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THE COMPARISON OF UNIDIRECTIONAL AND REVERSE ROLLING TEXTURES IN POLYCRYSTALLINE FCC METALS WITH DIFFERENT STACKING FAULT ENERGY

PORÓWNANIE TEKSTUR WALCOWANIA JEDNOKIERUNKOWEGO ORAZ REWERSYJNEGO DLA METALI O STRUKTURZE RSC I RÓŻNEJ ENERGII BŁĘDU UŁOŻENIA

The formation of texture and microstructure in polycrystalline Cu and Cu-5 wt. % Al alloy during two modes of homogenous rolling have been compared. Two samples of each metal were rolled. One sample was rolled unidirectionally, while the other by reverse rolling. Some differences in the textures depending on the rolling mode have been observed in the range of deformation of the Cu-5 wt. % Al alloy where intensive twinning took place. It was also found that the texture of reverse rolling was more homogeneous across the thickness of the rolled alloy sheet than the texture of unidirectionally rolled material. No clear effect of the rolling mode on microstructure has been observed.

W pracy porównano tekstury dwóch sposobów walcowania polikrystalicznych metali: miedzi i stopu Cu-5% Al. Dla każdego z metali jednorodnie przewalcowano po dwie próbki. Dla jednej z nich, kierunek walcowania był taki sam w każdym przepuście (walcowanie jednokierunkowe). Dla drugiej próbki po każdym przepuście kierunek walcowania zmieniano na kierunek przeciwny (walcowanie rewersyjne). Sposób walcowania wpływał na teksturę jedynie w przypadku stopu Cu-5% Al, w tym zakresie odkształceń, w którym zachodziło intensywne bliźniakowanie. Dla stopu, stwierdzono większą jednorodność rozkładu tekstury na grubości płaskowników przewalcowanych rewersyjnie niż w przypadku płaskowników przewalcowanych jednokierunkowo. Nie obserwowano wyraźnego wpływu sposobu walcowania na mikrostrukturę.

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1. Introduction

Rolling is one of the most commonly used deformation processes in industrial practice as well as in scientific investigations. The influence of rolling geometry, especially the l/h ratio, where l – the length of contact between the roll and the sample, projected on the rolling direction, h – the mean thickness of the sample before and after a pass, on texture heterogeneity is well documented in literature [1, 2]. Even when maintaining the same rolling geometry, the rolling process can be executed in a different way; a sample can be rolled only in one direction in all passes or in both directions by reversing it ends between passes. The information concerning the rolling mode is rare in scientific publications. Due to the complexity of the processes in the rolling gap it is not clear whether the differences in the rolling mode significantly influence the development of the crystallographic texture in polycrystalline metals. It is known that the deformation process introduces a symmetry into the global deformation texture and the effect is directly visible in pole figures. It is the orthorhombic symmetry for reverse as well as for unidirectional idealised sheet rolling ("plane-strain compression"). Because rolling process has lower symmetry [3], the global deformation texture should be more symmetrical for reverse rolling. In general, for both rolling modes symmetry of the deformation process is more distinctly reflected in the global texture at increasing a deformation degree. The final rolling texture can be obtained due to slip only or due to mechanical twinning and slip. In fcc metals deformed at room temperature, twinning plays an important role only if stacking fault energy (SFE) of the metal is medium or low. The slip is reversible, thus slip in one direction and the slip in direction opposite to it are equivalent. It is not true for mechanical twinning, because the twinning direction is always polar. The direction of twinning results from stacking of the atoms in the twinning plane ({111} type plane for fcc metals). An atom can move easily in the twinning direction (<112> type), but would be hindered from moving in the opposite direction because such process is energetically unfavourable. The single crystal experiments indicate that low SFE is not sufficient for the twinning deformation [4, 5]. For the twinning to occur, the imposed strain state and the twinning strain must be consistent.

