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THE ROLLING TEXTURE OF Cu_3Au†

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The rolling texture of Cu_3Au has been investigated by X-ray diffraction. At room temperature, independently of the degree of long-range order, Cu_3Au developed a mixed or "hybrid" texture; it consisted of elements of each of the prototype face-centered cubic textures characterized by pure copper and 70/30 brass. However, on rolling at 77 K the alloy in the disordered state was significantly more "brass-like" than when it was fully ordered. This result may be explained by a stacking fault energy texture reversal analogous to that observed in wire drawing at low SFE. The lack of twinning (or other deformation mechanism such as slip by partial dislocations) in the ordered alloy could be responsible for this reversal.

INTRODUCTION

The development of texture during cold-rolling of fcc metals and alloys has been a subject intensively studied during the past quarter of a century.[1] Such materials are usually classified according to whether they develop a "copper-type" or a "brass-type" texture. Transitions from one kind of texture to the other may be affected by altering the alloy content[2] or in the same alloy by changing the deformation temperature[3] or deformation rate.[4] There is substantial evidence[1] that "copper-type" textures are associated with high stacking fault *energies* (SFE) or low stacking fault *frequencies*, whereas "brass-type" textures are associated with low SFE or high stacking fault *frequencies*.

A copper-25 at. % gold alloy in the chemically disordered state is fcc. Camanzi *et al.*[5] observed that when this alloy was quenched and aged, vacancy clustering caused prismatic dislocation loops to form in the disordered regions of the alloy but *faulted* loops resulted when the region showed some chemical order. Earlier Mikkola and Cohen[6] measured by X-ray diffraction the stacking fault frequency of Cu_3Au and found higher frequencies in specimens that had a higher degree of order. Marcinkowski and Zwell[7] observed stacking faults by transmission electron microscopy in ordered Cu_3Au but not when it was disordered. All these observations suggested a lower SFE for the ordered state and led to speculation[8] that ordered Cu_3Au might develop a "brass-like" texture on rolling whereas the disordered alloy should probably show a "copper-like" texture.

Two experiments[8,9] designed to investigate this possibility have been presented thus far. Starke *et al.*[8] reported that long-range order had a marked effect on the rolling texture of Cu_3Au at intermediate (40 to 50%) rolling reductions. In this range of deformation the texture of the initially ordered alloy was thought to be "brass-like" while further rolling suggested a return to the more "copper-like" texture characteristic of the disordered alloy. Dillamore and Stoloff[9] examined both ordered and disordered Cu_3Au rolled up to 95% reduction at room temperature and found only slight texture differences between these. They stated that pole figures for both materials were significantly different from those previously published for copper and 70/30 brass, however, the textures were thought to more closely resemble brass.

In an effort to clarify some of the uncertainties raised by these investigations, further experimental study of the Cu_3Au alloy was undertaken. This paper presents the results of these experiments. We determined the texture evolution of initially disordered, partially ordered, and fully ordered stoichiometric Cu_3Au as a function of rolling deformation up to 96% reduction in thickness. Rolling was carried out at both room temperature and 77 K. For comparison purposes, the prototype

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textures of OFHC copper and a commercial 70/30 brass were also obtained.

EXPERIMENTAL PROCEDURE

A 100-g ingot of the Cu_3Au alloy was prepared by induction melting appropriate amounts of 99.999% pure copper and gold together in a graphite boat under a vacuum of 10^{-6} torr. After eight zone leveling passes the alloy was unidirectionally solidified, sealed in an evacuated quartz tube containing 1/2 atm. argon and homogenized for 21 days at 1050 K. Strips 2.5 cm wide by 0.125 cm thick were produced from the homogenized ingot by a series of 40 to 50% reductions in area by either compression or cross rolling alternated with recrystallization anneals of 1 hr at 870 K. The final grain size was 2.5 μ. Chemical analysis revealed a gold content of 51.0 wt % whereas exactly stoichiometric Cu_3Au should contain 50.8 wt % gold.

