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EFFECT OF SHEAR BANDS ON TEXTURE EVOLUTION IN MIDDLE-HIGH STACKING FAULT ENERGY METALS AS CHARACTERIZED ON MODEL POLYCRYSTALLINE COPPER

WPŁYW PASM ŚCINANIA NA EWOLUCJĘ TEKSTURY W METALACH O ŚREDNIEJ I DUŻEJ ENERGII BŁĘDU UŁOŻENIA ANALIZOWANY NA PRZYKŁADZIE POLIKRYSTALICZNEJ MIEDZI

Periodic crystal lattice rotations within compact clusters of shear bands (SB), developed in copper (purity of 99.98%), have been characterized to examine the role of lattice re-orientation within grains on slip propagation across grain boundaries. Polycrystalline copper (grain size 50μm) was deformed 50% in plane strain compression at room temperature to form two sets of well-defined macroscopic shear bands (MSB). The deformation-induced sub-structures and local changes in crystallographic orientations were investigated by FEG-SEM, equipped with high resolution EBSD. In all the deformed grains examined (within MSBs) a strong tendency to strain-induced re-orientation could be observed. Their crystal lattice rotated in such a way that one of the {111} slip planes became nearly parallel to the direction of maximum shear. A natural consequence of this rotation is the formation of a specific MSB microtexture which facilitates slip propagation across grain boundaries without any visible variation in the slip direction although the slip plane did not coincide exactly in the adjacent grains.

Keywords: shear bands, texture, microstructure, copper, orientation mapping

W pracy analizowano zmiany orientacji sieci krystalicznej w obszarach zwartych pakietów makroskopowych pasm ścinania (PS) w polikrystalicznej miedzi o czystości 99.98% i o wyjściowej wielkości ziaren 50μm. Szczególną uwagę skoncentrowano na zagadnieniu propagacji PS poprzez granice ziaren. Próbki odkształcano w płaskim stanie w próbie nieswobodnego ściskania, w temperaturze otoczenia, do momentu, gdy następowało uformowanie się dwu rodzin makroskopowych pasm ścinania. Rozwój tekstury dyslokacyjnej oraz zmiany orientacji analizowano za pomocą systemów pomiaru orientacji lokalnych w mikroskopie skaningowym i transmisyjnym. We wszystkich analizowanych ziarnach w obszarze makroskopowych pasm ścinania obserwowano silną tendencję do rotacji sieci krystalicznej. Kierunek rotacji związany był z obrotem sieci krystalicznej do takiego położenia, w którym jedna z płaszczyzn typu{111} pokrywa się z płaszczyzną ścięcia. Naturalną konsekwencją takiej rotacji jest uformowanie się specyficznej mikrotekstury makroskopowych pasm ścinania. Rotacja ta umożliwia także propagację pasm poprzez granice ziaren bez widocznej zmiany w kierunku ścięcia.

1. Introduction

It has been well known for decades that plastic deformation of metals is not homogeneous but concentrated in different kinds of inhomogeneities of plastic flow. Shear bands (SB) or their compact clusters, called macroscopic shear bands (MSB), are frequently observed examples of unstable behavior of face centered cubic (fcc) metallic materials at large strains, e.g. [1]. However, their formation and development within the as-deformed structures and their influence on the overall texture evolution are still not completely understood.

The crystallographic aspects of shear banding in single crystals of medium-high stacking fault energy (SFE) metals have been analyzed in the past, e.g. by Wagner et. al. [2]., Jasieński et al. [3], Paul et al. [4] and for low SFE metals in servies work by Paul and Driver [5-8] using local orientation measurements in TEM and SEM. The generally accepted facts associated with shear banding within fcc single crystals are as follows:

- Shear banding is closely related to the mechanical anisotropy of the pre-existing microstructure. This suggests that shear banding is preceded by the formation of obstacles to homogeneous dislocation glide in the crystallite. The formation of these obstacles is strongly influenced by the crystallography and SFE.

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- Two groups of SB can be distinguished. If the obstacles are fine twin-matrix lamellae, typical for metals with low SFE [5-8], the SBs are classified as *brass-type*. If the precursory obstacles are the elongated dislocation walls of a cell block structure the shear bands are of the *copper-type*. They are typically observed in materials with high or medium SFE [2-4].
- In the both cases rotation-induced mechanical instability within narrow areas of the anisotropic structure of elongated cells or twin-matrix layers (and kink-type bands formation), leads to the formation of SBs.