Even for homogenous rolling, strain/stress state in the middle layer of the rolled bar thickness can be different from that outside of this layer. For this reason one can expect some differences in the texture resulting from differences in the number of twins along the thickness of the rolled bar. The aim of the present paper is to investigate the influence of the modes of straight rolling on the texture and microstructure of fcc metals with different SFE (i.e., copper – SFE of 40 mJ/m^2, deformation by slip and Cu – 5 wt. % Al – SFE of 16 mJ/m^2, deformation by slip and mechanical twinning). Another aim of this study is to check if the texture formed in the alloy (assuming deformation by slip and twinning) in the middle layer of the rolled bar thickness differs from that outside of the middle layer and if the difference depends on the rolling mode.

2. Material and experimental methods

The investigations were carried out on polycrystalline copper and on a Cu-Al alloy. Chemical compositions of the metals are given in Table 1. To produce an uniform grain size without significant preferred orientation (crystallographic texture), both metals with 30% reduction in thickness imposed by initial rolling and with additional 20% reduction in thickness imposed by perpendicular rolling (after changing rolling direction (RD) with the transverse direction (TD)) were subsequently recrystallized for 1 hour: Cu at 650°C, and Cu-Al alloy at 800°C. Such the procedure resulted in an uniform grain size of ~ 110 μm in both materials without significant preferred orientation.

TABLE 1

Composition of investigated metals (weight %)

Al	Fe	S	Pb	Zn	Ni	As	Sn	Sb	O_2	Bi	Cu
–	0.005	0.005	0.003	0.002	0.002	0.002	0.002	0.002	0.001	–	bal.
4.73	0.01	0.001	0.002	0.002	0.001	0.001	0.001	0.0008	–	0.0009	bal.

Strains, after which the investigations were carried out, were applied by homogeneous symmetrical rolling at room temperature of the samples with initial dimensions (in mm): 5×30×80 and 8.5×30×80. To minimise texture variation across the thickness of the rolled samples, the l/h ratio was kept between 1 and 2.7 during each pass, usually the value was near 1.5. To keep rolling temperature close to the room temperature, the samples were cooled in water between passes. For each metal two samples were rolled, in such a way that the partial deformations of samples were the same. One of the samples was rolled only in one direction in all passes. The second one was rolled in both directions by reversing the ends between passes. The investigations were performed for samples deformed 30% (samples of initial thickness 5 mm), 60% and 85% (samples of initial thickness 8.5 mm). The total true strains were respectively 0.36, 0.92 and 1.9.

Texture analysis was performed by use of the three-dimensional orientation distribution functions (ODFs) in the Euler angles space, calculated by ADC method [6,7] from incomplete pole figures. Pole figures were measured by the back-reflection Schulz method [8] for {111}, {100}, {110} and {311} planes, using the X-ray diffraction technique from the middle of the rolled bar thickness (s = $\frac{1}{2}$) and for 60% deformed Cu-5 wt.% Al also in the distance from the rolled surface equal to $\frac{1}{4}$ of the rolled bar thickness (s = $\frac{1}{4}$). A modified technique of pole figure measurement giving a higher accuracy and reliability of the measurement results has been employed. Details of the technique have been described elsewhere [9]. The textures were presented as standard skeleton lines (ODF values) along the characteristic α-fibre (connecting orientations for which $\{011\}\parallel$ND, i.e., $G = \{110\}<001>$ and $B = \{011\}<211>$) and β-fibre (connecting the three main components of the copper rolling texture: $C = \{112\}<111>$,

$S = \{231\}<364>$ and $B = \{011\}<211>$ positions) and for the Cu-5 wt. % Al additionally along the τ-fibre ($\varphi_2 = 45°$, $\varphi_1 = 90°$) connecting the orientations: $\{100\}<011>$, *C* and *G*.

The metallographic investigations were performed on longitudinal sections (perpendicular to the TD) of the rolled bars.