Coupons 2.5 cm by 2.5 cm were cut from the prepared strip, sealed in a Pyrex tube under 1/2 atm. of argon, annealed at 825 K for 45 min and then quenched into ice water. X-ray diffractometer traces revealed no evidence of long-range order in specimens treated in this manner. Some of these coupons were fully ordered by annealing at 625 K for 93 hr, cooling to 585 K at about a 1°/hr rate and then furnaced cooled to room temperature. Other disordered specimens were partially ordered by heat treating in a salt bath at 625 K for various times.

For comparative purposes, 2.5 cm by 2.5 cm by 0.125 cm thick coupons of OFHC copper and 70/30 brass were fabricated from commercial 0.250 in. plate stock by cross rolling to reductions of 30 to 40 pct. alternated with a recrystallization anneal of 1 hr at 600 K for the copper and 725 K for the brass. The final grain size was estimated to be 3 μ for the brass and 4 μ for the copper. A very weak texture was evident in these specimens.

Rolling was carried out on a two-high, hand-operated laboratory rolling mill with 7 cm diameter rolls. Samples were rolled without lubrication to total reductions of between 33 and 96% reduction in thickness at either room temperature or 77 K in the manner described previously.[10] The rolled specimens were chemically polished to remove disturbed surface layers.[8]

The (111), (200), and (220) pole figures were determined by the Schulz reflection technique using a PDP–8 computer-operated, Norelco texture goniometer and nickel-filtered CuK_α radiation. The diffracted intensities were automatically recorded, corrected for background, normalized to data from a random powder of the appropriate material and converted to a pole figure using a program written by Love[11] for the IBM 360–75 computer. The Bragg-Williams long-range order parameter, S, was determined according to the method outlined before.[8]

RESULTS

The texture development of Cu_3Au initially ordered to $S = 0.52$ and rolled at room temperature to 40, 79, and 96% reduction in thickness is presented in the form of (111) and (200) pole figures in Fig. 1. Examination of over 20 Cu_3Au specimens in various states of initial order and then rolled *at room temperature* disclosed no significant texture difference due to different degree of order. The pole figures were always remarkably similar to those shown in Fig. 1 for equivalent rolling reductions. Extensive evaluation of pole figures obtained from samples deformed from 35 to 55% failed to reveal the marked effect reported by Starke *et al.*[8] for ordered material.

Figure 2 compares the (200) pole figure of Cu_3Au with those of 70/30 brass and OFHC copper for room temperature rolling deformations that produced fully developed textures in each case. To discuss similarities and differences between these textures, a description in terms of ideal orientations is useful. Such representations are recognized as being subjective and will vary from researcher to researcher. We propose that the texture be interpreted in terms of low index ideal orientations and continuous ranges of orientations extending from certain of these to others.[10] Each orientation within a given spread shares a common crystallographic direction (RA) with the other orientations in the spread, and thus, is related to the others by a simple rotation about this direction. For example, the copper texture (Fig. 2) which is very ridge-like, may be described as an orientation spread extending between ideal orientations of the type $\{110\}\langle 112\rangle$ and $\{225\}\langle 554\rangle$ as depicted in Fig. 3. In this ideal description, the rotation axes are $\langle 110\rangle$ type directions located at $\pm 60°$ from the normal direction (ND) along the ND to RD (rolling direction) diameter of the pole figure.

The brass texture on the other hand has a major component centered at ideal orientations of the type $\{110\}$ $\langle 112\rangle$. The brass pole figure also strongly suggests a spread of orientations from

