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AN ODF STUDY OF THE DEFORMATION AND RECRYSTALLIZATION TEXTURES OF ROLLED AND CHANNEL-DIE COMPRESSED HIGH PURITY COPPER

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The rolling deformation has widely been considered equivalent to plane strain compression. The validity of this presumption, particularly at high strains, was tested by comparing the deformation and recrystallization textures in rolled and channel-die compressed copper using the ODF techniques. Noticeable differences were observed in both the deformation and recrystallization (cube) textures of the strips produced by these two deformation methods. For the deformation texture, the rolled strip shows stronger "copper" and "S", but weaker "brass" components, in comparison with the channel-die compressed strip. For the recrystallized specimens, the cube texture is stronger in the rolled than in the channel-die compressed specimens, and their microstructures are also noticeably different. These observed differences are all more prominent at higher reductions. The causes of these differences will be discussed.

KEY WORDS Rolling, channel-die compression, recrystallization, textures.

INTRODUCTION

It has widely been considered that rolling deformation is essentially equivalent to plane strain compression. Theoretical treatment of rolling deformation has restricted its scope to thin-sheet rolling for which the width to thickness ratio and width to contact-length ratio are large (Hill, 1950). The contact length is commonly expressed as $l = (R/\Delta h)^{1/2}$, where R is the radius of the rolls and Δh is the reduction of thickness by the rolling pass. Hence, for high degree reductions (e.g., 95% and higher) when the initial thickness of the work piece is large, the deformation geometry varies considerably from the early passes to late passes toward finishing because of changes in thickness and in pass reduction. However, results of classical works on this problem (Orowan, 1943; Bland and Ford, 1948) indicated that the correction is very small when the arc of contact is greater than the mean thickness of the strip.

The greatly increased interest in the study of the origin of cube texture in fcc metals has induced the use of single crystals and bicrystals with controlled orientations for a systematic study of the problem, hopefully for more definitive results. (Hu, 1986). To enable more precisely controlled deformation of these crystals, a channel-die compression device has been employed instead of a laboratory rolling mill. It is known that for the formation of a strong cube texture upon recrystallization, a high degree of reduction, preferably 95% or higher, is required (Baldwin, 1942). It is also known that the formation of the cube texture is highly sensitive to many other factors besides the degree of deformation. These include the effects of the alloying elements or impurities, those of the penultimate grain size, annealing temperature, and rate of heating, etc. It appears, therefore, highly desirable to test the validity of the presumption that rolling deformation is essentially equivalent to plane strain compression, particularly at high strains, by comparing the deformation and recrystallization (cube) textures of the strips carefully processed by these two deformation methods.

A preliminary investigation of this problem was conducted not long ago by simply comparing the deformation and recrystallization textures in rolled and in channel-die compressed strips of an electrolytic copper, using conventional pole figure techniques. The results of this work was published recently (Butler and Hu, 1989). To ensure the reliability of the results, a more detailed and carefully controlled study was undertaken in the present investigation, using high purity copper and the ODF techniques. The new quantitative results, which are in essential agreement with, but more extensive than, those of an earlier investigation, will be reported in the present paper.

EXPERIMENTAL PROCEDURE

Material Preparation

High purity copper (99.995% pure) was melted in an induction furnace with an Ar atmosphere, and the melt was cast into a preheated mold. The ingot was machined to an initial dimension of $50 \times 55 \times 65\ \mathrm{mm}^3$. To break up the cast structure into a uniformly fine-grained work stock with nearly random texture, the piece was cold compressed in a 600-ton forging machine along the three orthogonal directions (20 to 25% reduction in each direction), then annealed 1 h at 400°C for recrystallization. Such forging and annealing cycle was repeated three times while the initial shape of the piece was approximately preserved. The grain size and texture of the processed material were then examined at an interior section of the piece. The grain size was fairly uniform, and the average diameter was $\approx 33\ \mu\mathrm{m}$. The texture of the processed piece, as judged by the low and flat intensity distribution along the α- and γ-fiber skeleton lines, and by the small intensity variations of the rotated-cube orientations around unity, is assured to be practically random.

This processed piece of copper was used as the starting stock for the present investigation. It was cut into two parts: one for the rolling deformation and one for corresponding channel-die compression. Five levels of deformation, in range of 70–95% reduction, were included in the study. To avoid possible uncertainties arising from a texture gradient in the specimen, texture measurements were taken at or very near the mid-thickness plane of the specimen. For the same reason, we chose to use different initial thickness of the piece for the various levels of deformation to be employed that would all yield the same final thickness

(0.9 mm). These start materials were then machined to pieces of different initial thickness, ranging from 3 mm (for 70% reduction) to 18 mm for (95% reduction). For rolling, the width of these pieces was ≈ 35 mm, for channel-die compression, 15.88 mm, the width of the channel.

Deformation

Rolling. A laboratory rolling mill (roll diameter 250 mm) was used for the rolling deformations. In order to assure homogeneous deformation of the specimens the width of the starting piece is at least (for the highest or 95% reduction) ~ 2 times its initial thickness. For the pieces to be rolled to lower reductions, the initial width/thickness ratio is correspondingly larger. Of course, as the thickness continues to decrease during rolling, this ratio increases to much larger values. In formulating the rolling schedule, the ratio of the contact length to the mean thickness of the strip (l/d) was kept greater than 1 as practiced in an earlier work (Asbeck, 1973). To reduce surface friction in rolling, lubrication with oil was applied. The thickness and width of the strip were measured.

Channel-die compression. The procedures for plane strain compression in a channel-die device was described previously (Bulter and Hu, 1989). The work piece was cut to fit the 15.88 mm channel, and was wrapped in thin Teflon film (0.064 mm thick) to reduce surface friction during deformation. A die was placed on top of the work piece, and the assembly was carefully compressed in a hydraulic testing machine. As the length of the strip approached that of the channel, 125 mm long, the strip was cut in half and each half was further deformed separately.

During deformation, by rolling or by channel-die compression, the work piece was kept cool. After deformation, the strips were stored in a freezer to prevent significant recovery or possible recrystallization from occurrence at room temperature.

Annealing

For recrystallization, the rolled and the correspondingly channel-die compressed samples were annealed side-by-side in an oil bath at 171°C till recrystallization is complete. The annealing behavior was characterized by hardness measurements and optical microscopy. To avoid the effect of surface layer on the recrystallization texture, the recrystallized specimens were etched to remove about 10% of the material on the surface before hardness and microstructure were examined.

Texture Determination and Representation

Texture measurements on the midthickness plane of the specimens were carried out on a fully automatic X-ray texture goniometer (Köhlhoff, 1989). For the rolled strips, samples (14 mm wide by 24 mm long) were cut from the middle portion of the strip to minimize the effect of widening on texture near the edges. For the channel-die compressed strips, no cutting of the width was necessary. Four incomplete pole figures from the {111}, {200}, {220} and {113} planes in the reflection mode with tilt angle up to 85° were determined. After corrections for the defocussing error and the background intensity, the intensities were expressed in random units.

The 3-dimensional orientation distribution functions (ODFs) were calculated by the series expansion method (Bunge 1969). They are presented in the orientation space with the Eulerian angles (ϕ_1, Φ, ϕ_2) as the rectangular coordinates. Corrections for the ghost orientations were applied according to the method of Lücke *et al.* (1981). Further evaluation of the ODF data were represented by the orientation density maxima along the skeleton lines of the orientation tubes and by the volume fractions of texture components calculated according to the Gaussian distribution model for scattering as proposed by Virnish *et al.* (1979)

EXPERIMENTAL RESULTS

Experimental results produced in the present investigation were fairly voluminous. For brevity, only those results significantly relevant to the main purpose of the study will be presented and discussed.

