Patterns of folded structure formation in the maximum bending zone of [111] FCC single crystals

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Abstract. Formation of folded structure in the zone of [111] FCC single crystals maximum bending has been studied on the example of nickel under compression tests. Quasi-periodical behavior of misorientation change in the folded structure has been established following the direction to increasing Schmid factor for the acting slip systems. Change in misorientation inside and on the boundaries of the formed folding coincides with its accumulation in dislocation system: inside and on the boundaries of deformation bands.

1. Introduction

While pressure shaping of metallic materials folding is observed in bulk materials, as well as wrinkling of surface during presswork of irregular-shaped products made from thin sheets and tubes flexure.

Generally folds and wrinkles are located perpendicularly to compression stress direction and are presented as local instabilities releasing compression strength. Folds and wrinkles could be considered as functional defects decreasing structural properties of material under further static and dynamic loadings. For the other part, formation of controlled folds could be applied as the means of obtaining special purpose products possibly used in micro- and nano- units of different applications.

Folding can be observed under different ways of deformation; it could be seen differently and could be initiated both by slipping and by twinning. Taking as an example, folding was observed in steel deformed by twinning [1]. Gubernatorov V.V. considered formation of corrugated boundaries to be the reason of folding [2]. The given results were obtained while studying the surface of rolled 3% silicon iron. It was established that such boundary in separate zones created significant misorientation (around 30°). Panin A.V. studied folding under tension on the surface of EK-181 steel polycrystals [3]. Panin V.E., Panin A.V. pay special attention to the fact that deformation of surface layer can be considered as deformation of the separate structural level of deformation system [4]. Folding effect occur ahead the moving slip while surface smoothing [5]. Finite element modeling demonstrated that the folding zone does not differ by the significant increase in deformation rate, and maximum deformation follows the slip. Similar results have been described in [6], through the mentioned work is devoted to the process of metal cutting. Apart from the given above studies important research direction in metal treatment under pressure is modeling of folding under deformation (pressing) of sheet material, e.g. Hamdan M.N. [7]. Research results in this field enable to predict folding depending on the parameters of deformed system and deformation-inducing system.

Therefore studying folding in ductile metallic materials is of fundamental and applied interest for multilevel analysis of plastic strain and working out the pressure shaping modes.

The present research is aimed at studying the patterns of folding in FCC single crystals on the example of nickel with compression axis orientation [111].

2. Materials and method

The object of the present study is nickel single crystals with compression axis orientation [$\bar{1}$11] and lateral faces (110) and (112). Slipping is performed along crystal systems <110> {111}. Selection of this type of crystal-lattice orientation is defined by its demonstration of maximum instability of samples under compression tests and subsequently the intensively developing bending of boundaries. In the zone of maximum degree of boundaries bending the most intensive folding occurs. The mentioned zone is under study within the present work. The samples under study were deformed by 22% (0.22 in relative units), thus corresponding to transition to the stage III of strain hardening curves. According to data of transmission electron microscopy this deformation leads to formation of dislocation cell structure and disoriented dislocation substructures start to grow [8]. The deformation relief were examined using the SEM instrument Tescan Vega II LMU c EBSD- console nd optical microscope Leica DM 2500P. To study the surface morphology using other methods, such as in [9] for estimating fracture parameters using the acoustic emission method. Methodology of samples preparation, deformation and their further study are described in [10].

3. Experimental results

Samples tested under compression are always influenced by frontal friction. Friction value can be reduced by using different kinds of lubricants and binders. However according to calculations by finite element analysis method it was noted that in frontal-surrounding zone stress redistribution always occurs creating inhomogeneous stress field in the sample volume [11]. While activation of friction forces the scheme of primary stresses of uneven all-round compression is realized in this zone, and in the central part of crystal – uniaxial compression scheme. At the boundaries of zones with different schemes of primary stresses macro-bending of sample is observed and this zone is characterized by intensive folding. Structural study of folding process in this zone has been held.

The zone of folded structure formation has been studied by electron backscatter diffraction. Studies of misorientations accumulations have been carried out on perpendicular boundary with excluded deformation relief (boundary (110)). This allowed considering misorientation development as long as removing from folding on the surface of sample.