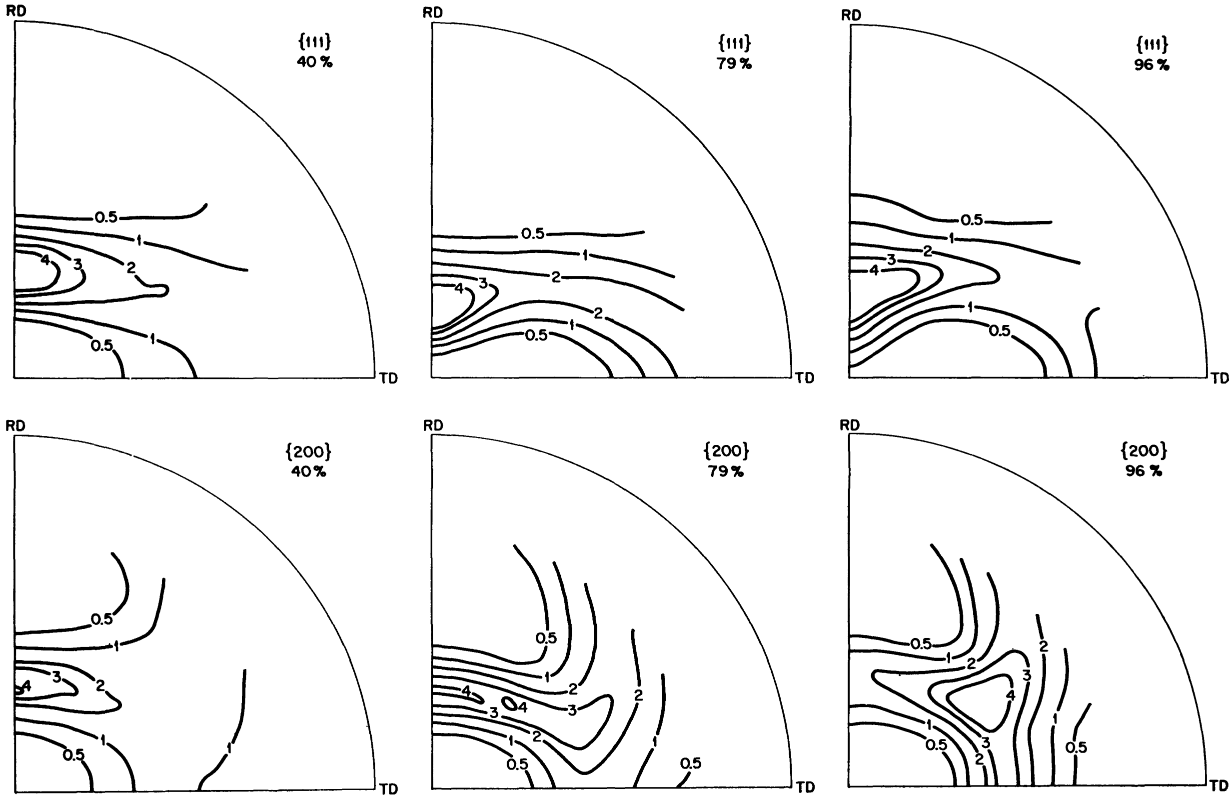
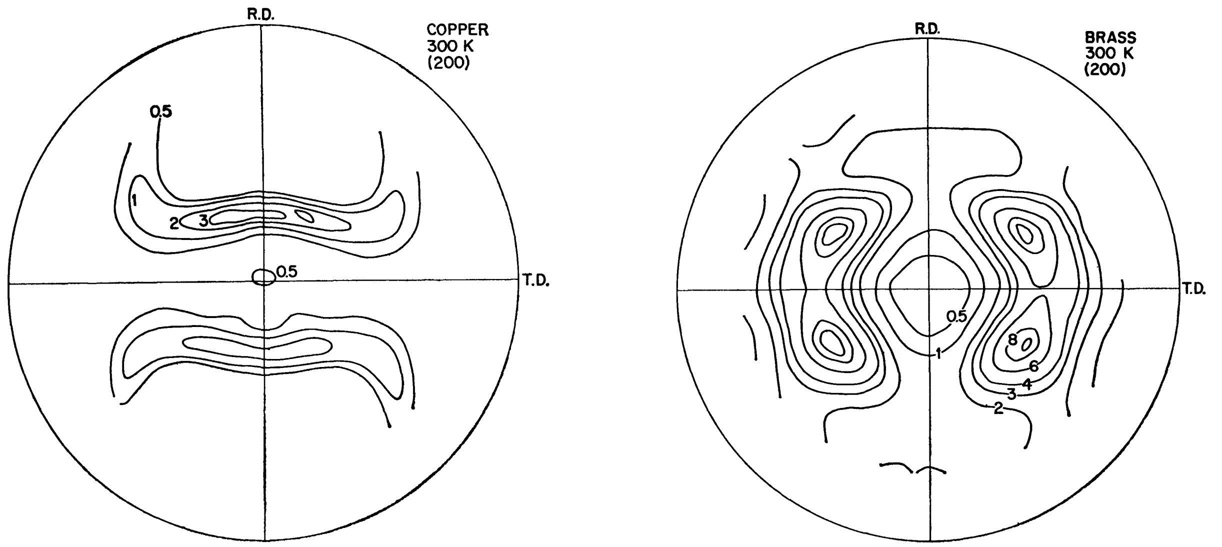
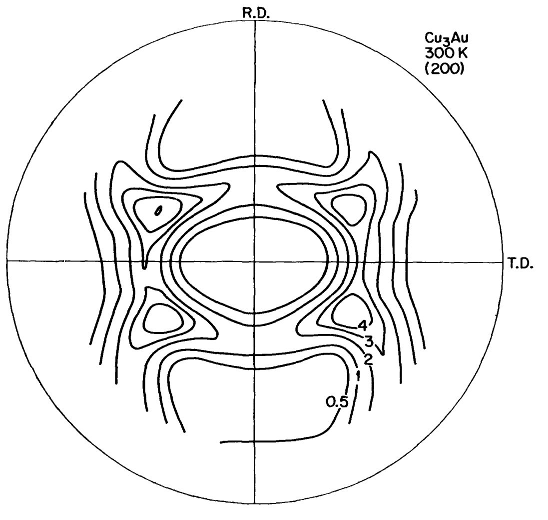