Deformation Textures

The deformation textures of the strips deformed by rolling and by channel-die compression were largely similar, but significant differences were developed with increasing reduction. The ODFs of the 95% deformed specimens are shown in Figure 1, where (a) shows the texture of the rolled strip and (b), that of the

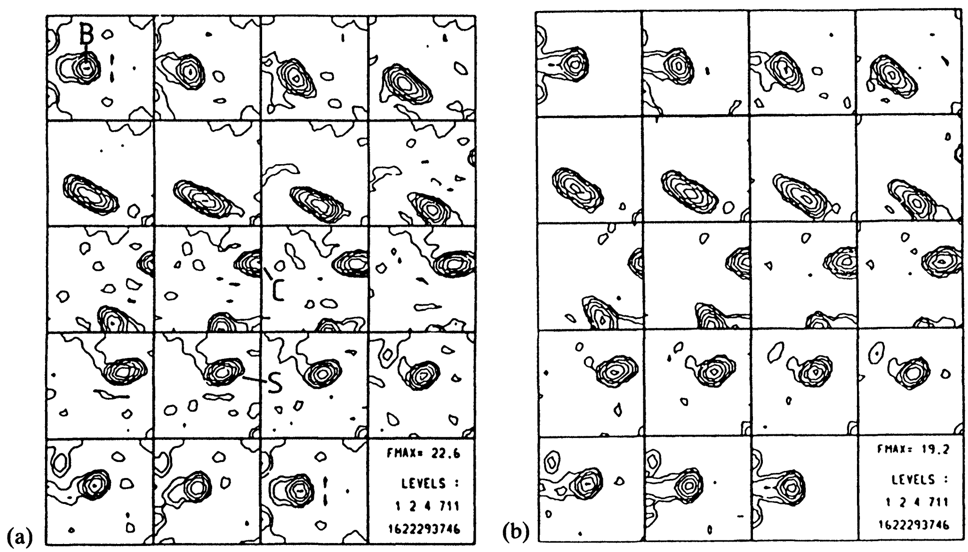

Figure 1 The ODFs of the deformation textures of h.p. copper deformed to 95% reduction by: (a) rolling, and (b) channel-die compression.

channel-die compressed strip. The brass, copper, and S orientations (B, C, and S,) are indicated. The texture can be described by two orientation tubes or fibres with varying intensities. The α-fibre runs from the Goss position {011} ⟨100⟩ to the brass position {011} ⟨211⟩, i.e. from $\phi_1 = 0$ to 35° at $\phi_2 = 0$, $\Phi = 45°$. The β-fibre runs inclined to the $\phi_2 = 0$ plane from the copper position {112} ⟨111⟩ (ϕ_1, Φ, $\phi_2 = 90°$, 35°, 45°) through the S position {123} ⟨634⟩ (59°, 33°, 65°) towards the brass position {011} ⟨211⟩ (35°, 45°, 0°). From Figures 1(a) and 1(b), one notices that the orientation spread in the rolled specimen is somewhat larger than that in the channel-die compressed specimen, although the maximum intensity of the textures differs only slightly.

The difference between the deformation textures of the strips deformed by rolling and by channel-die compression can be noticed with much clarity by comparing the orientation density of the skeleton lines of their orientation tubes or fibre textures. These are shown by the various plots in Figure 2 (for rolled strips) and Figure 3 (for channel-die compressed strips). The plots shown in Figure 2 for rolling texture are in good agreement with those determined earlier for h.p. copper by Hirsch and Lücke (1989). By comparing Figure 2(a) with Figure 3(a), one sees immediately that there are distinct differences in the deformation textures, particularly at high deformations, produced by these two deformation methods. For example, at 95% reduction, the rolled strip has considerably stronger {112} ⟨111⟩ copper, and {123} ⟨634⟩ S components than its {011} ⟨211⟩ brass component, whereas in the channel-die compressed strip, the orientation density of these three components is approximately equal. In other words, deformation by rolling produced a texture that is strong in copper and S orientations, but weak in brass orientation. On the other hand, channel-die compression produced a texture which is strong in brass orientation, but relatively weak in copper and S orientations in comparison with those produced by rolling.

As a function of increasing deformation, the characteristics of texture development, in particular for the {112} ⟨111⟩ copper component, show also an obvious difference by comparing Figure 2(a) with Figure 3(a). In rolling, this orientation increases its density with increasing deformation in a way normally expected. In channel-die compression, this orientation appears to have developed earlier, but with further increasing deformation this orientation seems to have increased its density only very slightly until a substantial increase occurred at 90% reduction. From 90 to 95% reductions there is no further increase in the density of this orientation. This unusual behavior, which is consistently shown in the τ-fibre plot in Figure 3(d), is not understood at present.

From Figures 2(c), 2(d), and 3(c), 3(d), one notices that there is a difference in the behavior of the Goss component, i.e. {011} ⟨100⟩, for the strips deformed by the two deformation methods. In rolling, the Goss orientation is appreciable at 70% reduction; it decreases to almost nil at 95% reduction. In channel-die compression, the Goss component remains stable with increasing reduction. At 95% reduction, the Goss component is, therefore, considerably stronger in the strip deformed by channel-die compression than by rolling. This observation on the Goss component is not surprising because the Goss orientation is closely associated with the brass texture. The plots shown in Figures 2(b) and 3(b) indicate that the orientation of the β-fibre skeleton lines has very small variations in the strips processed by either of the deformation methods.

A qualitative comparison of the relative differences between the deformation

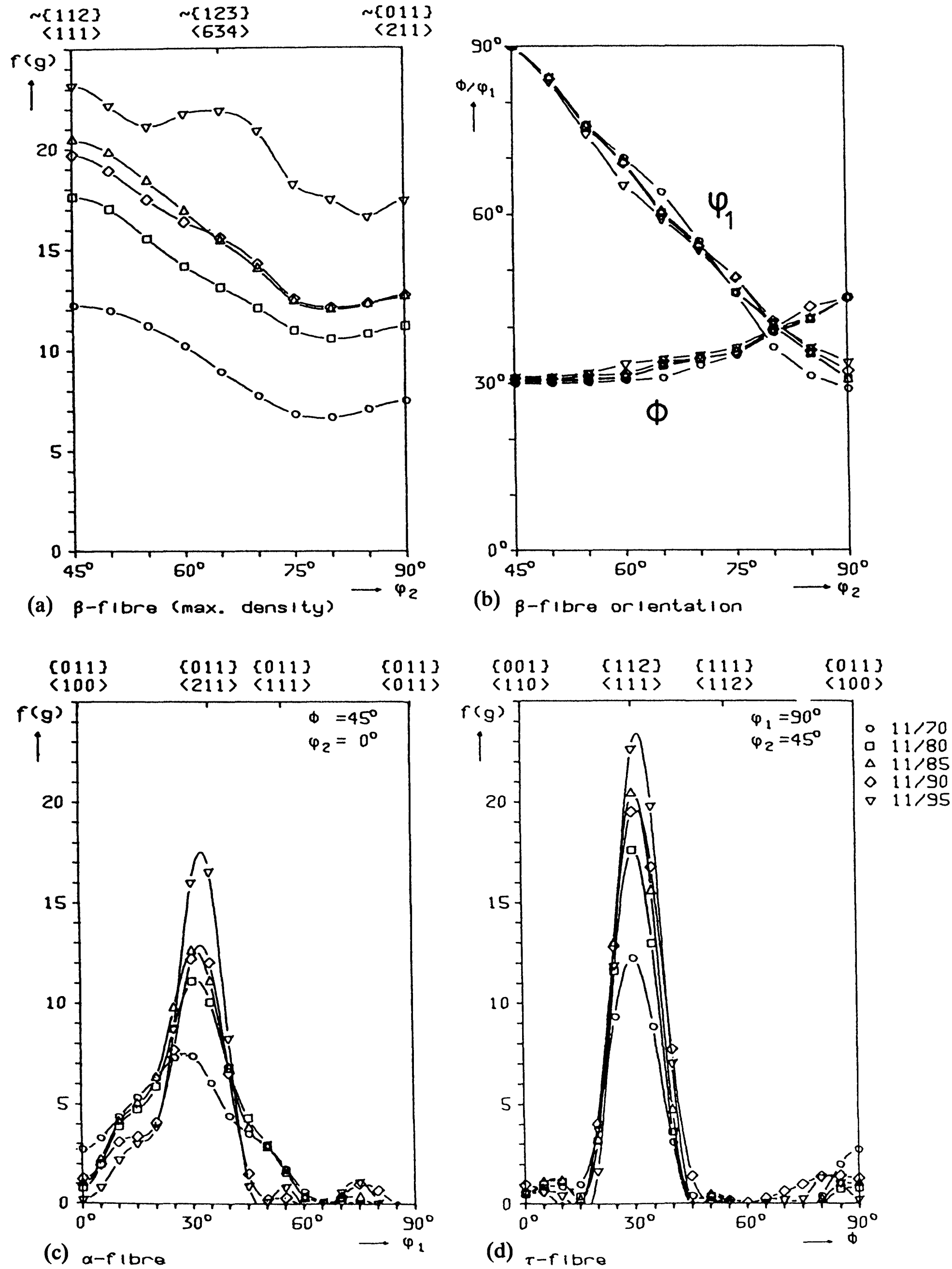

Figure 2 The characteristics of the various fibre components of h.p. copper deformed by rolling to various reductions. (a) the orientation density of the β-fibre, (b) the Euler angle positions of the β-fibre, and (c) the orientation density of the α-fibre, and (d) the orientation density of the τ-fibre.