The orientation changes induced by shear banding have been studied in fcc polycrystals by both X-ray diffraction, e.g. Donadille et al. [9], Weidner and Klimanek [10], Do Costa Viana et al. [11] and locad orientation measurements, e.g. Inagaki et al. [12], Huot et al. [13] and Ridha and Hutchinson [14]. However, in polycrystalline metals the situation can be quite complicated. In this case macroscopic shear bands very often cross the grain boundaries without any significant change in shear direction. From the point of view of crystallography the requirement of slip propagation across grain boundaries leads to some basic questions about the mechanisms responsible for slip system organization along traces of the shear plane within differently oriented grains situated inside the sheared zone. In this context, the main debate centers on whether *slip within an MSB is crystallographic or non-crystallographic*, i.e. whether the shear occurs on {111}-type planes and in <110>-type directions. A second question relates to *how the SB can influence the global texture development*.

In this work, the (micro)texture development in pure polycrystalline copper has been investigated in order to characterize the influence of local lattice re-orientations within particular grains on slip propagation and the formation of macroscopically visible clusters of copper-type shear bands. Computer-automated electron backscattered diffraction (EBSD) is a particularly suitable method of investigating the phenomenon.

2. Material and methods

Polycrystalline copper (99.98%) samples of size 10x10x10mm^3 were deformed in plane strain compression to a thickness reduction of 50% at a strain rate of $\sim 10^{-3}s^{-1}$. The experiment was performed in two stages using markers to locate the MSBs. The initial sample was channel-die compressed 24%. Then, on the longitudinal face (ND-ED plane, in which: ND and ED were normal and extension directions, respectively) three scratches along ED were made (Fig.1a). The sample was further compressed up to ~50%, at which clearly defined MSB were visible (Fig.1b). The deformation-induced dislocation structures and local changes in crystallographic orientations were investigated by TEM (200kV Philips CM20) and SEM - JEOL JSM 6500F equipped with a field emission gun and facilities for electron backscattered diffraction (EBSD). To reveal the crystallographic contrast backscattered electrons operating at 20kV were used. The microscope control, pattern acquisition and solution were carried out with the HKL Channel 5 system. For more global (i.e. sample) scale microstructure observations an optical microscopy was used on mechanically and chemically polished samples. Additionally, the texture variation in the global scale were analysed by X-ray diffraction from the as-received to final as-deformed states.

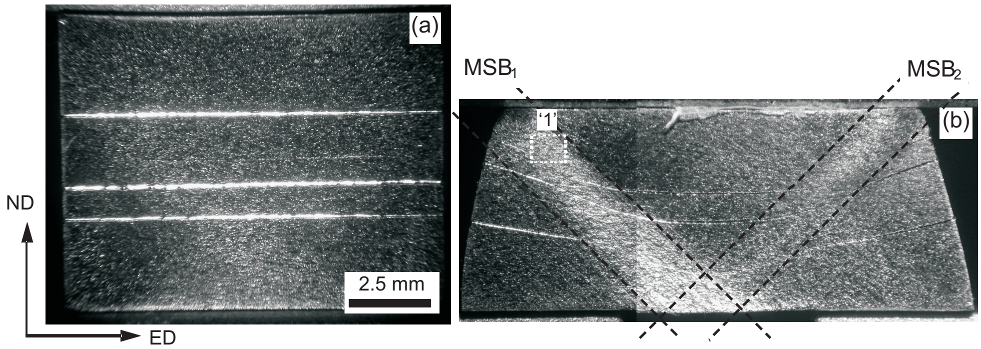

Fig. 1. MSB formation and shear deformation in copper samples deformed in channel-die. (a) initial position of scratches after 24% reduction. (b) bending of the scratches within MSB$_1$ and MSB$_2$ after further 25% deformation up to a final 50% reduction. Optical micrographs on longitudinal (ND-ED) plane

3. Results

3.1. Macroscopic changes at the sample scale

The microstructure of the as-received copper consisted of nearly equiaxial grains with an average grain size of ~50μm. The orientation distribution, determined by X-ray diffraction, revealed a relatively weak texture without any significant tendency for peak texture components. After deformations of 24% and 50%, the global texture measurements clearly indicated a systematic formation of stronger components close to the two complementary positions of brass{110}<112> with a scattering towards S{123}<634> and copper{112}<111> (Fig.2).