FIGURE 1 Texture of Cu_3Au rolled 40, 79 and 96 pct reduction in thickness at room temperature. Initially ordered to S = 0.52.



(2a) (2b)



(2c)

FIGURE 2 Comparison of room temperature rolling texture of (*a*) OFHC copper, (*b*) 70/30 brass, and (*c*) Cu_3Au.

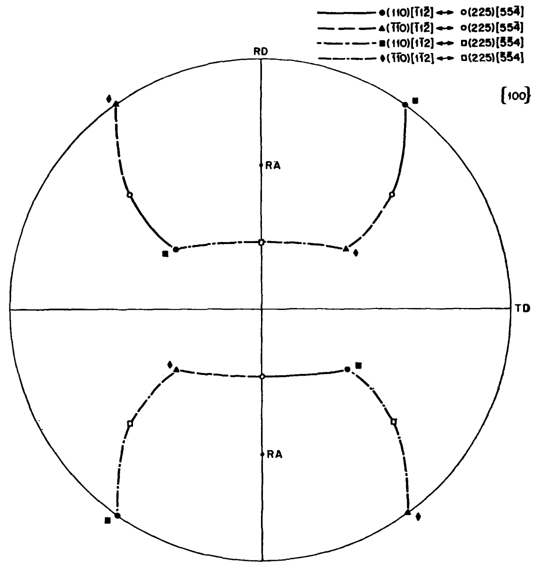


FIGURE 3 Idealized description of copper-type texture for a (200) pole figure.