3. Results and discussion

Microstructure development. It was found that independently of the rolling mode, the development of the microstructure during deformation of Cu and Cu-5 wt.% Al was typical for fcc metals with SFE respectively high and low. No significant differences in the microstructure of materials rolled unidirectionally in comparison with the microstructure of materials rolled in both directions were found. Microstructure of both metals (Cu and the Cu-Al alloy) with deformation 30% was relatively homogenous. Microstructure of copper after 60% deformation was still rather homogenous (Fig.1). Some structure heterogeneities were present in some grains, but they were limited to single grains only. The microstructure of the Cu-Al alloy after 60% reduction in thickness (Fig.1) was much more heterogeneous than the microstructure of copper with the same deformation. Well defined shear bands were present in the Cu-Al microstructure. Shear bands were confined

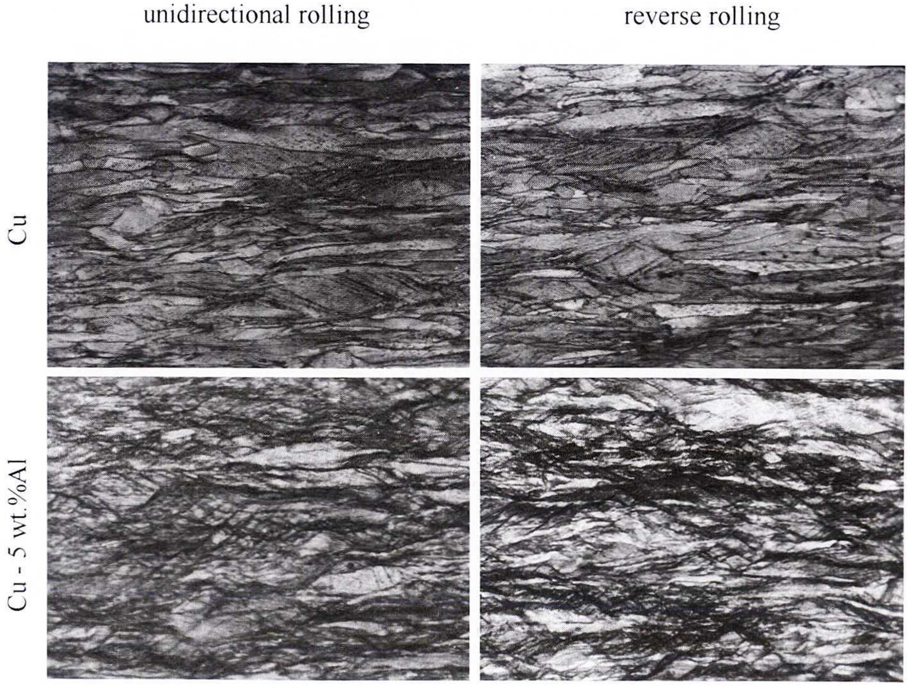


Fig. 1. Typical microstructures of Cu and Cu-5wt.%Al samples after 60% deformation (220x)

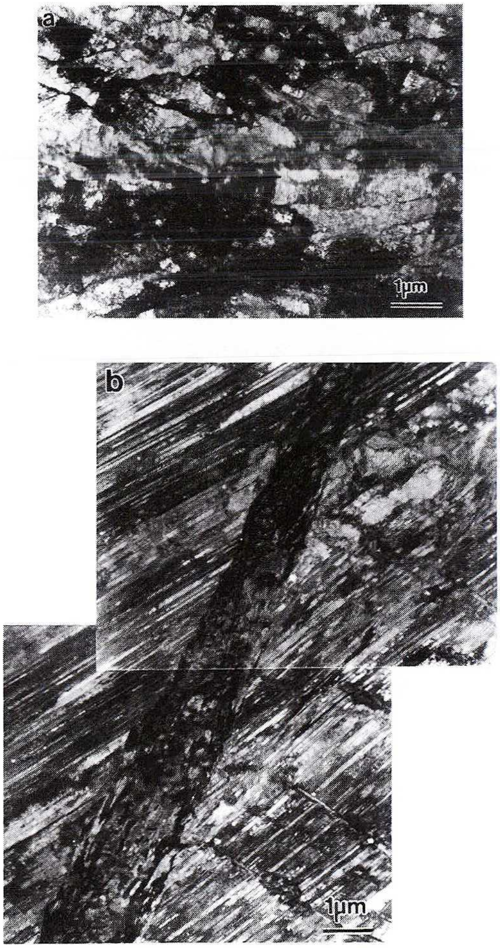


Fig. 2. Typical microstructures of the materials with deformation 60%, dislocation bands in Cu (a), the shear band in the grain filled with the deformation twins in Cu-5wt.%Al (b)

