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FORMATION OF NUCLEATION SITES OF CUBE TEXTURE DUE TO INHOMOGENEOUS DEFORMATION DURING ROLLING IN COPPER SINGLE CRYSTALS.

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ABSTRACT

Copper single crystals of the (348)[$\bar{11}$,$\bar{4}$,6] orientation were cold-rolled up to 99% under two series of L/d condition. The formation of nucleation sites of (001)[100] orientation and the development of cube texture as well as their correlation were investigated. The slip-rotation from a stable orientation towards (001)[100] was discussed in terms of deformation inhomogeneity.

1. INTRODUCTION

The generation of cube or rotated cube texture after recrystallization of heavily cold-rolled copper single crystals of the (123)[$6\bar{3}\bar{4}$] and (145)[$\bar{10}$,$\bar{5}$,6] orientations has already been reported [1][2]. A close correlation was found between the development of cube texture and the formation of (001)[100] deformation structure. The preferential nucleation from the (001)[100] deformation structure was concluded as an essential factor of the development of cube texture in copper single crystals of S-orientation. Any model based on the homogeneous deformation can not predict the formation of metastable (001)[100] deformation structure from a stable orientation such as (123)[$6\bar{3}\bar{4}$]. Hence, the slip-rotation towards (001)[100] will start in the area deviating from a stable orientation by some chance due to inhomogeneous deformation occurring during rolling. Deformation inhomogeneity depends on rolling condition such as roll-diameter, thickness of specimens and drawght. These factors characterizing the rolling geometry can be expressed by L/d or delta-parameter [3]. L/d is defined as

$$L / d = [R (d_o - d)^{1/2}] / d_o$$

where d_o and d are the thickness of a material before and after rolling, respectively. R is a roll-diameter and L is a contact length. Unless the roll-diameter is changed, it is difficult to roll beyond 95% under constant L/d condition. As will be shown later, the probability of an inhomogeneous deformation which causes a deviation from a stable orientation is expected to increase, when rolling is carried out under high L/d. In this study, copper single crystals of the (348)[$\overline{11}$,$\overline{4}$,6] orientation were cold-rolled under two series of L/d condition. The effects of L/d on the formation of nucleation sites of (001)[100] orientation and on the development of cube texture after recrystallization are investigated by an ordinary pole figure technique.

2. EXPERIMENTAL PROCEDURE

Two cubic slices of 20mm were cut mechanically from a cylindrical single crystal ingot made of electrolytic copper to the (348)[$\overline{11}$,$\overline{4}$,6] orientation within 2^o. This belongs to S-stable orientation of fcc metals of high SFE and possesses a common [111] axis with (001)[100]. Crystal 1 and 2 were cold-rolled reversely up to 90% by 44 and 20 passes, and 90% to 99% by 33 and 11 passes, respectively, under oil lubrication. Average L/d of the latter in crystal 1 and 2 were 5.9 and 10.8, respectively. All the specimens were subsequently annealed for 100 seconds in a salt bath at 773K. (111) and (100) pole figures of crystals cold-rolled 90, 95, 97.5, and 99% were determined, using the usual transmission and reflection techniques with Ni filtered Cu-Kα radiation. The height of contour lines was normalized by comparing the intensity levels of these pole figures with those of polycrystalline sheets.