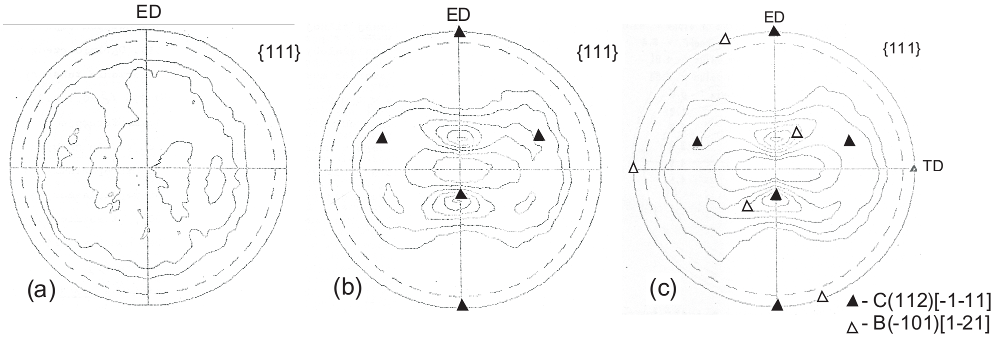

Fig. 2. X-ray diffraction {111} pole figures showing global texture development measured on the compression plane: (a) in initial material, (b) after 25% and (c) 50% compression in channel die

After the higher deformation, clearly visible differences were observed in the intensity of plastic flow due to successive strain localizations within MSBs. This was especially well pronounced at a final reduction of 50%, where the MSBs formed a characteristic V shaped set of two families (Fig 1b). The width of each set was 1.5-2mm and they were positively and negatively inclined at ~45° to ED. The scratches made on the longitudinal plane (along ED) showed a well-defined rotation (Fig.3a), of opposite sign within each set of bands. This rotation occurs with the increasing inclination of the line segments crossed by MSBs. The values of the rotation angles inside MSB_1 and MSB_2 attain ~ ± 20° (Fig.3b). The inclination of the lines decreased outside the bands. Clearly the macroscopic rotation observed within both families of bands influences the crystal lattice rotations of grains situated within the MSB volumes.

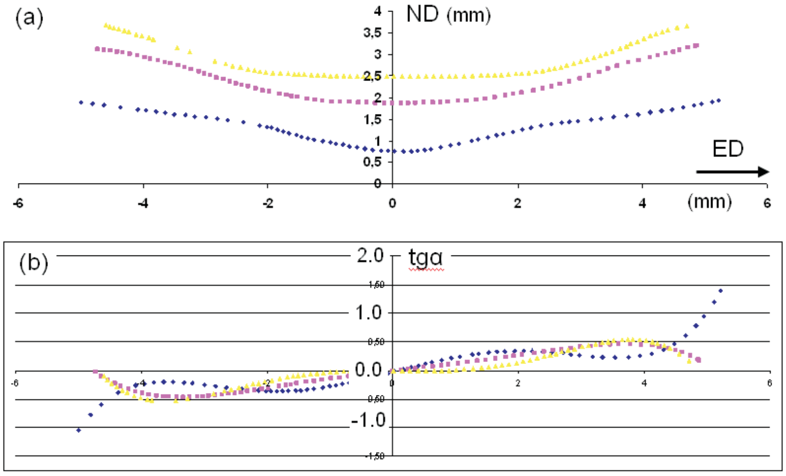

Fig. 3. (a) Changes in the inclination angle (α) of the scratches made on longitudinal plane and (b) values of tg(α) along ED for particular lines. X axis is distance in mm. Sample deformed 50%

3.2. Slip propagation across grain boundaries

Figure 4 shows the EBSD grain boundary map from a representative region of localized shear in the compressed 50% copper sample. More or less parallel bands are the important features of the MSB deformation microstructure, with a crystallographic orientation different from the surrounding matrix. The microtexture analysis of the whole map shows the formation of two nearly complementary brass{110}<112> orientations with scattering towards S{123}<634> and Cu {112}<111> components. However, this explains neither the mechanisms responsible for slip propagation across grain boundaries nor slip organization inside the MSB.

