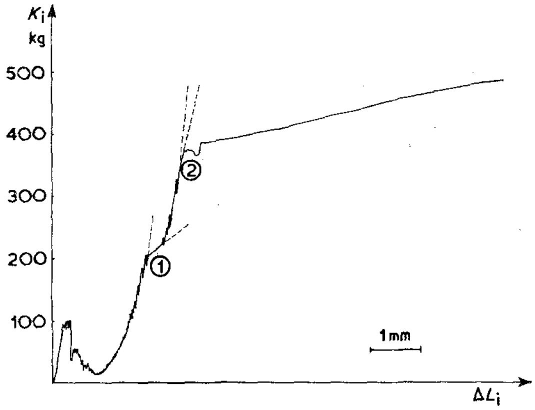

Figure 3 Load-elongation curve of Cu_3Au I showing serrations due to twinning. 1, lowering the strain rate to 3.5×10^{-5} sec^{-1}. 2, increasing the temperature.

The change of τ_{00}* versus temperature is plotted in fig. 1; the results of Davies and Stoloff [6] for the critical resolved shear stress τ_0 have been included for comparison. Fig. 2 gives the shear stress-shear strain curves at 78° K for the three structures together with their orientation.

The strain-hardening in the second part of the shear stress-shear strain curve θ_{II} at 78° K for the three structures is given in table II.

At point P of the shear stress-shear strain curve (fig. 2) for Cu_3Au I the test was interrupted, the specimen was remounted, the stress axis being non-coincident with the specimen axis and the test continued at 78° K. This mounting probably will cause complex stresses and facilitate twinning in an analogous way to pre-straining 90° to the stress axis [8].

Fig. 3 represents the as-recorded load-elongation diagram and displays numerous load drops, normally indicative of twinning. The twinning, accompanied by crackling sounds, started at a shear stress of about 2.8 kg mm^{-2}.

Decreasing the strain rate or increasing the temperature for a short time during the test stopped the twinning and the strain-hardening associated with the glide decreased (fig. 3). Re-

TABLE II Strain hardening θ_{II} for Cu_3Au at 78° K

Composition / Structure	$Cu_{70}Au_{30}$ θ_{II} (g mm^{-2})	$(\theta_{II}/G\dagger) \times 10^3$	Cu_3Au Davies and Stoloff [6] θ_{II} (g mm^{-2})	$(\theta_{II}/G\dagger) \times 10^3$
Disordered	10 049	2.21	10 488	2.30
Cu_3Au I	14 416	3.11	10 254	2.21
Cu_3Au II	13 560	—	—	—

*τ_{00} is the shear stress on the primary glide system at the first perceptible departure from the elastic part.
†$G = [C_{44}(C_{11} - C_{12})/2]^{1/2}$ from the work of Flinn, McManus and Rayne [7].

straining at the original conditions made twinning reappear.

The specimen, having the Cu_3Au II structure, was tested in the normal way at 78° K and twinned easily in the elastic region at about the same shear stress (i.e. 2.6 kg mm^{-2}) as the Cu_3Au I structure. However, only five clicks were heard in the elastic region and no load-drops could be detected on the curve. During the plastic deformation twinning sounds were observed from time to time but no load-falls accompanied these events. In the specimen with the disordered structure no twinning occurred at all.

Summarising we can say:

(i) The temperature-dependence of the critical resolved shear stress for Cu_3Au crystals [6] appears to be the same as for $Cu_{70}Au_{30}$ crystals (this work) both in the disordered and in the Cu_3Au I condition. However, the slope of the line for the disordered structure is steeper for the $Cu_{70}Au_{30}$ than for the Cu_3Au crystals and the non-stoichiometric Cu_3Au I structure is about four times stronger than the stoichiometric structure.

The first difference may perhaps be approached by considering the excess gold atoms as solute atoms in a "pure" structure Cu_3Au I and producing an analogous effect as solute in a pure metal. The increase of yield stress, due to deviations from stoichiometry, has been reported earlier [9] for polycrystalline copper-gold alloys.

(ii) τ_{00} of the Cu_3Au II structure in $Cu_{70}Au_{30}$ does not vary with temperature and is almost the same as for the Cu_3Au I structure of the same composition.

(iii) The strain-hardening θ_{II} at 78° K for the disordered structure is nearly the same for the Cu_3Au and for the $Cu_{70}Au_{30}$ compositions (table II). For the Cu_3Au I structure it is about 40% higher for the $Cu_{70}Au_{30}$ than for the Cu_3Au alloy in a similar structure. The Cu_3Au II structure has approximately the same θ_{II} as the Cu_3Au I structure for the $Cu_{70}Au_{30}$ composition.

(iv) Twinning in Cu_3Au I has not been observed for the Cu_3Au alloy [6]. It occurred in the $Cu_{70}Au_{30}$ alloy having the same structure, though the stresses needed for it are probably high. In the present work twinning could be produced at 78° K under the influence of complex stresses.

(v) Cu_3Au II was observed to twin at 78° K and for the $Cu_{70}Au_{30}$ composition, but the twins were very fine (they did not produce any observable load-drop and could only be heard), and relatively scarce.

The two last points may indicate that twin nucleation is favoured by deviations from stoichiometry.

(vi) No twinning was observed in the disordered $Cu_{70}Au_{30}$ alloy.

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Received 20 February and accepted 13 March 1970.