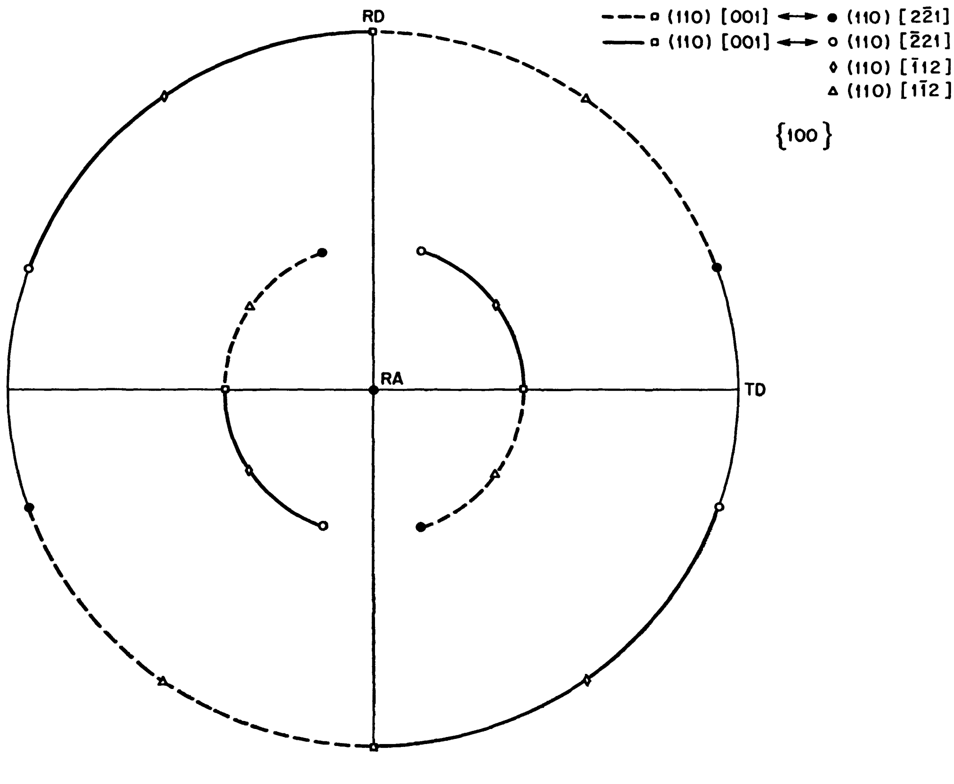


FIGURE 4 Idealized description of brass-type texture for a (200) pole figure.

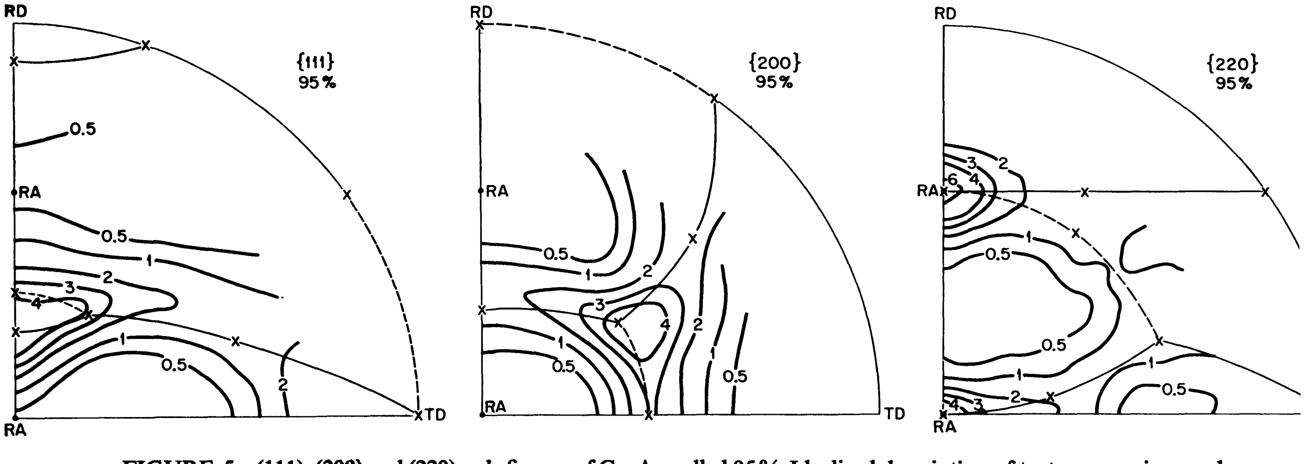


FIGURE 5 (111), (200) and (220) pole figures of Cu_3Au rolled 95%. Idealized description of texture superimposed.

{110} ⟨001⟩ towards {110} ⟨221⟩ including the {110} ⟨112⟩. These have a common ⟨110⟩ rotation axes parallel to ND. Figure 4 illustrates this idealized description of the brass texture. Finally, a minor feature of the brass texture can be described as {111} ⟨112⟩ orientations. These are not particularly evident in the (200) pole figure but are present according to the (111) pole figure.

The Cu_3Au pole figure in Fig. 2 may be interpreted to contain elements characteristic of both the copper and brass texture, i.e. it is a mixed or hybrid texture. Figure 5 superimposes the idealized copper and brass spreads (Figs. 3 and 4) upon one quadrant of each of the (111), (200), and (220) pole figures from Cu_3Au (S = 0.79) rolled 95% at room temperature. The {111} ⟨112⟩ and {110} ⟨221⟩ orientations present in brass, however, seem to be absent in Cu_3Au.