Figure 1a demonstrates crystal-lattice orientation of lateral faces and sample orientation with respect to microscope coordinate system. Dashed lines demonstrate form alteration under compression by 22%. Given are the zones with different schemes of primary stresses and disoriented zones. Location of folds is almost parallel to the sample face; they are well developed and have sharp boundaries. Apart from that, rough short slip traces intersecting the folds can be distinguished. Folds are shown in Figure 1b.

The data received during experimental studies prove development of reorientation of local zones inward the crystal. In the zone of maximum bending reorientation of boundary (110) zones from its initial direction (as shown by arrow from the center of straight pole figure, fig. 1d) can be observed. Reorientation process in folded structure is characterized by blurring of orientations. This process is realized by means of alternate arrangement of zones with orientation that is close to direction [120] and orientation located between directions [221]-[121] (blurring of central spot, Fig. 1c-d). At this time inside the misorientation bands some oscillation of misorientation close to the mentioned directions is observed. Similar results are noted in works of Gubernatorov V.V., Gervasieva I.V. and their colleagues [12-13]. They show that corrugation is caused by loss of stability of material layers under plastic strain in conditions of constrained shear. Resulting from that, alternating load occurring at meso-level lead to formation of volumes with regularly alternating misorientation with respect to the initial orientation. Authors note that corrugation is the consequence of gradient of the stress-strain state along the sample section and deformation constraint of material layers in the core zone. Corrugation in its turn influences the formation, structure and location of banded structures.

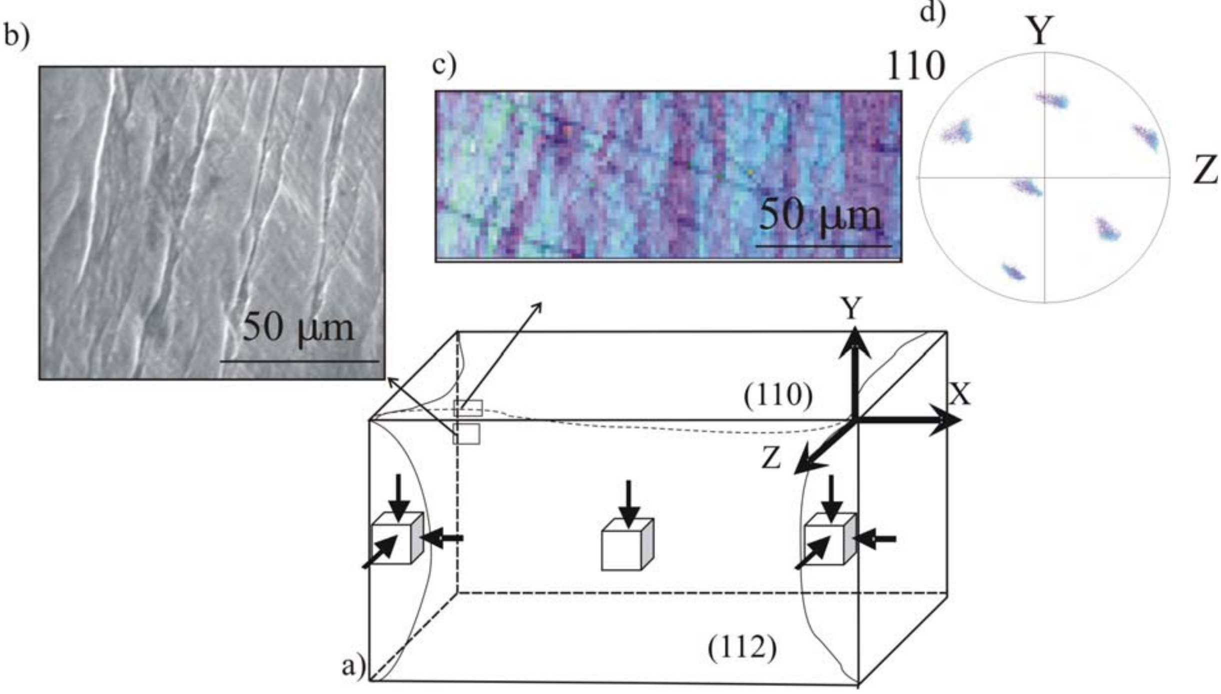

Figure 1. Crystal-lattice orientation and sample orientation with respect to the microscope coordinate system (a), folds morphology (b), reorientation in local zones (c), pole figure (d).