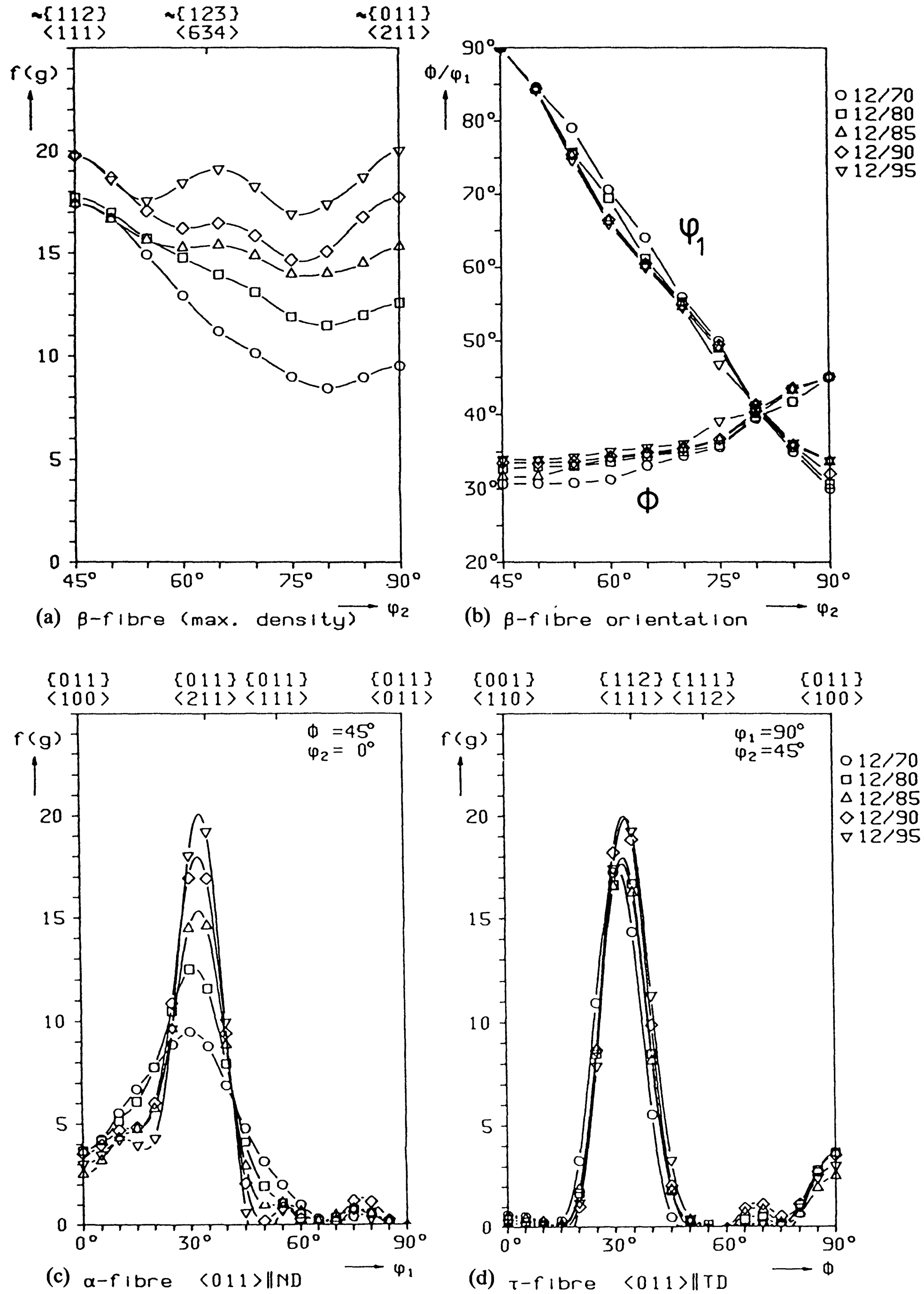

Figure 3 The characteristics of the various fibre components of h.p. copper deformed by channel-die compression to various reductions. (a), (b), (c), and (d) have the same descriptions as in Figure 2.

Table 1 A qualitative comparison of the relative differences between the deformation textures of h.p. copper processed by rolling and by channel-die compression at 95% reduction.

Texture characteristics	*Processing methods* — *Rolling*	*Channel-die compression*
$C\{112\}\langle 111\rangle$	Stronger	Weaker
$S\ \{123\}\langle 634\rangle$	Stronger	Weaker
$B\ \{011\}\langle 211\rangle$	Weaker	Stronger
$G\ \{011\}\langle 100\rangle$	Weaker	Stronger
Orientation spread	Larger	Smaller
Maximum intensity	Slightly higher (or nearly the same for both)	Slightly lower

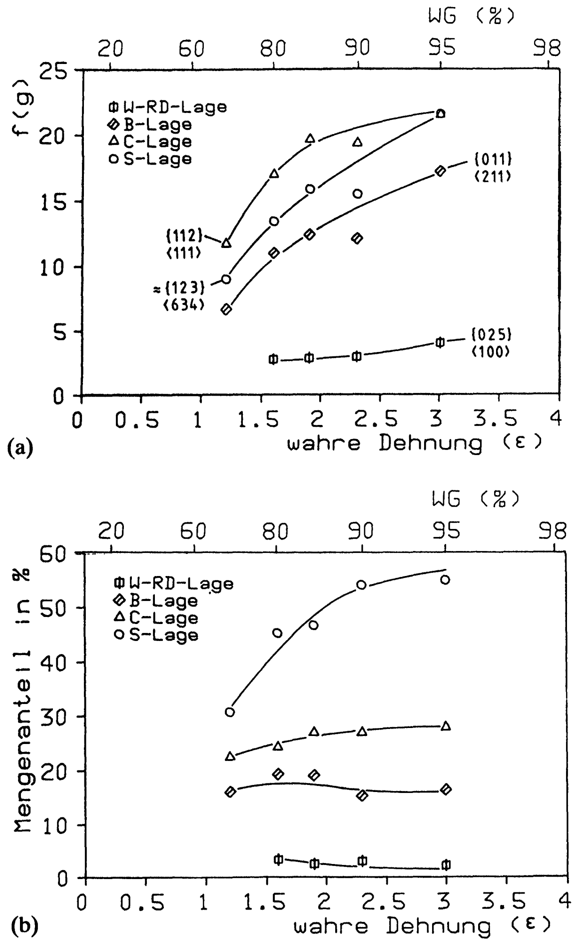

Figure 4 (a) The orientation density, $f(g)$, and (b) the amount in %, of the various texture components in the rolled strip, plotted as a function of % reduction and true strain (ε).

textures of h.p. copper processed by rolling and by channel-die compression at 95% reduction is summarized in Table 1. To examine the observed differences more quantitatively, the orientation density and the volume fraction of the various components of the deformation texture were calculated according to a Gaussian scattering model around the ideal orientations (Virnish *et al.*, 1979). The results are shown as a function of strain in Figures 4 and 5 for the rolled and the channel-die compressed specimens, respectively. It can be noted that at high reductions, the copper and S components are stronger and larger in the rolled than in the channel-die compressed specimens. On the other hand, the brass component in the channel-die compressed specimens is stronger and larger than in the rolled specimens. Similarly, the Goss orientation is appreciable in the channel-die compressed, but is undetected in the rolled specimens. The RD-

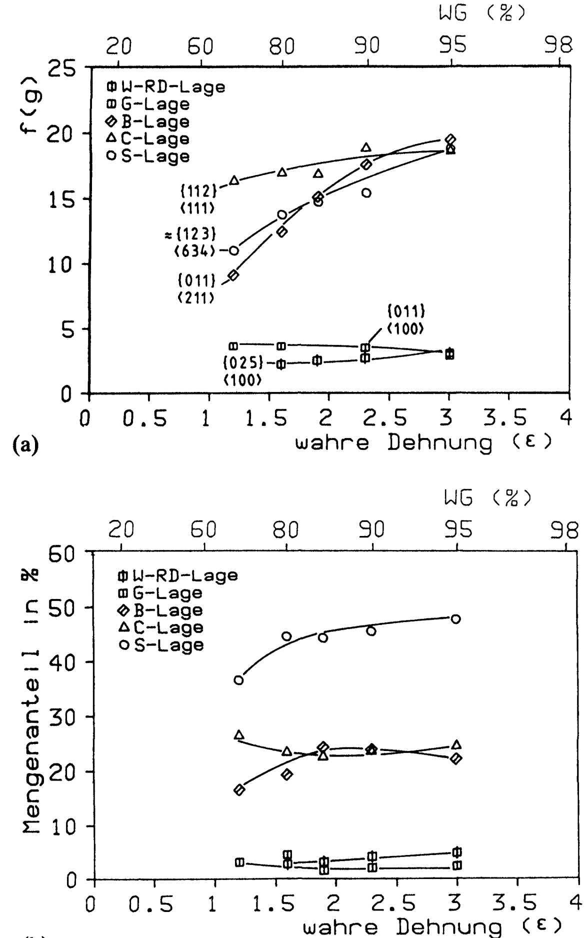

Figure 5 (a) The orientation density, $f(g)$, and the amount in %, of the various texture components in the channel-die compressed strip, plotted as a function of % reduction and true strain (ε).