The evolution of deformation texture in Cu_3Au and how it compares with copper and brass may be discussed qualitatively with the aid of texture parameters. These are ratios of observed intensities measured at selected pole figure positions. Dillamore, Smallman and Roberts[12] found that a texture parameter, P_{DSR}, based on the (111) intensity ratio in the transverse direction (*TD*) to that at 20° from *RD* towards *TD* was inversely related to the *SFE* of the material. To evaluate P_{DSR} requires X-ray texture data obtained in transmission rather than by the Schulz reflection technique. Instead of taking transmission data we used a texture parameter based on intensities at selected positions in the (200) pole figure. Our parameter is defined as

$$P_{VO} = I_c/(I_c+I_a) \qquad (1)$$

where I_a is the intensity at the ideal orientation {110} ⟨112⟩ and I_c is the maximum intensity along the *ND* to *RD* diameter of the (200) pole figure. P_{VO} was selected because it essentially indicates the relative amount of material at the {225} ⟨554⟩ extreme of the copper spread. As such it bears as close a relationship to the recent deformation texture theory of Dillamore[13] as does P_{DSR}. According to the theory, P_{VO} should be greater than 1/2 when cross slip contributes extensively to texture development, i.e. high *SFE* materials. It should approach zero, on the other hand, when there is only {110} ⟨110⟩ restricted glide, i.e. low *SFE* materials. Hence P_{VO} should be inversely related to P_{DSR}.

Figure 6 plots P_{VO} versus percent deformation

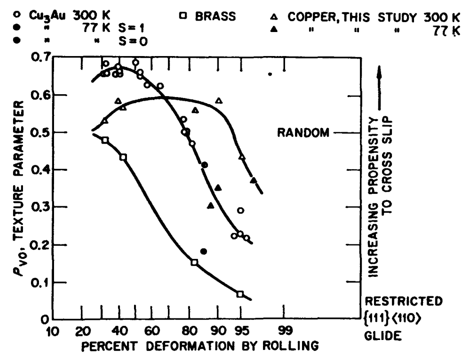


FIGURE 6 Texture development in Cu_3Au, OFHC copper and 70/30 brass as measured by the texture parameter P_{VO}. Filled triangle was estimated from the room temperature rolling texture data of Hu, Sperry, and Beck, *Trans. AIME* **194**, 76 (1952).