Figure 2a shows distribution of misorientation boundaries in the zone under consideration. It is seen that inside the reorganized bands the value of angles is 2°…8°, while along the boundaries of zones with different orientation it increases up to 30°. At this deformation degree the largest part is composed by boundaries with misorientation value 2°…3° (Fig. 2b). By analyzing alteration in the value of misorientation angles along the bands it was found that alteration has oscillating nature and varies within 3° for the zones oriented in direction [221]-[121] and within 7° for the zones that are oriented in direction [120]. Similar analysis across bands indicated compatible behavior and value of angle within 5°…6° in both cases.

When analyzing distribution of misorientation angles of the neighboring zones along the secant line in direction from point 1 to point 2 (secant line is given in Fig. 2a) oscillating behavior of alteration in value of angles is noted. In this case the values of angles that are higher than 10°…20° fall into the boundary of zones oriented in direction [120] and [221]-[121 (Fig. 3a). Misorientation accumulation with respect to the fixed point 1 (Fig. 3b) also occurs by means of periodical alteration of misorientation value. Along with that arises tendency to increase in misorientation value relatively to the initial point. This could be connected with macro-bending of the sample.

The maximum values of angles are observed with interval of 5 µm. Correlation with the behavior of dislocation structure [8] proves that such misorientation can be accumulated in misoriented dislocation cellular or micro-banded nickel substructure. Structural elements having the size of 0,5 µm at the marked higher step value misorientation of 5°…6° are accumulated on about 10…11 structural elements. When passing through the boundary of bands the angle value increases up to 15°…30°, i.e. boundaries with larger misorientation angles outline the local zones with less misorientation. Therefore the process of how misorientation zones occur from cellular structure can be seen. Similar mechanism has already been discussed before in the works of Khaterly M, Malin A.S. [14-15].