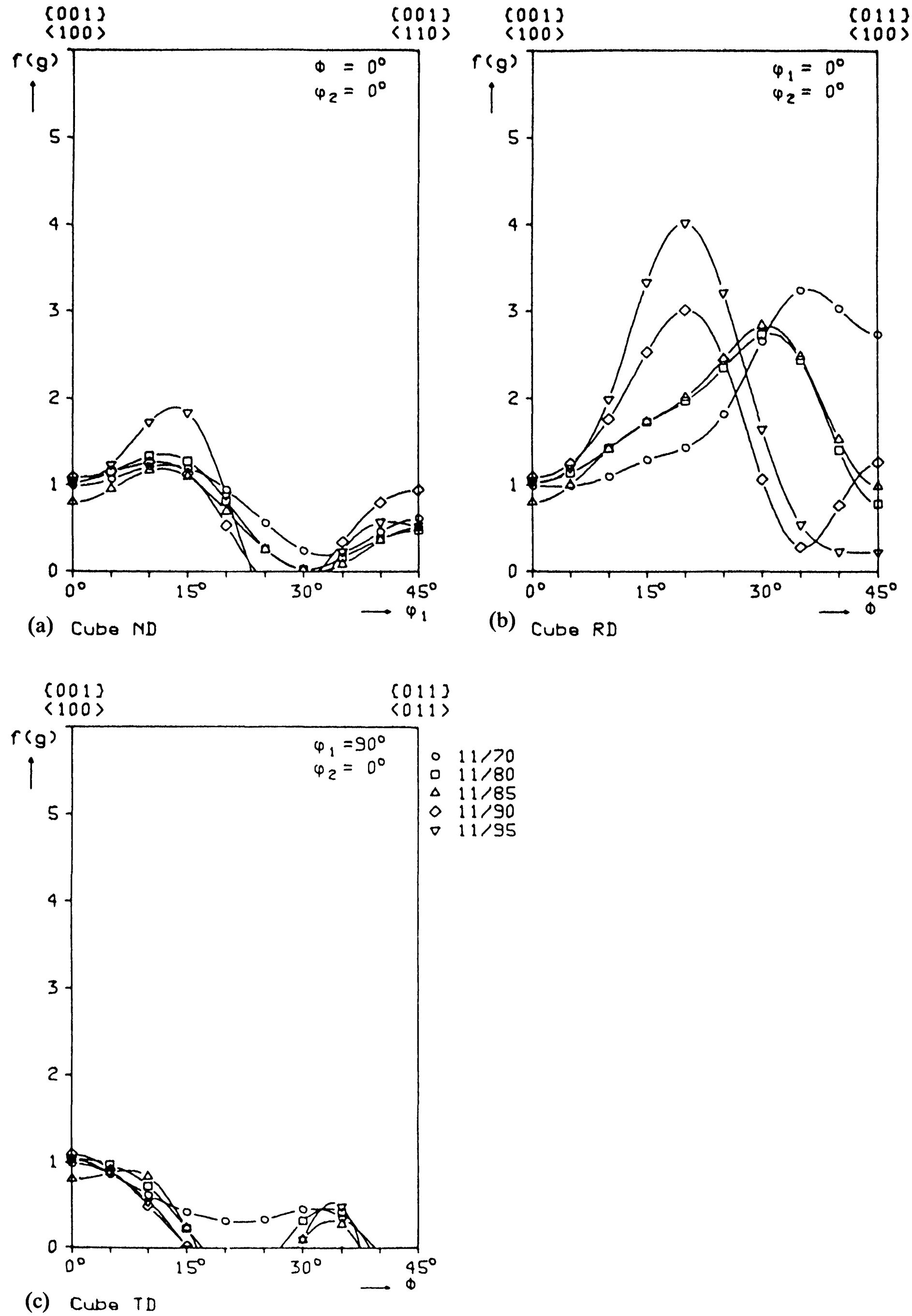

Figure 6 The scatter of the deformation texture as rotated-cube orientations around (a) ND, (b) RD, and (c) TD in strips deformed by rolling to various reductions.

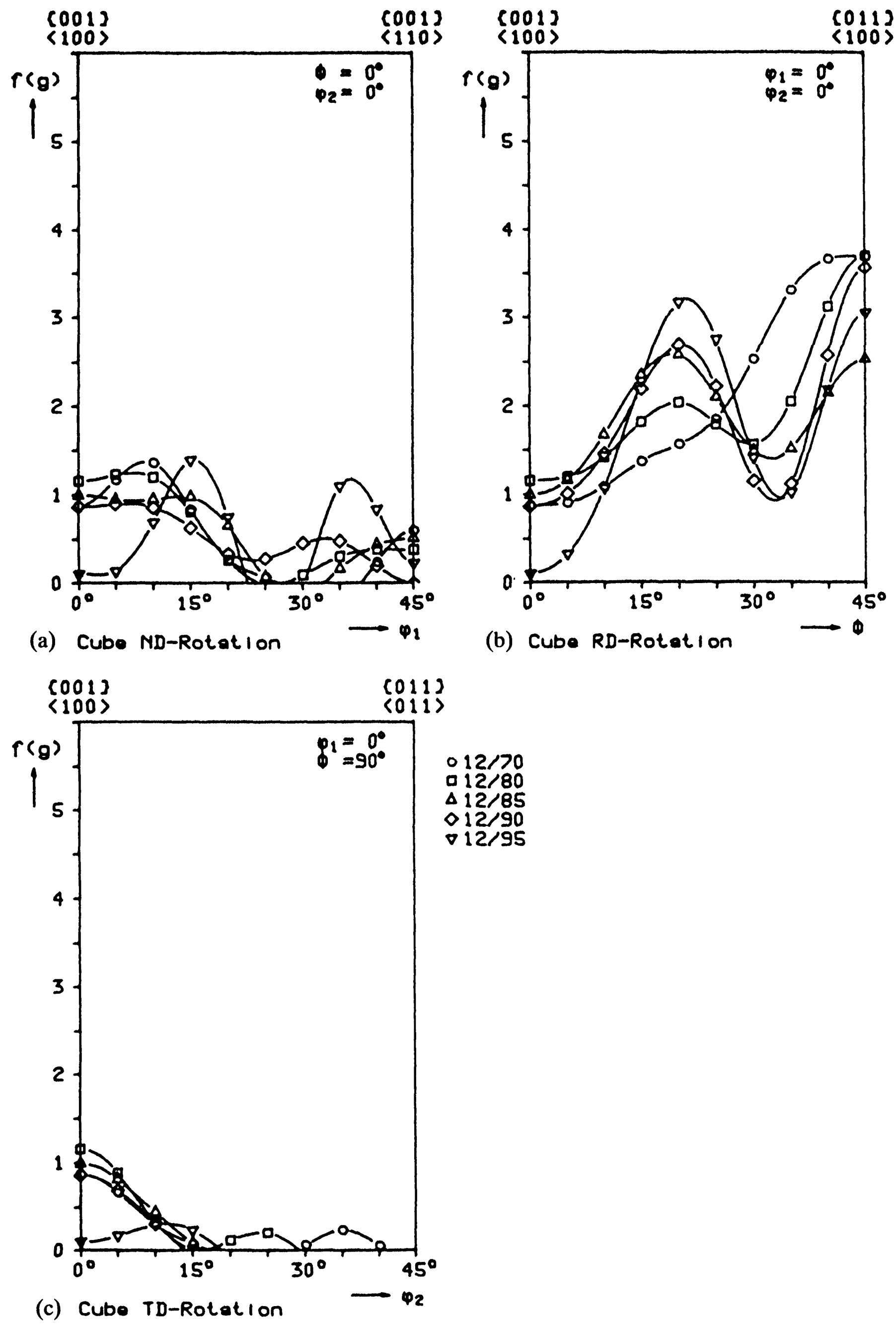

Figure 7 The scatter of the deformation texture as rotated-cube orientations around (a) ND, (b) RD, and (c) TD in strips deformed by channel-die compression to various reductions.

rotated cube orientation, e.g. {025} ⟨100⟩, which is a very minor constituent, appears to be existing equally in both rolled and channel-die compressed materials.