to single grains or to a group of neighbouring grains, however any shear bands did not traverse the entire specimen thickness. Typical dislocation structures of both metals are shown in Fig. 2. Microstructures of both metals with deformation 85% were much more heterogeneous than those of the metals with the lower deformations. Some microstructural heterogeneities confined to a group of neighbouring grains were present in copper. The observed high density of shear bands was typical for the Cu-Al alloy.

Texture development in Cu. The copper textures after the two different modes of rolling described by pole figures in Figs 3 and 4 and also by values of the orientation distribution function (ODF) along skeleton lines present the characteristic β-fibre and α-fibre respectively in Fig. 5 and Fig. 6. The texture symmetry observed in the pole figure is more pronounced for the case of reverse rolling. The skeleton lines of textures for the unidirectional rolling, are marked by continuous lines and for samples after

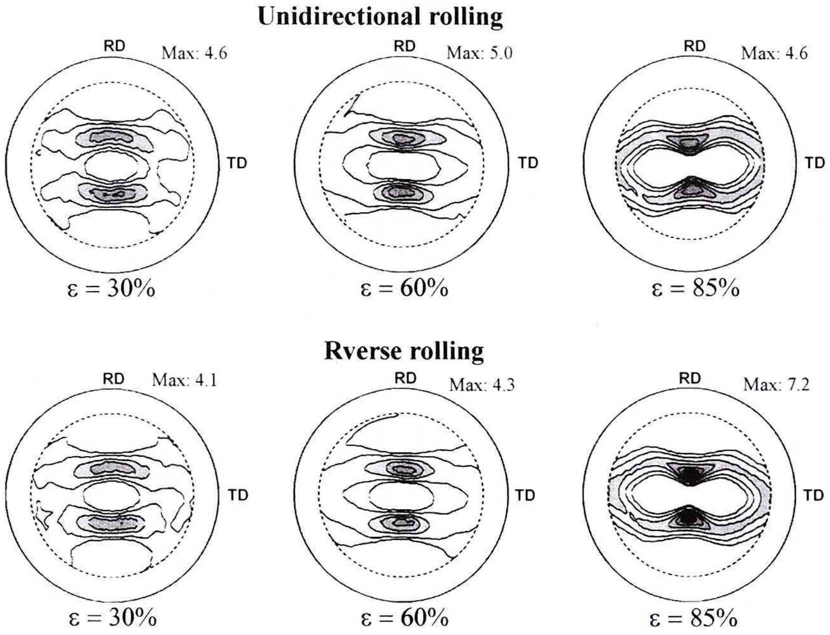


Fig. 3. Experimental {111} pole figures for Cu with different rolling reductions (ε). Levels: 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0.