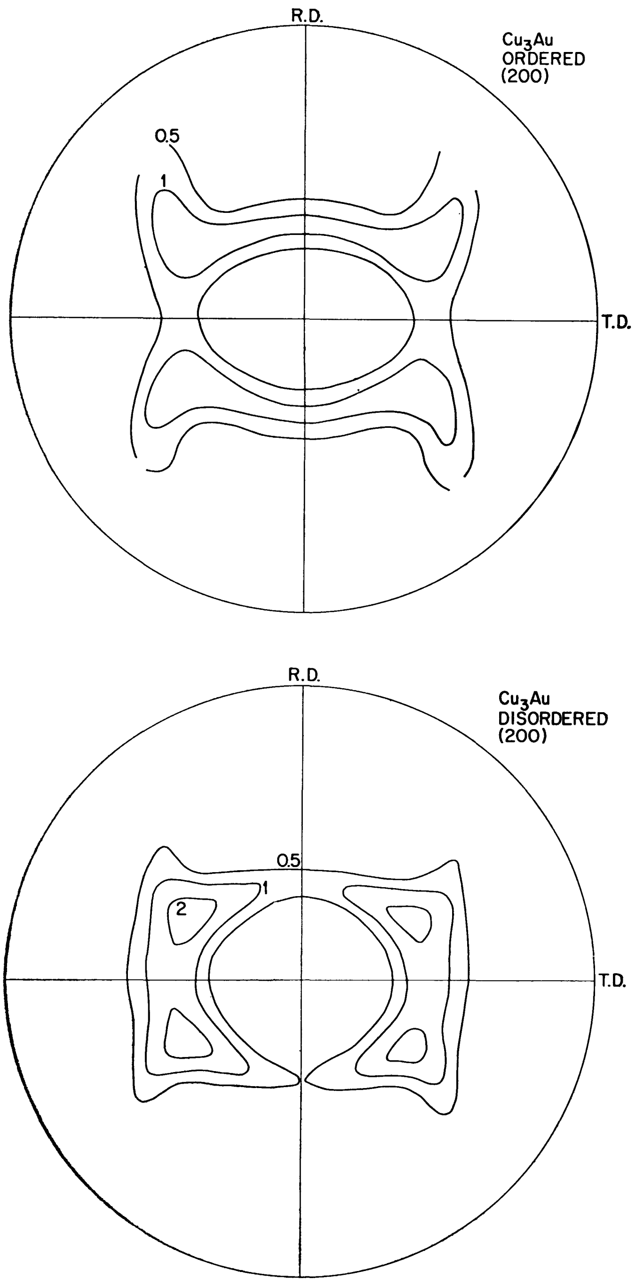


FIGURE 7 Effect of long range order on the texture of Cu_3Au rolled at 77 K.

by rolling for Cu_3Au, copper and brass. The pattern of texture development suggested for Cu_3Au at room temperature by this parameter and the pole figures themselves may be summed up as follows: Up to rolling reductions of about 70 to 80% the Cu_3Au texture was more like copper than brass. Beyond 80% reduction the Cu_3Au texture changed its character and tended to become more "brass-like" [except that the {111} ⟨112⟩ and {110} ⟨221⟩ orientations were missing]; the {110} ⟨112⟩ to {225} ⟨554⟩ "copper-like" spread diminished and the {110} ⟨112⟩ to {110} ⟨001⟩ "brass-like" spread was built up at the heavier deformations. The final Cu_3Au texture was considered to be a mixed texture consisting of both copper and brass components.

We note that in Cu_3Au the range of orientations referred to as "copper-like" could in fact be better described by a {110} ⟨112⟩ to {112} ⟨111⟩ spread rather than the {110} ⟨112⟩ to {225} ⟨554⟩ spread. (The {225} ⟨554⟩ orientation is 5 3/4° farther out along the *ND* to *RD* radius than is the {112} ⟨111⟩.) This was verified by recording the intensity of north-south diametral X-ray diffraction scans across (200) pole figures. A number of such detailed scans disclosed that I_c was on the average 30.6° from *ND* for copper and 35.9° for Cu_3Au. The significance of this 5° difference is as yet obscure in the present understanding of the mechanism of texture development in fcc materials.

In contrast to the room temperature results, rolling Cu_3Au at 77 K produced a conspicuous texture difference due to degree of long-range order. Figure 7 compares the (200) pole figure of Cu_3Au in the ordered state ($S = 1$) to that in the disordered state ($S = 0$) when both were rolled 86% at liquid nitrogen temperature. Both textures were not as sharply developed as when rolled at room temperature to equivalent reductions. Nevertheless it is obvious that the disordered alloy was considerably more "brass-like", whereas the ordered alloy still contained a remanent of the "copper-like" spread. The texture parameter substantiates this as well (see Fig. 6).

DISCUSSION

Rolling texture evolution in fcc materials may be discussed with reference to the behaviour of copper and 70/30 brass. Reductions in thickness up to 40 or 50% result in very little texture difference between these two prototype materials.[1,14] Increasing deformation beyond this amount causes a texture transition in the brass; the distinctive "brass texture" emerges and by 85 to 95% is essentially fully developed. Associated with this texture transition is the emergence of a microstructural feature thought to be microtwinning or deformation faulting.[1,14] In copper, increasing deformation merely sharpens the texture pattern. The decrease in P_{VO} (Fig. 6) for copper at deformations greater than about 90% could be rationalized as due to the onset of appreciable dynamic recovery,[15] presumably by dislocation climb processes rather than by a shift towards a brass texture.