The scattering of cube orientations rotated around ND, RD, and TD were also examined, as shown in Figure 6 (for rolled) and Figure 7 (for channel-die compressed). These plots indicate that the scatters are within very low intensity ranges. The small peaks are developed at orientations away from the {001} ⟨100⟩ cube position by rotation around ND, RD or TD. It is interesting to note that in rolling the cube orientation remains at about the random level (~1) in orientation density with increasing reduction. However, in channel-die compression, the cube orientation decreases to a level, which is barely detectable, at 95% reduction. The previously noticed difference in the Goss orientation between the rolled and channel-die compressed strips at 95% reduction is, again, consistently shown here, Figures 6(b) and 7(b). Other features of these plots are largely similar for materials deformed by both methods.

To ensure that the texture of the rolled strip had no significant variation in texture across the width of the strip, the textures of two specimens cut out 14 mm wide from the left and the right edges of the 90% rolled strip were examined. The pole figures showed no detectable differences from that of the specimen cut out from the central portion of the strip.

Recrystallization textures

As was expected, the cube textures formed upon recrystallization was weak in strips deformed to the relatively low reductions (e.g., 70 to 85%). Figure 8 shows the {111} pole figures of the recrystallization textures for the strips rolled 85, 90, and 95% [in (a), (b), and (c), respectively]. For those channel-die compressed strips, the recyrstallization textures of the corresponding specimens are shown in Figure 9. It can easily be noted that the cube texture formed upon recrystallization in the rolled sample is substantially sharper and stronger than in the channel-die compressed specimens. Also, the maximum intensities of the twin

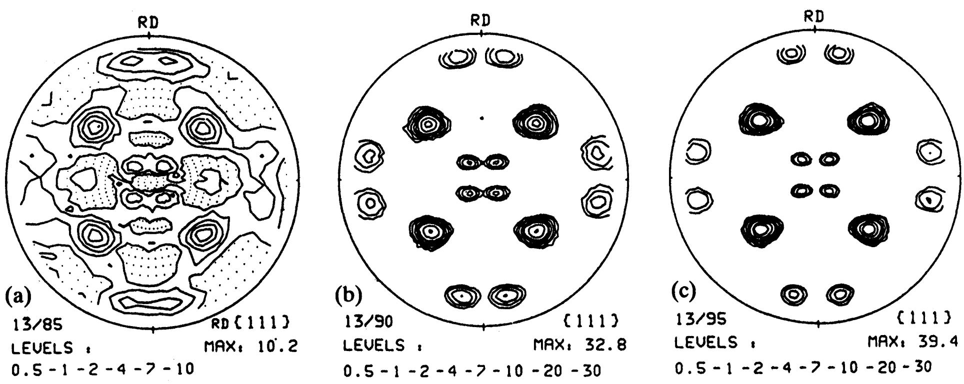

Figure 8 The {111} pole figures showing the recrystallization textures of the strips rolled (a) 85%, (b) 90%, and (c) 95%, then annealed in oil bath at 171°C for 20 min., 10 min., and 5 min., respectively.

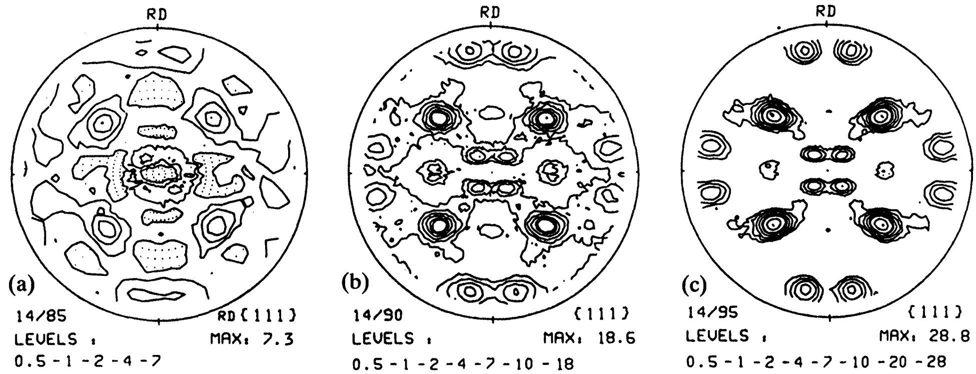

Figure 9 The {111} pole figures showing the recrystallization textures of the strips channel-die compressed (a) 85%, (b) 90%, and (c) 95%, then annealed in oil bath at 171°C for 20 min., 10 min., and 5 min., respectively.

orientations are somewhat lower, and the extent of scatter of these twin orientations is less extensive in the rolled than in the channel-die compressed specimens. For the 95% deformed specimens, Figures 8(c) and 9(c), the difference in their recrystallization textures is more strikingly shown by the low-intensity contour lines of the pole figures, Figure 10. The information given by these low intensity contours suggests that the second-order annealing twins are more prominent in the channel-die compressed than in the correspondingly rolled specimens.

It is generally recognized that the application of the series expansion method for ODF calculations in texture analysis runs into serious difficulties when a very strong single-orientation texture, such as the cube texture, is encountered. In such cases, the problems associated with the ghost and the trancation errors are

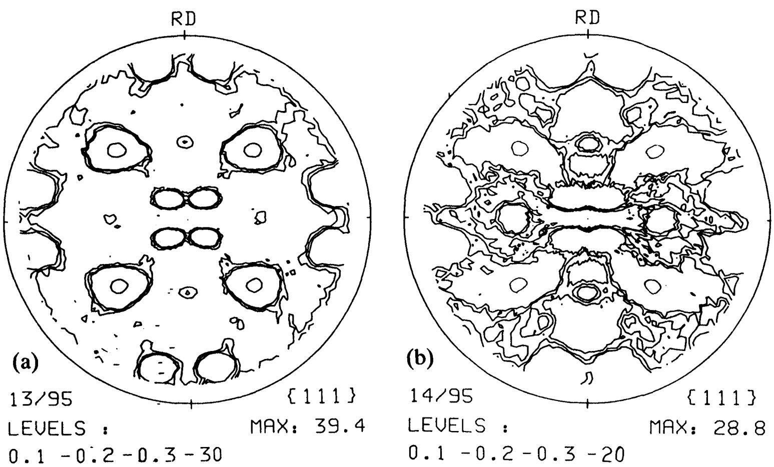

Figure 10 The low-intensity contour lines of the {111} pole figures determined for the recrystallized specimens of (a) the 95% rolled strip, and (b) the 95% channel-die compressed strip.

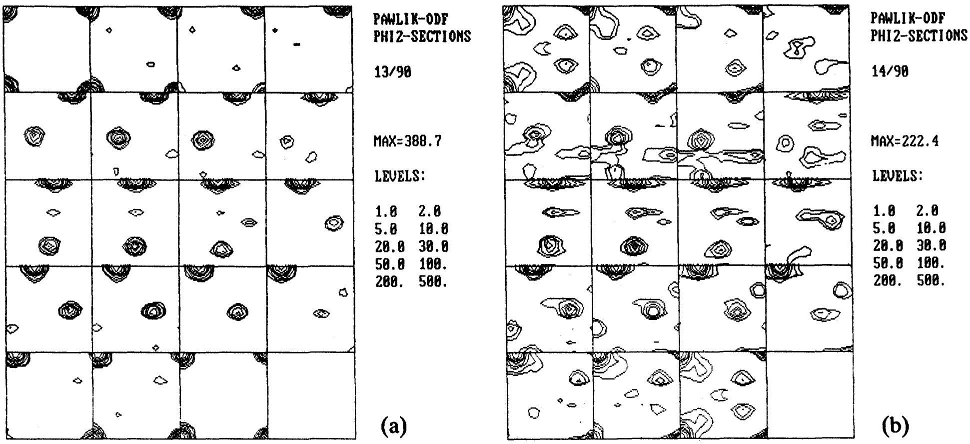

Figure 11 The ODF determined by the Pawlik iterative method for the recrystallization textures of the strips (a) rolled 90%, and (b) channel-die compressed 90%.

too great to be corrected. For this reason, the recrystallized cube and twin textures of the present investigations were treated by the iterative method of Pawlik (1986), which was shown by Pawlik and Pospiech (1986) to give a reliable approximation of the ODFs. Figures 11(a) and (b) are the ODFs of the recrystallization textures for the specimens rolled and channel-die compressed, respectively, to 90% reduction then recrystallized. Similarly, for the 95% deformed strips, the ODF of the rolled and recrystallized specimen is shown in Figure 12(a), and that of the channel-die compressed specimen, Figure 12(b). As can be noted from these figures, the maximum intensities of the recrystallized cube textures are considerably higher in the rolled, than in the channel-die