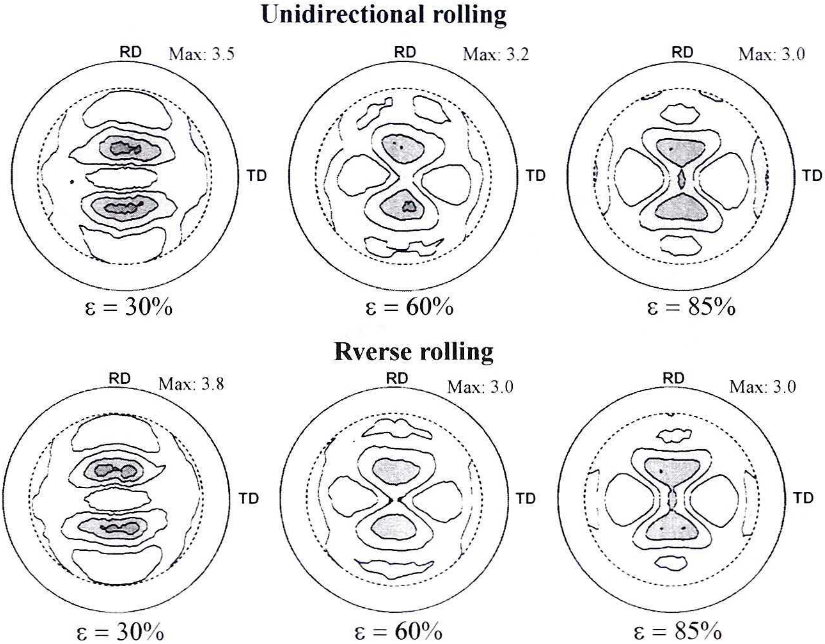


Fig. 4. Experimental {111} pole figures for Cu-5wt.%Al with different rolling reductions (ε). Levels: 0.5, 1.0, 2.0, 3.0.

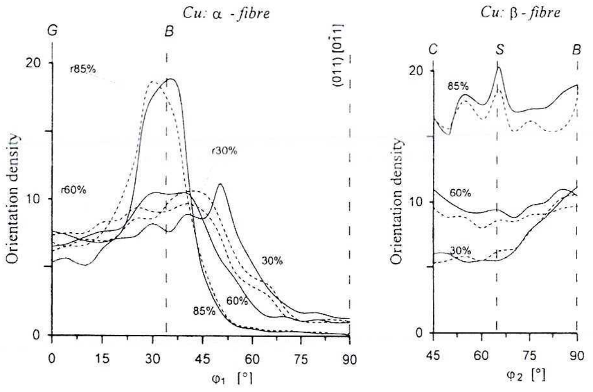


Fig. 5. The skeleton lines of the texture function for Cu after 30%, 60% and 85% deformations. Continuous lines correspond to the unidirectional rolling and the hatched ones to the reverse rolling

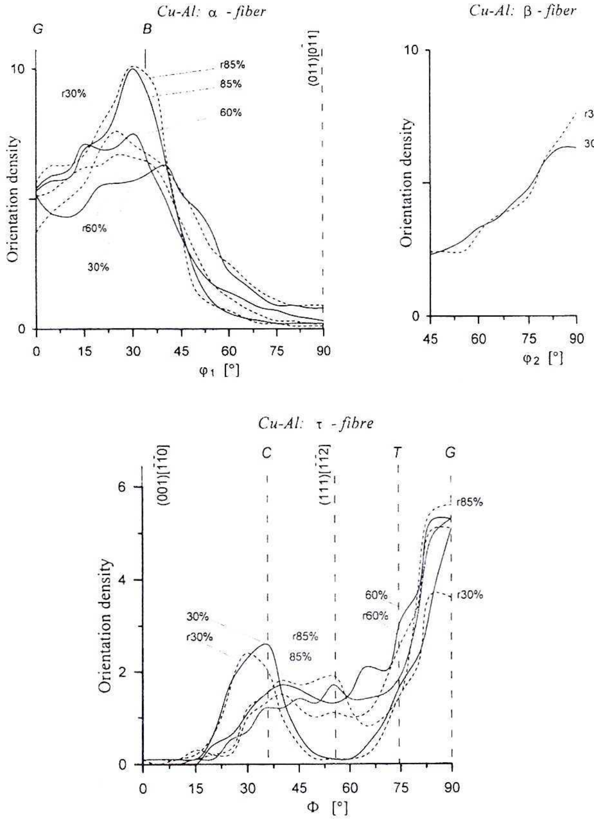
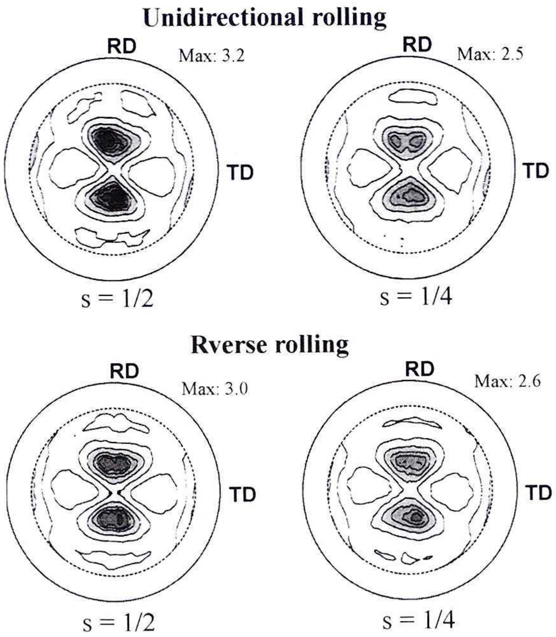