3. EXPERIMENTAL RESULTS

Figure 1 shows the (111) pole figure for the rolling texture of crystal 1 cold-rolled 99%. The rolling textures of both crystals were very sharp up to the highest reduction, as far as the orientation spread were estimated by the iso-intensity lines of the level 0.5. However, the center of the four (111) intensity peaks corresponding to the main component deviated a few degrees from the initial orientation, so that the rolling textures cold-rolled more than 95% were better described as (357)[$\overline{7}$35]. A symmetrical component of the main component with regard to the transverse direction co-exists in the pole figures. The (100) pole figures for the rolling texture of crystal 1 cold-rolled 95 and 99% are given in Fig.2 and Fig.3, respectively. The (100) pole figures show in the same way as the (111) pole figures that the rolling texture of both crystals are the sharp (357)[735] orientation. However, weak components whose orientations can not be identified are found throughout the pole figures. Their intensity levels are less than 0.2 of random intensity. Two (100) poles near the rolling direction and the transverse direction are in the lowest level region of the pole figure Fig.2. The (100) intensity level near the rolling direction in Fig.3 is increased and very weak peaks can be seen in the vicinity of the transverse direction along outer circle. That is, a rotated cube deformation structure is formed in crystal 1 after 99% rolling. Figure 4 represents the (100) pole figure for the rolling texture of crystal 2 cold-rolled 99%. The main component of the rolling texture is quite similar to that of crystal 1 but the formation of a weak (001)[100] deformation structure is clearly observed.

The recrystallization texture of crystal 1 cold-rolled 90% consisted of the retained component of rolling texture with large scatter. The (100) pole figure of crystal 1 cold-rolled 95% and subsequently annealed at 773K is given in Fig.5. The main components of recystallization texture of crystal 1 cold-rolled more than 95% were rotated cube orientations, which were tilted few degrees mainly around the normal direction from (001)[100], and their twin. The main component changed gradually from a rotated cube to (001)[100], with an increase in the rolling reduction. A symmetrical cube texture was developed in crystal 2 cold-rolled 99% under higher L/d, as shown in Fig.6. Thus, rolling of copper single crystals of S-orientation under higher L/d gave rise to the formation of (001)[100] deformation structure and leaded to the symmetrical cube texture. Therefore, it can be concluded that the (001)[100] deformation structure formed by inhomogeneous deformation during rolling, should act as available nucleation sites of the cube texture. The sharp cube texture observed in polycrystalline copper and aluminum sheets would be developed by the same nucleation mechanism as functioned on heavily rolled copper single crystals of S-orientation.

4. DISCUSSION

The orientation change towards (001)[100] observed in this study, can hardly be explained with ordinary theories of slip-rotation such as Taylor's model and Sachs' model. Inhomogeneous deformation will be responsible for an unpredictable slip-rotation. Thus, deformation inhomogeneity should be quite important for the formation of nucleation sites, provided that the formation of a new component fairly deviating from the initial orientation is not a discontinuous process such as deformation twinning.

The inhomogeneity of texture over the sheet thickness resulted, when L/d was lower than unity [4]. The reason was that the surface layer of material elongated more extensively when deformed by rolls of a very small diameter. On the contrary, when a one pass reduction with large diameter rolls was too high, the intensity corresponding to the main component decreased rapidly, so that the rolling texture of single crystal disappeared within a low reduction. Namely, the higher was L/d the more extensively developed the inhomogeneity of texture. The surface of sheets is elongated in the longitudinal direction corresponding to the amount of one pass reduction. Frictional stress is uniformly subjected between the rolls and the material, but slip and stick between them varies depending on sites, so that elongation of the surface layer will be irregular. Material should be supplied from the inner part of the sheet to the surface layer much stretched. This material flow is not the same with the homogeneous flow in rolling. Hence, unexpected orientation changes will occur in the inhomogeneously deformed areas.