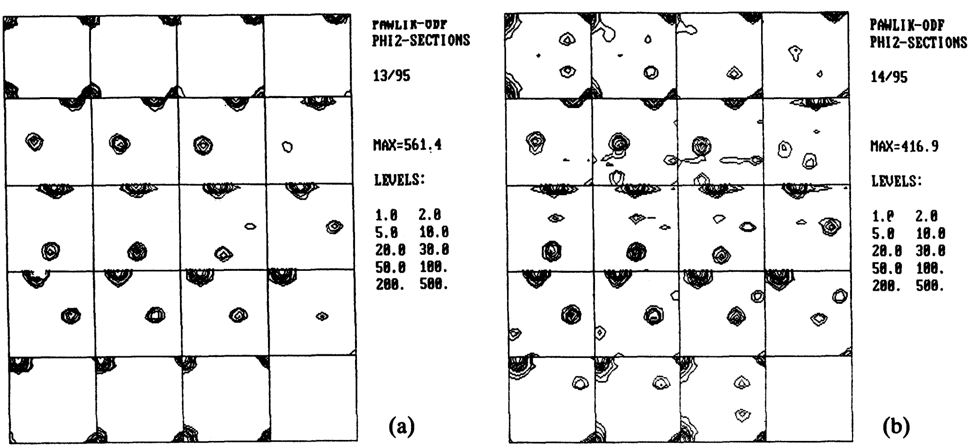

Figure 12 The ODF determined by the Pawlik iterative method for the recrystallization textures of the strips (a) rolled 95%, and (b) channel-die compressed 95%.

compressed, specimens. With reference to Figure 13, in which the positions for the first and second order twins are indicated, one notices that the second order twins are more prominent in the recrystallization textue of the channel-die compressed sample than that of the rolled sample.

The orientation densities of the cube and the twin textures in the recrystallized specimens are shown as a function of strain in Figure 14(a) for the rolled, and Figure 14(b) for the channel-die compressed, specimens. The results are consistent with the information obtained from the pole figures. For example, a strong cube texture forms upon recrystallizations only in strips deformed to high reductions (⩾85%, or true strain $\varepsilon \geqslant 2$). At a corresponding deformation, the cube texture is stronger in the rolled than in the channel-die compressed specimens. There is also some difference in the behaviour of the annealing twins. For the first order twins, there is a slight decrease in the twin density with increasing reduction from 90 to 95% for the rolled specimens, whereas for the channel-die compressed specimens, the twin density continues to increase but at a lower rate within the same deformation range. The density of the second order twins is somewhat higher in the channel-die compressed specimens.

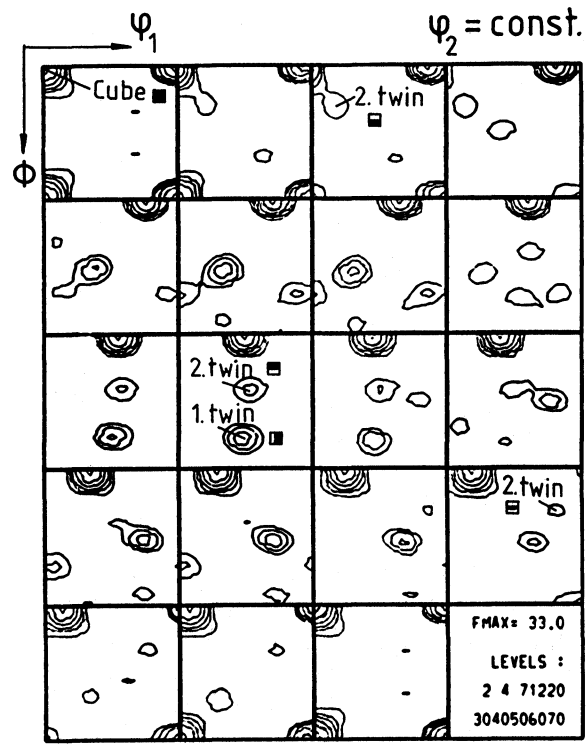

Figure 13 Positions of the cube orientation, the first order twin orientation, and the second order twin orientation in the Eulerian space.

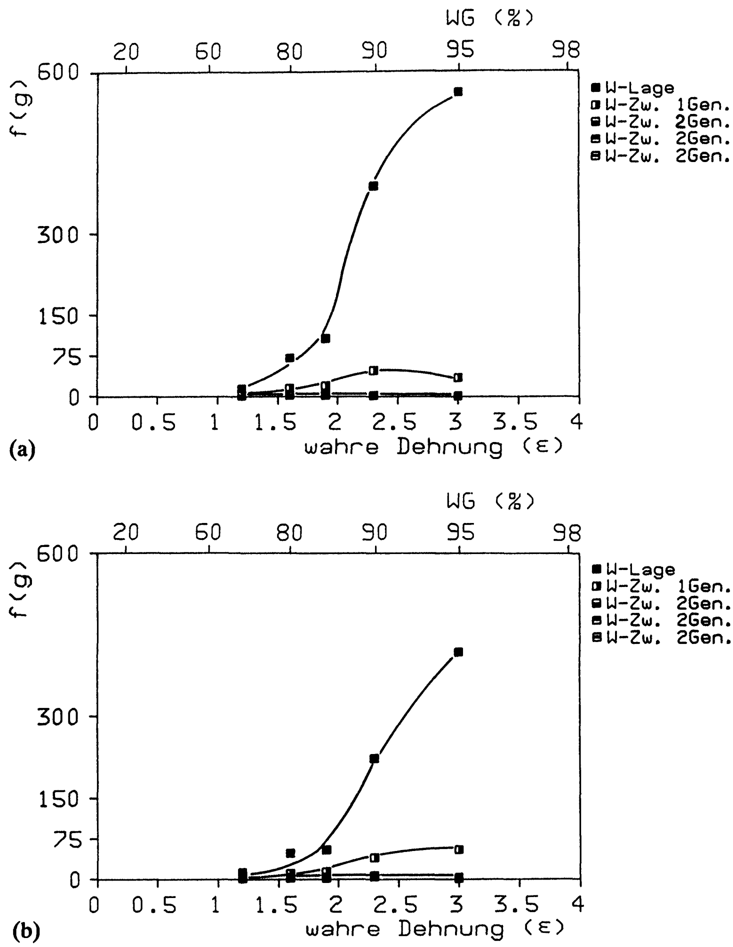

Figure 14 The orientation density of the cube texture, the first order twin, and the second order twin components, plotted as a function of % reduction and true strain (ε). (a) specimens deformed by rolling, and (b) specimens deformed by channel-die compression.

DISCUSSION OF RESULTS

From the experimental results as described in the above, it appears quite certain that there are definite differences in both the deformation and subsequent recrystallization textures of the specimens deformed by rolling and by channel-die compression to high reductions. What causes these differences in the deformation texture, which in turn, influences the subsequent recrystallization texture, would be of great interest to many of us who wish to seek a fundamental understanding of the formation of cube texture in fcc metals. We shall direct our limited discussions first pertaining to the methods of deformation employed, then to the recrystallization behavior of a highly deformed metal in relation to its textural characteristics.

Deformation Method and Texture

An obvious difference between the two deformation methods (rolling and channel-die compression) employed in the present investigation is the rate of straining. Even for laboratory rolling mills, which are usually operated at a low speed, the rate of deformation in each pass is substantially greater than the rate of straining in channel-die compression. For the purpose of comparison, the mean strain rate of every pass for the strip rolled 95% in reduction was calculated from the rolling data, using the equation given by Harris (1983):

$$\dot{\varepsilon} = V\left(\frac{2}{D\Delta h}\right)^{1/2} \ln\left(h_b/h_a\right)$$

where V is the rolling speed, D is the roll diameter, Δh is the thickness reduction $(h_b - h_b)$ of the rolling pass. Hence, $\ln(h_b/h_a)$ is the true strain of the pass. The strain rate varied from $1.50\,\mathrm{s}^{-1}$ for the first pass to $8.88\,\mathrm{s}^{-1}$ for the last pass. The averaged mean strain rate was found to be approximately $4\,\mathrm{s}^{-1}$. The rate of straining in channel-die compression was only 0.01 to $0.001\,\mathrm{s}^{-1}$. Therefore, the difference in the rate of straining between these two deformation methods was about 3 orders of magnitude. However, it was shown many years ago by Leffers (1968) that the rolling texture of a 5% Zn-brass indicated a slight change of the texture toward the brass-type by increasing the reduction rate by a factor of 5000. In the present investigation, the observed difference in the deformation textures of the rolled and the channel-die compressed specimens is in the opposite direction, i.e., the rolling texture is more prominently the copper-type than the channel-die compression texture. Therefore, the effect of rate of deformation has *not* caused the observed difference in the deformation texture.