Fig. 6. The skeleton lines of the texture function for Cu-5wt.%Al after 30%, 60% and 85% deformations. Continuous lines correspond to the unidirectional rolling and the hatched ones to the reverse rolling

reverse rolling by hatched lines. For both modes of rolling typical β-fibres are formed which density become stronger with the increase of the amount of deformation. The results make evident that the change of unidirectional rolling into reverse rolling introduces only slight differences into the texture image. Relative densities along the fibres and even details of the orientation density for deformations: 30%, 60% and 85% are very similar. Gradually, with the increase of the rolling reduction, the main rolling components of the copper type texture: *C*, *S* and *B* become stronger. The domination of the *S* component after the highest reduction and the characteristic diminishing of the Goss component *G* is observed. The results correspond to the observations by Hirsch and Lücke [10]. The description of the most important features of the copper texture is completed by the presentation of the α-fibre (Fig. 5). Also in this case, the excellent agreement between the textures of the two modes of rolling is confirmed.

Texture development in Cu-5 wt.% Al. The pole figures are typical for the alloy type texture. Similarly as in the case of copper, the symmetry is more pronounced for the case of reverse rolled sample. In the sample deformed 30%, the copper type texture is formed and similarly as for copper it is characterised by the β-fibre and the α-fibre (Fig. 6). The effects of the rolling mode weakly influence the β-fibre orientations, but it can be noticed that the *B* component appears stronger for the reverse-rolled sample.


Unidirectional rolling

Rverse rolling

Fig. 7. Experimental {111} pole figures for Cu-5 wt %Al after 60% deformation for the middle rolled bar thickness (s = 1/2) and in the distance from the rolled surface equal to 1/4 of the rolled bar thickness (s = 1/4). Levels: 0.5, 1.0, 1.5, 2.0, 2.3, 2.5, 2.8, 3.0

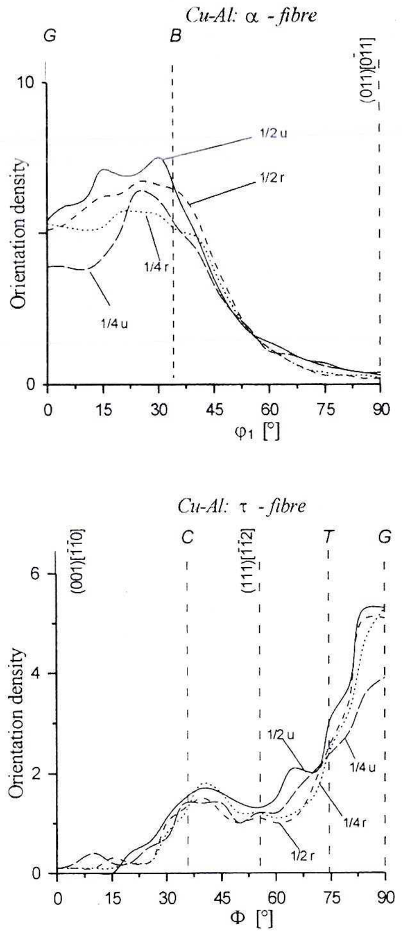


Fig. 8. The skeleton lines (the fibres: α and τ) of the texture function for Cu-5wt.%Al after 60% deformation for the middle rolled bar thickness (s = 1/2) and in the distance from the rolled surface equal to 1/4 of the rolled bar thickness (s = 1/4) for unidirectional rolling (1/2 u and 1/4 u, respectively) and for reverse rolling (1/2 r and 1/4 r, respectively)