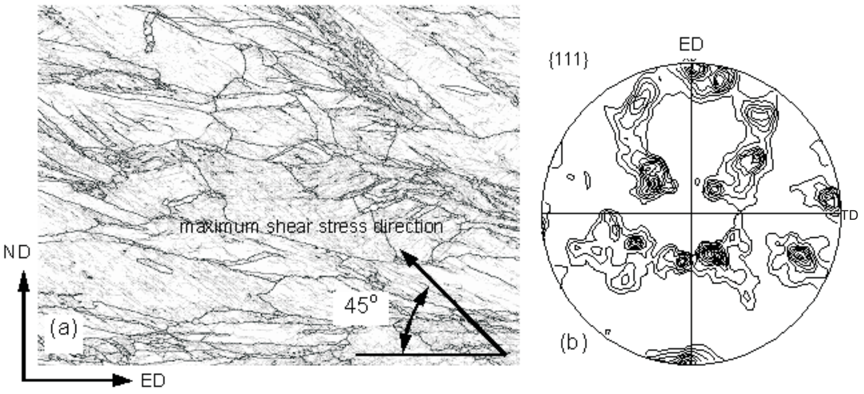

Fig. 4. (a) Grain boundary orientation map showing microstructure within highly localized regions of MSB and (b) corresponding {111} pole figure. SEM-FEG/EBSD measurements with step size of 200nm

Figure 5a shows the orientation map taken within the deformed microstructure of an MSB, in which microbands cross a grain boundary. As a result, characteristic steps are formed on the boundary indicating large shear strains due to localized slip associated with microbands. The height of each step in the band direction might be different, depending mainly on the width of the microband, and the values attain in some cases 1-2μm. However, an obvious question concerns the way in which the slip propagates across grain boundaries, i.e. whether the stress concentration near the grain boundary leads to slip on {111} plane in <110> directions in the neighbouring grain.

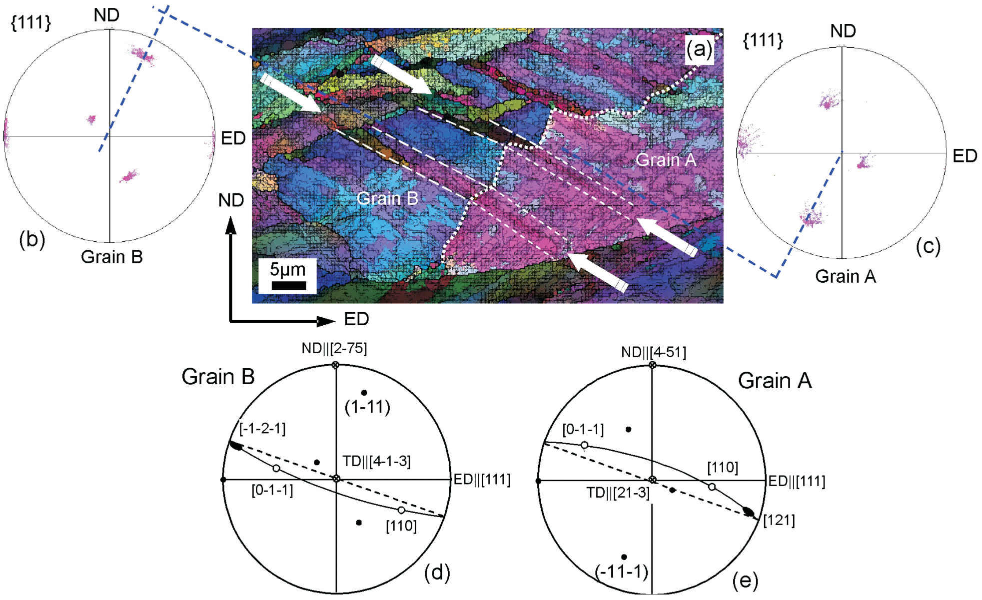

Fig. 5. (a) Orientation map showing microbands crossing grain boundary. (b) and (c) {111} pole figures corresponding to orientations of grains A and B and (d) and (e) stereographic projections presenting situation of the active slip systems within both grains. SEM-FEG/EBSD measurements with step size of 200nm

A detailed analysis of the slip traces within both grains (A and B) showed that they could be related with {111} planes. An 'average' orientation of grain A could be described as near $(4\ \bar{5}\ 1)[111]$ or in Euler angles (144, 81, 141), whereas grain B is near $(2\ \bar{7}\ 5)[111]$ (135, 55, 164). The grain orientations were misoriented by a ~33° <111> rotation. Although the traces of the bands observed in the longitudinal plane were nearly parallel, in fact the {111} planes, which were important for the analysis in each grain were only slightly misoriented (Fig.5b and c). The situation can be illustrated by stereographic projections for the 'average' orientations of the grains in the $(21\bar{3})$ plane for grain A and in the $(4\bar{1}\bar{3})$ plane for grain B. It is clearly visible that band formation resulted from the operation of two pairs of co-planar slip systems: $(\bar{1}\ 1\ \bar{1})[110]+[0\bar{1}1]$ (A) and $(1\bar{1}1)[110]+[0\bar{1}\bar{1}]$ (B). In the both cases the [121] axis ('direction of the resultant slip system') coincided with the shear direction. In the longitudinal section the traces of the {111} planes for both grains were situated along one line and corresponded to the observed traces of the bands. This situation is schematically presented in Fig.6. A similar case is shown in Fig.7a, where adjacent grains were penetrated by SBs and formed compact clusters of MSB.