On the other hand, the strip widening in rolling deformation, which was found to increase with increasing rolling reduction, as shown in Table 2, may have played an important role in causing the textural difference observed. In channel-die compression, the width of the specimen is restrained by the width of the channel. Hence no widening is occurred in deformation. This difference in material flow would cause a difference in the participation of the major shears (e.g. the brass, the copper, and the S shears) between the two deformation methods. Consequently, a difference in the deformation texture results.

To test the validity of this idea, a computer simulation of the rolling texture with strip widening (12.75% widening at 95% reduction) and of the channel-die compression texture without strip widening (0% widening at 95% reduction) was

Table 2 Widening of the rolled strips

Initial width mm	*Reduction in thickness %*	*Final width mm*	*Strip widening %*
34.65	95	39.05	12.7
34.65	90	37.00	6.7
34.65	85	36.30	4.8
34.65	80	36.10	4.2
34.65	70	35.90	3.6

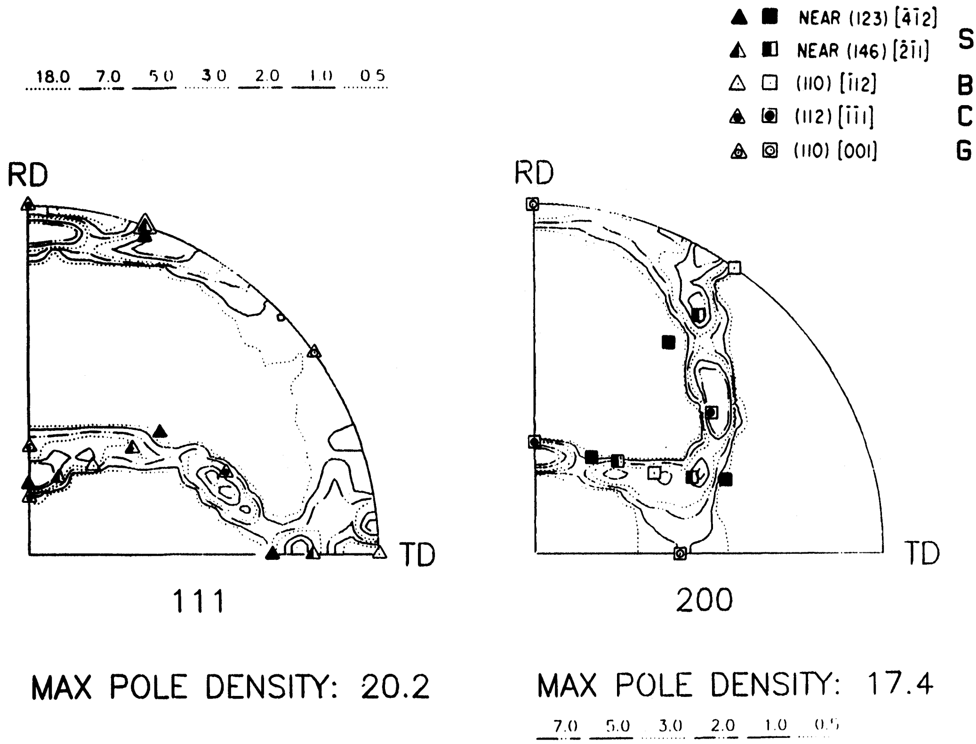

Figure 15 Calculated pole figures showing simulated texture produced by rolling with 12.75% strip-widening after 95% reduction (after Leffers).

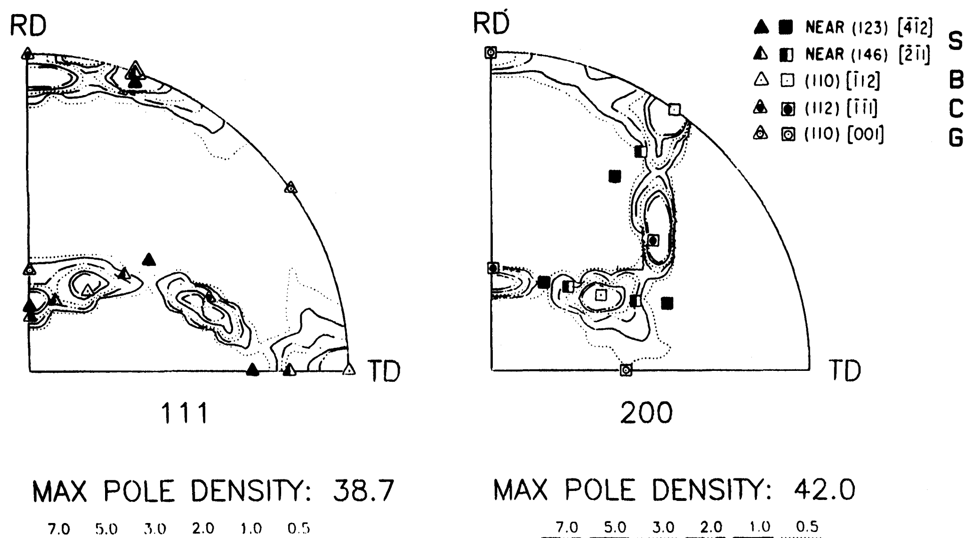

Figure 16 Calculated pole figures showing simulated texture produced by channel-die compression with zero strip-widening after 95% reduction (after Leffers).

Table 3 Comparision of calculated pole figures produced by simulated rolling (with strip-widening) and C-D compression (no strip-widening)

Texture components	*Rolling*	*C-D compression*
S near (123) [412]	Do not seem to fit to either texture very well	
near (146) [211]	Definitely stronger	Definitely weaker
B (110) [112] (Brass)	Definitely weaker	Definitely stronger
C (112) [111] (Copper)	About the same to both textures	
G (110) [001] (Goss)	Sligthly stronger	Slightly weaker
Orientation spread	Definitely more extensive	Definitely less extensive
Texture intensity	Definitely weaker	Definitely stronger

conducted at Riso National Laboratory of Denmark. The calculated {111} and {200} pole figures are shown in Figure 15 (for the rolling texture) and Figure 16 (for the channel-die compression texture), with the various ideal orientation positions indicated on the pole figures. A comparison of these textures is summarized in Table 3. The characteristics of the calculated textures (except one particular orientation, {123} ⟨412⟩, which may be less suitable to the texture) are largely in agreement with experimental observations.

Recrystallization Behavior and Texture

A study of the kinetics of recrystallization of the rolled, and of the correspondingly channel-die compressed, specimens was conducted by Juul-Jensen (1988), also at the Riso National Laboratory. The kinetics of cube texture formation during recrystallization was determined *in-situ* during texture measurements with neutron diffraction. Both the formation of the cube texture and the disappearance of the main deformation texture were measured simultaneously. The results are shown for the 95% deformed specimens during annealing at 100°C in Figure 17 (for the cold rolled specimen) and in Figure 18 (for the channel-die compressed specimen). As shown, the increase in the cube texture intensity and the decrease in the main deformation texture intensity occurred simultaneously with nearly the same kinetics after the initial period of incubation. For complete recrystallization, the time required for the channel-die compressed specimen is longer by a factor of 2 than that for the rolled specimen. The observed difference in the recrystallization kinetics, i.e., the recrystallization rate for the channel-die compressed specimen is much slower than that for the rolled specimen, is consistent with the extent of orientation spread of the specimens. It is known that the recrystallization tendency for specimens with very sharp deformation textures is generally weaker than those specimens with less sharp deformation textures and more extensive orientation spreads.