Assuming that inhomogeneous deformation takes place with the same angle as shear band formation, material of a plate shape flow out from the inner part of sheet to the direction inclined 35^{o} from the rolling direction in the longitudinal section. The thickness of plate will decrease during such inhomogeneous deformation. The $(112)[\bar{1}\bar{1}1]$ orientation of crystal can be regarded as $(001)[\bar{1}10]$ with respect to the coordinate of plate inclined 35^{o} from the rolling plane normal. The $(001)[\bar{1}\bar{1}0]$ orientation of the plate changes to $(\bar{1}\bar{1}2)[\bar{1}\bar{1}\bar{1}]$ or $(112)[\bar{1}\bar{1}1]$ by the rotation around the transverse direction during inhomogeneous deformation. The latter is $(001)[\bar{1}10]$ with respect to the coordinate of rolling. Hence, a new component $(\bar{1}\bar{1}2)[\bar{1}\bar{1}\bar{1}]$, which has a twin relationship with the initial $(112)[\bar{1}\bar{1}1]$, can be produced during subsequent rolling. In case of $(123)[\bar{6}\bar{3}4]$ crystals [5], $(001)[\bar{u}\bar{v}0]$ component near $(001)[\bar{1}\bar{1}0]$ and $(111)[\bar{6}\bar{1}7]$ component were generated by the rotation around the axis near the transverse direction during inhomogeneous deformation. The former changed to $(001)[100]$ passing through a rotated cube orientation, and the latter to $(321)[\bar{4}36]$ symmetrical orientation, passing through $(211)[\bar{5}19]$ by subsequent rolling. Therefore, intensity peaks corresponding to the symmetrical component of the rolling texture and the $(001)[100]$ deformation structure should develop with an increase in the rolling reduction up to 99%.

5. SUMMARY

Copper single crystals of the $(348)[\bar{1}\bar{1},\bar{4},6]$ orientation were cold-rolled up to 99% under two series of L/d condition, so as to elucidate the effects of rolling geometry on the formation of nucleation sites of $(001)[100]$ orientation and the development of cube texture. The important results and the conclusions are as follows.

1) The rolling textures were very sharp up to the highest reduction, though the main component shifted to $(357)[\bar{7}35]$ orientation. A weak $(001)[100]$ deformation structure was found in the crystal cold-rolled more than 99% under higher L/d.

2) The recrystallization textures of crystal cold-rolled more than 95% under lower L/d were composed of rotated cube components. A symmetrical cube texture was developed by rolling of 99% under higher L/d.

3) It can be concluded that the formation of nucleation sites of (001)

[100] orientation depends greatly on inhomogeneous deformation during rolling and the cube texture is mainly attributed to the preferential nucleation from the (001)[100] deformation structure.

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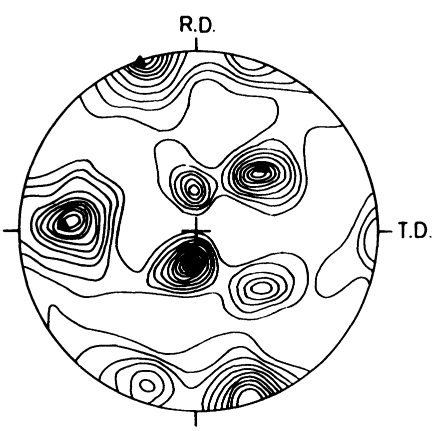


Figure 1 – (111) pole figure for the rolling texture of copper single crystal of the (348)[$\bar{1}\bar{1}$,$\bar{4}$,6] initial orientation cold-rolled 99% under lower L/d condition. Filled triangles indicate (357)[$\bar{7}\bar{3}$5] orientation. The height of counter lines are 0.15, 0.3, 0.5, 1.5, 3, 6, 9, 12, 15 and 20 of random level, respectively.

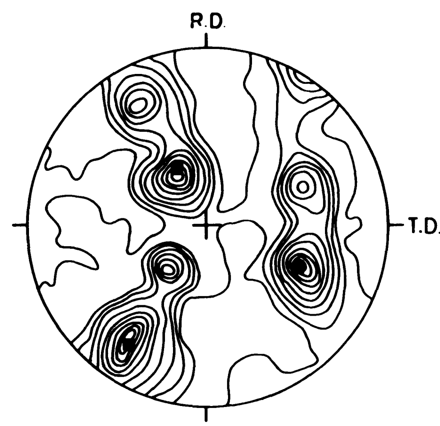
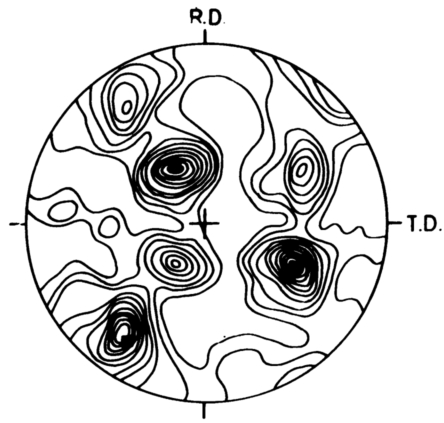