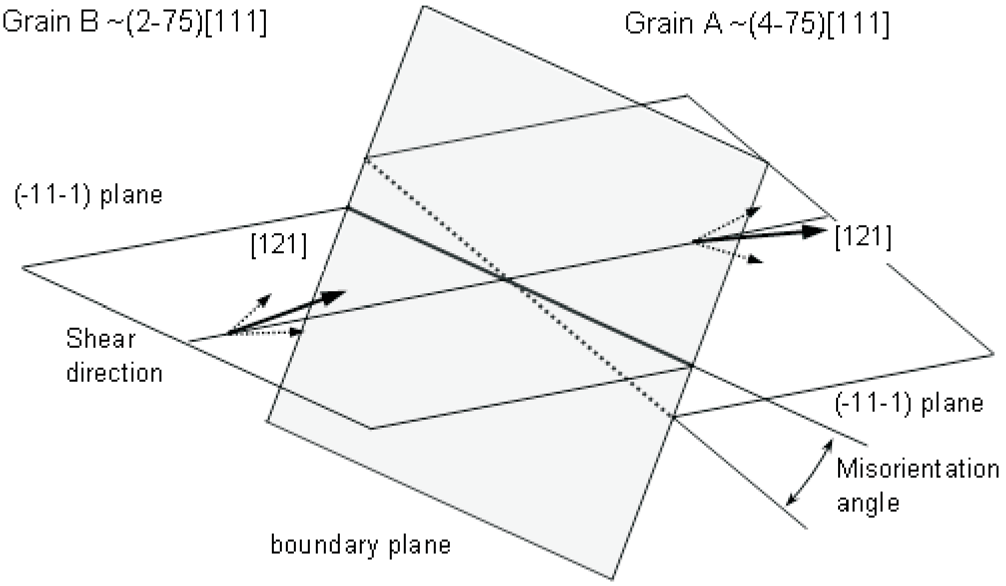

Fig. 6. Schematic presentation of situation analysed in Figure 5

3.3. Local lattice rotation vs. slip organization within macroscopic shear bands

The above mechanism of slip propagation across grain boundaries is essential for the organization of microshear bands within MSBs. The accumulation of SBs into bundles and their propagation through grain boundaries is an important problem in the process of MSB formation. The sharp crystallographic texture development, observed at increasing deformation, favors the penetration of slip in the MSB area through the neighboring grains. The situation is simple when neighboring grains have a similar orientation, and the {111} planes coincide with the plane of maximum shear stress. Slip penetration, however, occurs in regions of quite different orientations. Nevertheless, from the crystallographic point of view, the existence of a common plane for both areas is required; it is along this plane that slip can penetrate the boundary. This was clearly visible within the grains lying inside the MSB. In all analyzed grains a strong tendency to grain subdivision and strain-induced re-orientation was observed. Their crystal lattice rotated in such a way that one of the {111} slip planes became nearly parallel to the direction of the maximum shear. A natural consequence of this rotation is the formation of a specific MSB microtexture which facilitates slip propagation across grain boundaries along the shear direction without any visible variation in the slip direction. The possibility of local re-orientation of the crystal lattice as a result of SB formation in single crystals of metals with fcc lattice and low SFE has been demonstrated earlier, e.g. by Donadille et al. [9], Paul et al [5-8].

Figure 7a, shows three adjacent grains penetrated by bands of strongly localized strain. The orientations of particular grains are shown in Figs. 7(b-d). It is again clearly visible that their crystal lattice rotated in such a way that one of the {111} slip planes became nearly parallel to the direction of maximum shear although the orientations of grain 1 and 2 were quite different from that of grain 3. Additionally, in each case one of the <011>-type directions, lying in these planes, systematically tended to coincide with shear direction. This leads to the important conclusion that macroscopically observed shear plane in fact consists of small parts limited to particular grains (or their fragments) (Fig.8). These parts were only slightly deviated from the macroscopic shear plane (MSP). It is important to note that the higher the strain the smaller the deviations from the MSPs (built up compact clusters of SB). In Fig.7a the SBs are indicated by black arrows and are inclined 35-45° to ED. Across these shear bands the crystal orientation changed periodically and the accumulated point-to-origin misorientations varied by 35-40° but their axes were close to one of the <112> poles.