Due to intensive twinning at higher deformations (60% and 85% reduction of thickness) a decay of the *C* and *S* components forming (together with the *B* component) the β-fibre is observed. In this situation the typical alloy type texture is formed (Fig. 4) and the texture changes can be sufficiently characterised by the α-fibre and also by the τ-fibre (Fig. 6). The ODF values along the α-fibre show that with the increase in deformation, the component near the *B* position becomes stronger, whereas the density of the Goss component remains nearly unchanged. The change from unidirectional to reverse rolling introduces some differences in the surroundings of the main component near the *B*-position, which diminish with the increase of the rolling reduction.

The influence of twinning on texture can be analysed on the skeleton line along the τ-fibre (Fig. 6). Orientations in twin relation to *C*-component are placed on the τ-fibre near the *T*-position. For the samples with deformation 30%, density of orientations along τ-fibre is practically independent on the rolling mode. Such results which correspond of that of copper can be related to relatively low density of deformation twins observed in the microstructure of the Cu-Al alloy deformed 30%.

For samples after 60% and 85% deformations, the density of twins in the microstructure is significantly higher. For these greater deformations, twinning introduces significant texture effects visible in the τ-fibre: the diminishing *C*-component, the formation of twins related orientation densities, the appearance of the {111}<uvw> components, the influence of the twin fragmentation (near {111}<uvw>) by shear bands. The intensive twinning and the accompanied effects in the texture occur earlier in the case of reverse rolling. One can speculate that it can be related to the polarisation of twinning.

The texture effects caused by the process of twinning are most distinct on the τ fibre in the range between the components *C* and *G* (Fig. 6). A comparison of the skeleton lines for 60% deformation shows that the relative orientation concentrations occur in the surroundings of the twin position *T* in the case of unidirectional rolling which is the evidence for the developing twinning process. On the other hand, the symptoms of the disappearance of intensive twinning, and the appearance of the characteristic components {111}<112> of twins with their planes nearly parallel to the rolling plane can be observed along the τ line of reverse rolling. The twinning due to reverse rolling is also confirmed by the τ curves for 85% deformation in the range containing the position *T* and {111}<112>. After the reverse rolling one can observe a relatively strong decay of the twin component around *T* connected with the characteristic increment of the component *B* in the α-fibre (Fig. 6).

For the specimens with 60% deformation by unidirectional rolling, the pole figures determined for $s = 1/4$ are a little more symmetrical than these ones determined for $s = 1/2$. The opposite situation is observed for the reverse rolled specimens (Fig. 7). A more significant texture difference in these regions of the rolled bar was registered in the α and τ fibres (Fig. 8). In the case of the unidirectional rolled specimen, the texture component *G* was weaker and the component *B* was more sharp for $s = 1/4$ than for $s = 1/2$. Thus from the texture one can conclude that reverse rolling lead to more homogeneous texture across the thickness of the rolled bar, then the texture produced during unidirectional rolling.

4. Conclusions

1. The relatively small influence of the rolling mode (unidirectional or reverse rolling) on the development of the copper type texture in copper and in Cu-5 wt.% Al after 30% deformation can be related to the slip reverse symmetry and the specific rolling geometry.

2. The increase in deformation minimises the effect of the rolling mode on the texture, except when intensive twinning occurs in the deformation process of Cu-5 wt. % Al deformed higher than 30%. For these cases the texture changes are different for the two modes of rolling and the differences can result from the polarisation of twinning.

3. For the Cu-5 wt. % Al alloy, the texture produced during the reverse rolling was more homogeneous across the thickness of the rolled bar, than the texture produced during the unidirectional rolling.

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