The microstructure of the recrystallized specimens of the 95% deformed strips showed also some difference between the specimens deformed by the two deformation methods. For the rolled specimen, the recrystallized structure consisted predominantly of the cube-oriented grains of fairly uniform grain size with some short and narrow twin bands. For the channel-die compressed specimen, the recrystallized structure contained clusters of much smaller grains of non-cube orientations, besides the normal cube-oriented grains. Furthermore, the

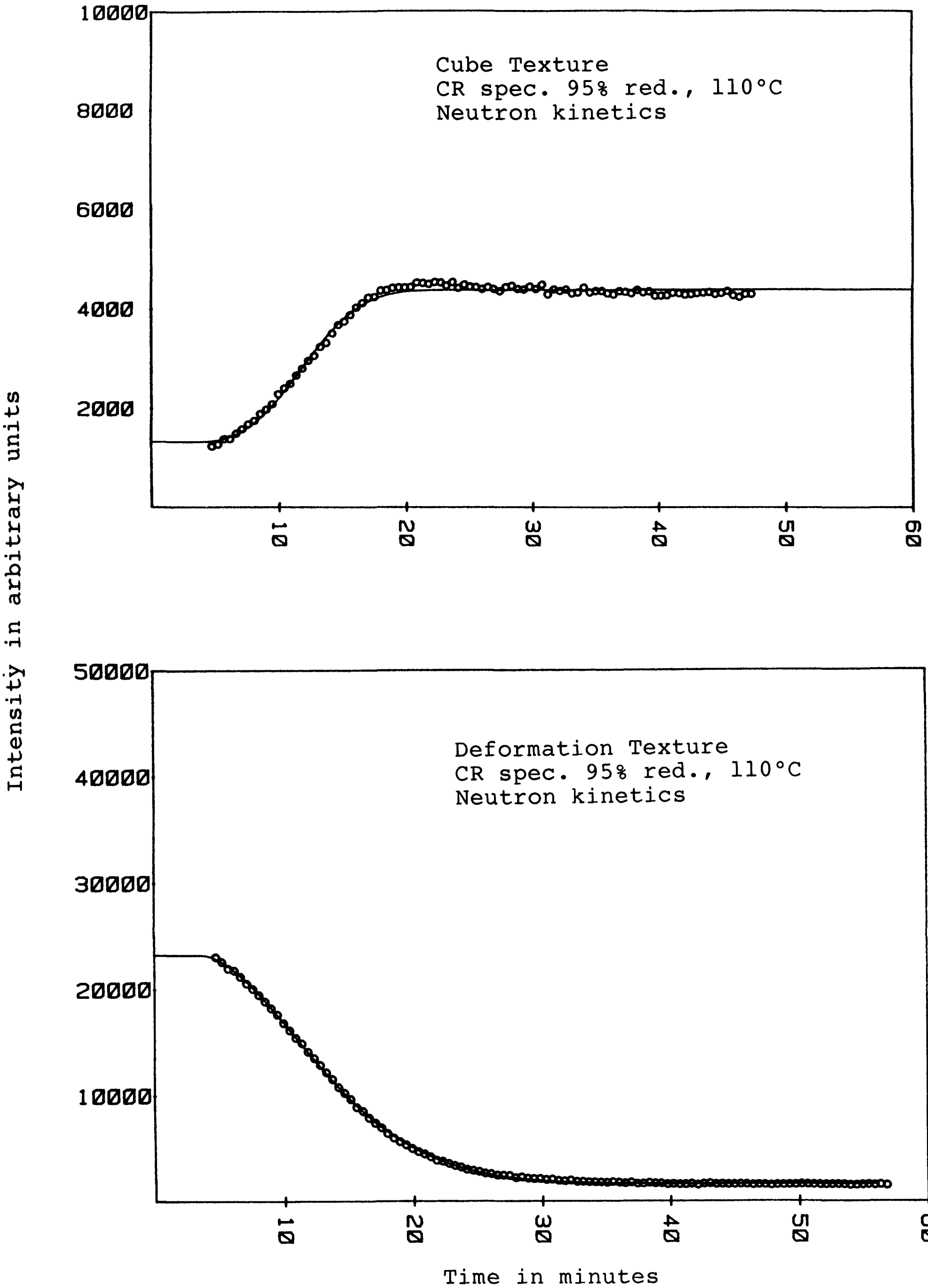

Figure 17 Recrystallization kinetics as determined *in-situ* during texture measurements with neutron diffraction. High purity copper rolled 95% (after Juul-Jensen).

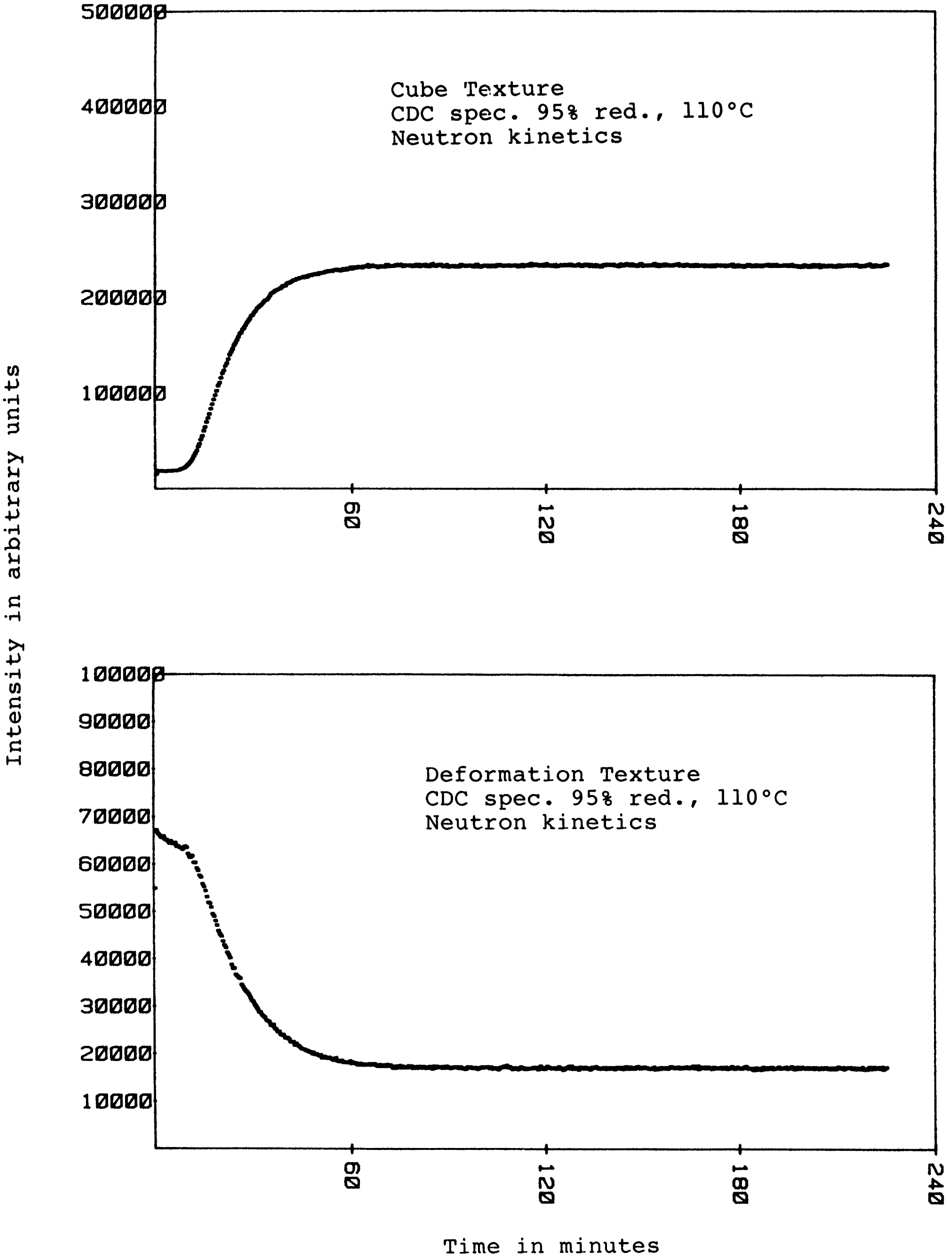

Figure 18 Recrystallization kinetics as determined *in-situ* during texture measurements with neutron diffraction. High purity copper channel-die compressed 95% (after Juul-Jensen).

annealing twins within the small grain clusters appeared to more numerous, and frequently they included second order twin bands. Whether this kind of microstructure represented an earlier stage of recrystallization, even for the rolled specimen, requires further investigation. For the observed differences in the recrystallization kinetics, and in the recrystallized microstructure and texture, how were these related to the differences in the deformation texture components observed? These and other related questions of fundamental interest must await additional research in the near future.

SUMMARY AND CONCLUSIONS

1. The deformation texture of rolled high-purity copper is significantly different from that deformed by channel-die compression, particularly at high reductions. The rolled strip shows stronger "copper" and "S" components, but weaker "brass" orientations. The orientation spread is somewhat larger in the rolled strip than in the channel-die compressed strip.

2. The observed difference in the deformation texture is due possibly to the widening of the strip in the rolling deformation. Results of a computer simulation of the effect of strip-widening on rolling texture seem to have confirmed this.

3. The recrystallization (cube) textures of the rolled and of the channel-die compressed strips of copper show also significant differences. The cube texture is sharper and stronger in the rolled strip than in the channel-die compressed strip. The twin orientations show also some differences between the strips deformed by these two methods.

4. The observed difference in the recrystallization texture appears to be a consequence of a significant difference in the recrystallization kinetics. An *in-situ* measurement of the cube texture formation kinetics by neutron diffraction indicates a considerably slower rate of recrystallization for the channel-die compressed strip. This difference in recrystallization kinetics is consistent with the extent of orientation spread of the specimens.

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