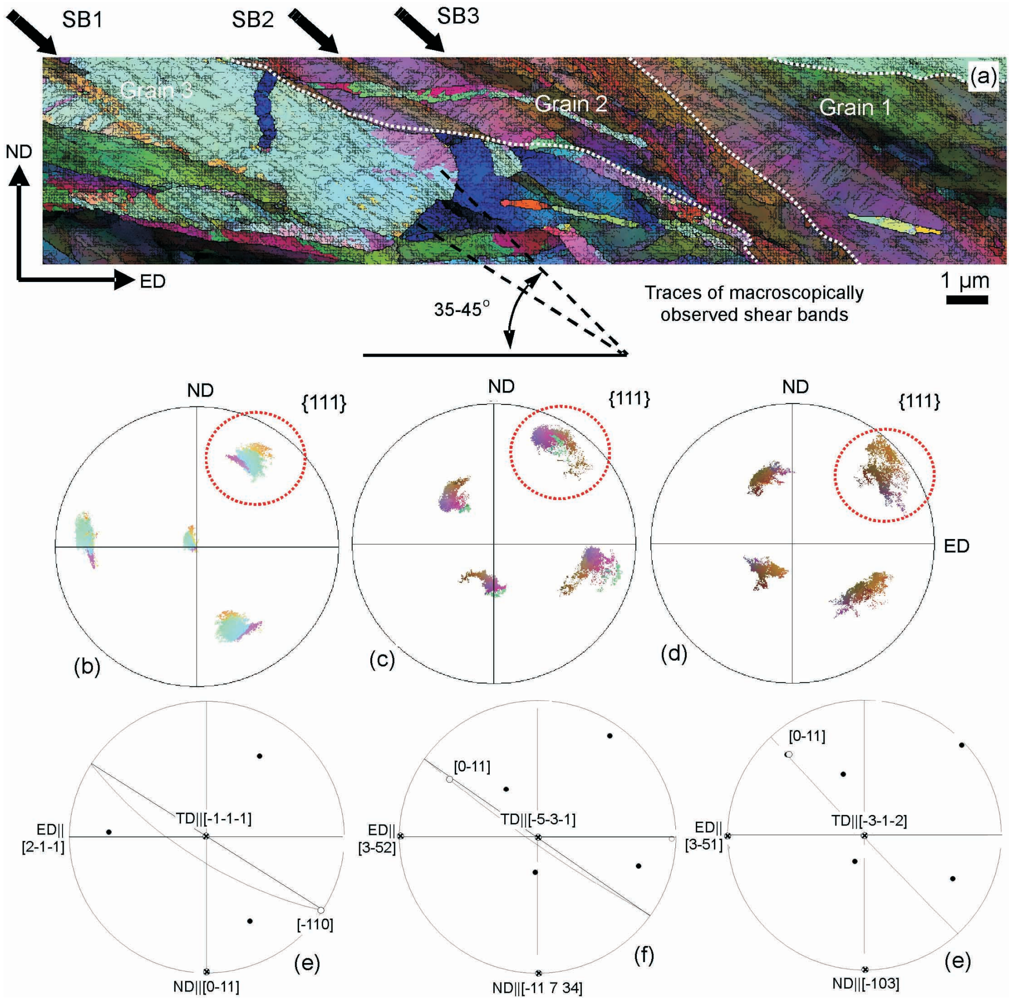

Fig. 7. (a) Orientation map showing compact clusters of shear bands crossing grain boundaries. (b) – (d) {111} pole figures corresponding to the orientations of grains 1-3. (e) – (g) stereographic projections presenting the situation of the active slip systems within all grains. SEM-FEG/EBSD measurements with step size of 200nm