Rolling texture development in Cu_3Au is in some ways similar to 70/30 brass. It does however differ in at least three respects: (1) the transition from a "copper-like" texture to a more "brass-like" texture did not begin until a deformation of 70 to 80% was reached, (2) the fully developed Cu_3Au texture never attained a completely "brass-like" state at room temperature, i.e. a significant "copper-like" component was always present, and (3) the {111} ⟨112⟩ and {110} ⟨221⟩ orientations were absent. The apparent "sluggishness" and inability to achieve a fully "brass-like" texture in Cu_3Au may be related to the difficulty for certain deformation mechanisms to operate in ordered or partially ordered structures.[16,17] Twinning or slip by partial dislocations can take place more easily in silver[18] and 70/30 brass.[1]

No effect of the degree of long-range order on texture development in Cu_3Au at room temperature was apparent in this work. This agrees with Dillamore and Stoloff[9] but is contrary to the findings of Starke *et al.*[8] Re-evaluation of the original pole figures of Starke *et al.*[8] suggested to us that some heterogeneity, perhaps related to an abnormal grain size or an off stoichiometry composition might have possibly influenced their results.

Rolling Cu_3Au at 77 K, however, disclosed a noteworthy difference in texture due to degree of long-range order. The more "brass-like" nature (see Figs. 6 and 7) of the disordered material whose *SFE* is considered to be higher than the ordered material[5,6,7] was contrary to the speculation[8] which led to this and the earlier[8,9] work. Furthermore, the observed behavior was unexpected when viewed in light of the proposed stacking fault energy (*SFE*)—rolling texture parameter (P_{DSR}) correlation of Dillamore, Smallman, and Roberts.[12] In that correlation higher *SFE* materials should be less "brass-like", i.e. more "copper-like" with a lower P_{DSR} (higher P_{VO}). To explain the texture behavior at 77 K we propose the existence of a *SFE*-texture reversal in rolling analagous to that in wire drawing. English and Chin[19] found that in low *SFE* materials deformed by wire drawing there was a reversal in the *SFE*-texture parameter correlation, i.e. the texture parameter increased with decreasing *SFE* and at low *SFE* passed through a maximum and then decreased with further decrease in *SFE*. No indication of such a texture reversal has been observed for deformation by rolling until very recently when Bunge and Tobisch[20] examined in detail the texture transition in α-brasses by means of neutron diffraction. Using three-dimensional orientation distribution functions, they found that the {011} ⟨100⟩ orientation density versus *SFE* passed through a maximum similar to the behavior of the Chin and English curve for wire drawing. We believe that our texture results on rolled Cu_3Au provide further evidence for such a texture reversal in rolling.

The texture reversal and its *SFE* dependence has been attributed by English and Chin[19] and Bunge and Tobisch[20] to a reduction in the ease of mechanical twin propagation as the *SFE* is lowered.[21] A somewhat similar argument could be invoked in the present case as well. Ordered Cu_3Au, according to the idea advanced by Cahn and Coll,[16] ought to twin only with great difficulty whereas disordered Cu_3Au should have a much greater proclivity for deformation twinning especially at low temperatures. The tendency for Group IB alloys to undergo deformation twinning at low temperatures in a tensile test is well known.[22] The room temperature texture behavior of disordered Cu_3Au then reflects a much decreased probability for mechanical twinning in agreement with these other observations.[22]

Mechanical twinning is not the only explanation for the texture reversal in ordered Cu_3Au. Hu *et al.*[1] proposed that slip by partial dislocations or deformation faulting could also cause a texture transition in fcc materials. Slip by partial dislocations in an ordered alloy ought to be more difficult than in a disordered one because of the additional antiphase domain boundary that would need to be created by such slip. The increased energy required to form this additional domain boundary would tend to keep the partial dislocations a minimal distance apart from each other and not allow them to travel individually. Analogous to the twinning situation this lack of deformation faulting would be expected to give rise to a texture reversal due to ordering.

CONCLUSIONS

1) Rolled Cu_3Au develops a mixed texture containing elements of both the copper and 70/30 brass textures at room temperature.

2) No effect of the degree of long-range order on texture was observed at room temperature.

3) Disordered Cu_3Au developed a strikingly more "brass-like" texture at 77 K than did the ordered alloy.

4) Evidence was presented verifying a texture reversal with decreasing *SFE* for the case of rolling deformation in Cu_3Au.

5) Lack of mechanical twinning or slip by partial dislocations could be responsible for the texture reversal in ordered Cu_3Au.

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