Figure 2 – (100) pole figure for the rolling texture of copper single crystal cold-rolled 95% under lower L/d condition. Filled squares indicate (357)[$\bar{7}\bar{3}$5] orientation. The height of counter lines are 0.05, 0.2, 0.5, 1, 2, 4, 7, 10, 13 and 16 of random level, respectively.



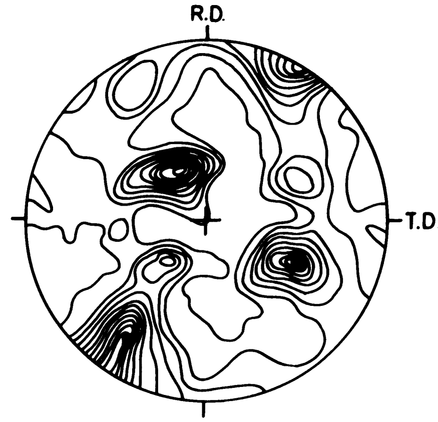
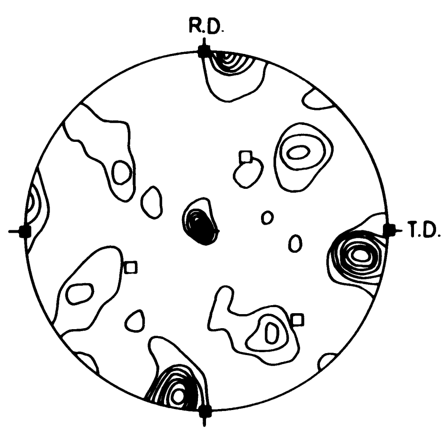


Figure 3 - (100) pole figure for the rolling texture of copper single crystal cold-rolled 99% under lower L/d condition. The height of counter lines are 0.1, 0.2, 0.5, 1, 2, 4, 6, 8, 10 and 14 of random level, respectively.

Figure 4 - (100) pole figure for the rolling texture of copper single crystal cold-rolled 99% under higher L/d condition. The height of counter lines are 0.1, 0.2, 0.4, 1, 2, 4, 6, 8, 10 and 14 of random level, respectively.



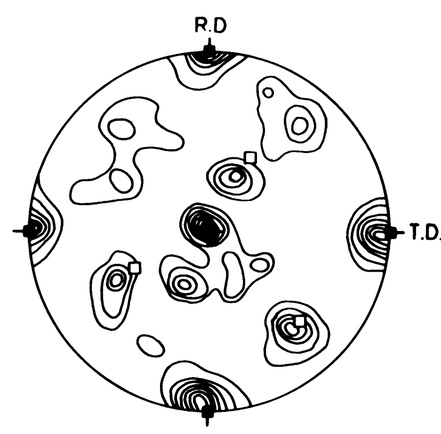


Figure 5 - (100) pole figure for the recrystallization texture of copper single crystal cold-rolled 95% under lower L/d condition and subsequently annealed 100 sec at 773K. Filled and open squares indicate (001)[100] and (122)[212] orientation, respectively. The height of counter lines are 1, 2, 4, 6, 8, 10 and 14 of random level, respectively.

Figure 6 - (100) pole figure for the recrystallization texture of copper single crystal cold-rolled 99% under higher L/d condition and subsequently annealed 100 sec at 773K. The height of counter lines are 1, 2, 4, 5, 7, 9 and 12 of random level, respectively.