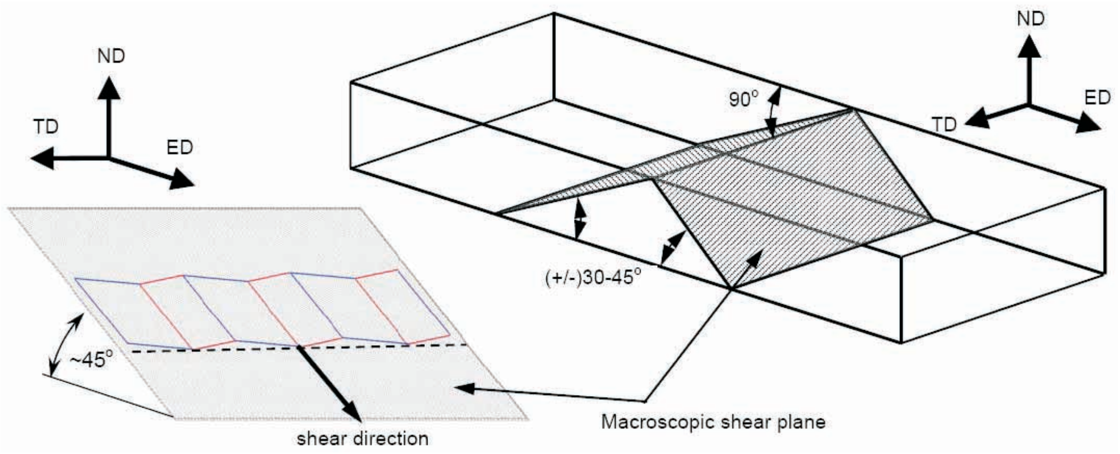

Fig. 8. Schematic presentation of the situation of active {111} – type slip planes in relation to a macroscopically observed shear plane (MSB plane)

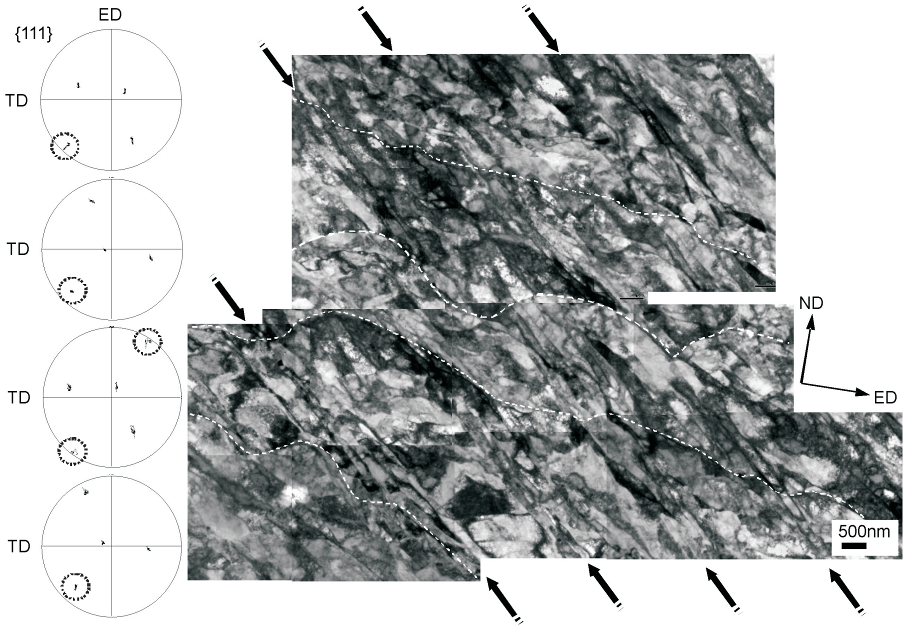

Fig. 9. TEM bright field image showing cluster of micro shear bands crossing grain boundaries and {111} pole figures corresponding particular grains. TEM local orientation measurements with step size of 30 nm

The orientation of the active slip systems progressively appears closest to the position of shear plane characteristic for actual state of planar anisotropy. The microstructure presented in Figure 9 shows TEM microstructure observed in sample deformed 70%. The traces of micro shear bands are crossing several grain boundaries without any significant change in shear direction. Despite the slip within particular grains occurs in different way one common point of this organization is the position of the {111} planes within all grains. Their position coincides with macroscopically observed shear band plane. Shear direction in some grains correspond to <011> crystallographic direction, whereas in other grains is parallel to <112>.

3.4. The change of the dominating slips system

The dominant slip system often changed within the highly localized areas of SB. The main reason for this phenomenon is the systematic crystal lattice rotation. This process quite often led to the appearance of orientations which are symmetrical with respect to the external axes. In the case of metals with middle-high

SFE they could be described by orientations close to {100}<011>, identified as a main component of the so-called copper-type SB [2-4]. In these orientations the old slip and the new one were nearly symmetrical. In the case presented in Fig.7a, significant parts of grains 1 and 2 represented these orientations. Therefore, a characteristic (of two sets) microband substructure in the form of low angle boundaries was observed. The traces of such slips lie symmetrically with respect to the shear direction.

Orientation changes within microband structures as a result of new system activation has also been observed by Dörner et al [15, 16] in bcc coarse-grained Fe-3%Si. In the case of MSBs this phenomenon was observed by Paul et al [5, 7] in highly deformed silver single crystal with {112}<111> orientation. However, in the case of low SFE metals this characteristic position was described by orientations close to Goss{110}<001>. The activation of new slip systems strongly disturbed the microbands or SB microstructures and is responsible for a new strong (although strictly defined) crystal lattice rotation. This is in agreement with the Schmid-Boas relationship for the activation of new slip systems.

4. Discussion

This study on a polycrystalline copper during plane strain compression clarifies the complex mechanisms responsible for the slip propagation across grain boundaries and texture evolution in metals with middle-high SFE. It is widely accepted that shear banding is one of the most important mechanism which can fully explain the frequently discussed [1, 9, 11-13] drastic texture transformation in the deformed state at medium and large strains of fcc metals. However, there are still unresolved problems. As for the SBs, the discussion is concentreted on details of the mechanism responsible for the 'destibilization' of the structure of elongated subcells leading to shear banding and the formation of new texture components.

In previous studies on low SFE single crystals [5-8] we ruled out non-octahedral glide as a mechanism responsible for SB formation. In our opinion, this mechanism cannot be discounted especially at low deformation temperatures. The proposed mechanism based on the observed rotation of the crystal lattice within SBs, can explain why SB plane is quite different from the {111} planes in the matrix or twins outside the band. In the past the observed non-parallelism of these planes directy led some authors, e.g. Morii et al. [17] (low SFE metals) and Korbel et al., [18] (high SFE metals), to the conclusion that slip within the SBs is non-crystallographic. However, we show that lattice rotation brings the selected {111} planes progressively into a position parallele to the SB plane and finally opens up the possibility of shear along highly privileged {111} slip planes.

Additionally, the experimental observations raise an important question. *What is the origin of the local crystal lattice rotation and the formation of new oriented volumes inside an SB?* In an eariel works [5-8] it was also shown that unbalanced bending moments are responsible for shear banding and they results from the reaction of the platens. These moments are relaxed by localized shear, i.e. shear stresses along the shear band line are accommodateed by local kinking1) of the crystal lattice along a potential shear plane. The inclination of the zone of the localized shear is dependent on actual state of anisotropy of pre-existing structure; if the anisotropy coefficients were known, this could be used for calculation of the SBs inclination angle with respect to the external axes [8].

The observet kink bands, described many times in the past, e.g. Donadille et al. [9], Jasieński et al. [3], Paul et al. [8] are a precursor to SB formation. The present work shows how the mechanism of lattice rotation within emerging SBs may lead to thier propagation across grain boundaries and to formation specific texture component. As strain becomes localised a strictly defined rotation occurs in the bands. In particular the re-orientation of selected {111} planes, within particular grains, towards the SB plane facilitates further dislocation slip in the shear direction (Fig. 8). The formation of kink-type bands make possible to conclude that mechanism of SB formation is strictly crystallographic. As a results of localized deflection, the orientation of the crystal lattice is observed to change progressively. This kind of rotation increases the Schmid factor of the systems opersting along microbands or twinning planes. This is the initial step of SB formation. The crystal lattice rotation within the shear areas systematically brings the selected {111} planes into coincidence with the shear plane. Consequently, the material outside the band is displaced. This lattice re-orientation and localised shear within narrow SBs accommodates a ceratin amount of strain at the sample scale even in the absence of slip outside the band. As shown previously [7, 8], the change of the sample height permitted by strain localization inside the SB, depends on the macroscopic band thickness and its inclination with respect to ED.

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1) Observed as a local kinking of the microband or twinning planes.

5. Conclusion

Microtexture measurements on polycrystalline Cu samples deformed in channel-die compression have been used to analyse the propagation of macroscopic shear bands. They showed that well defined crystal lattice re-orientations occurred in some grains situated within the area of the broad MSB, although those grains initially had quite different crystallographic orientations. Their crystal lattice rotated in such a way that one of the {111} slip planes became nearly parallel to the direction of maximum shear. A natural consequence of this rotation is the formation of specific MSB microtextures which facilitates slip propagation across grain boundaries along the shear direction without any visible variation in the slip direction. It was thereby established that shear banding occurred across grain boundaries by the continuity of slip direction although the slip plane did not coincide exactly in the adjacent grains.

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