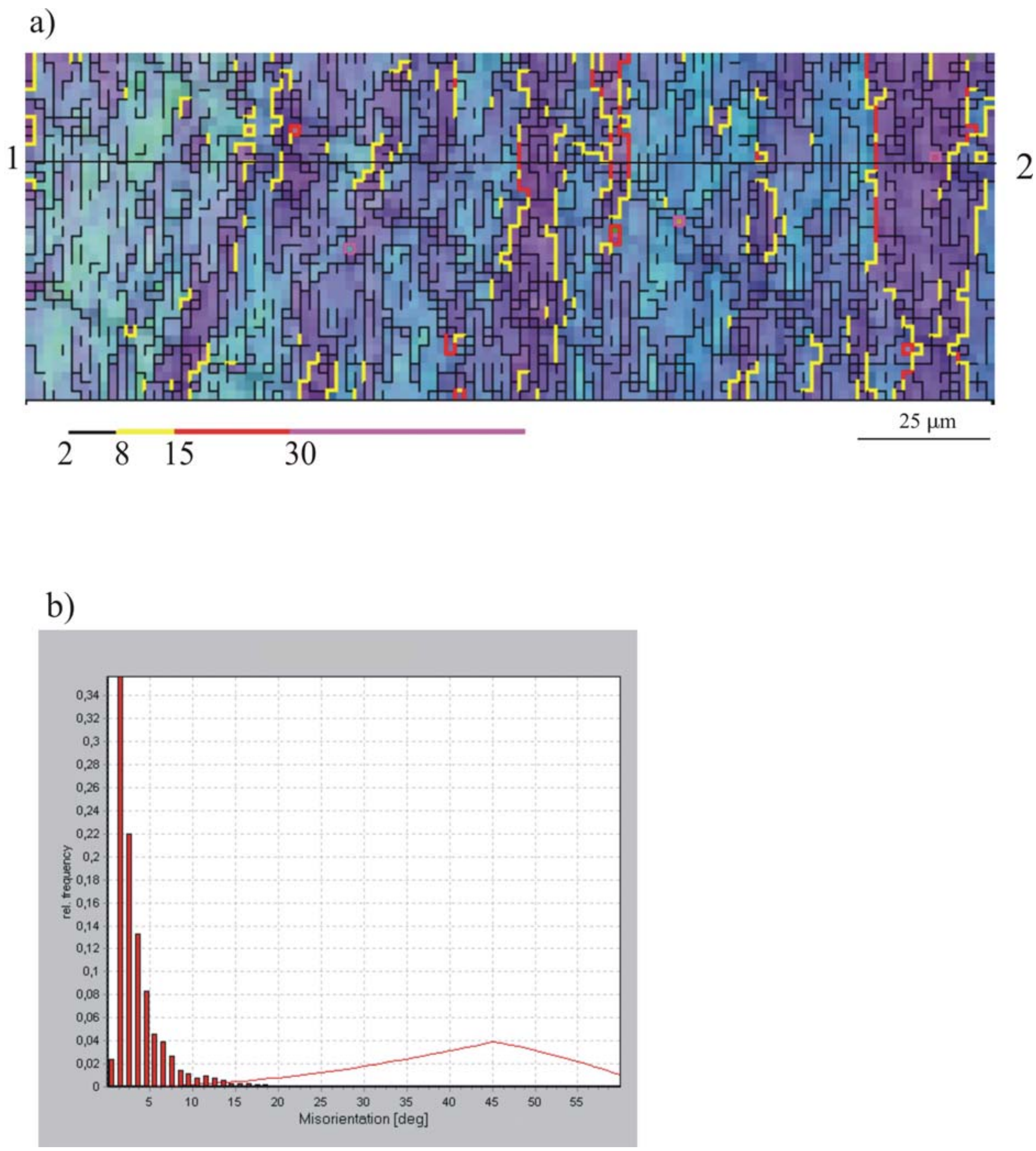

Figure 2. Distribution of misorientation boundaries (a), misorientation angles distribution bar chart (b).

The process of folded structure formation in single crystal in the zone of maximum bending can be presented as follows. With the deformation initiation six equally loaded slip planes with Schmid factor 0.27 start to act. However, only some of them are acting in local zones. Due to action of the particular shear systems local zones are characterized by bending of boundaries. In this case in order to accommodate shape alteration of boundaries the process of folding is being launched. Due to orientation alteration in folds, the acting slip systems are also changing. This phenomena observed in the experiment corresponds well with the common convictions on orientation alteration as a result of slipping in materials with fcc lattice and alterations in dislocation structure.

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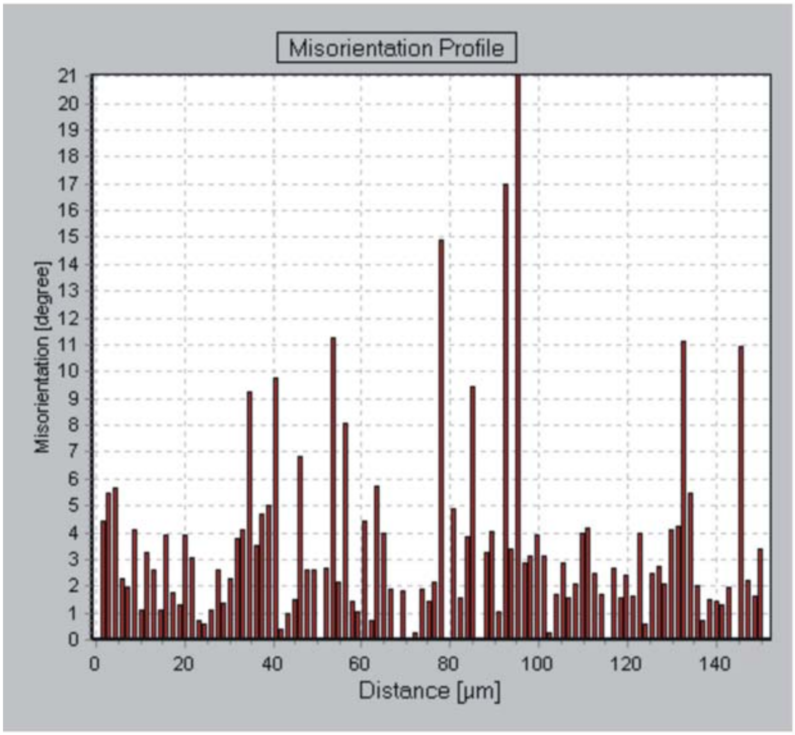
a)



b)

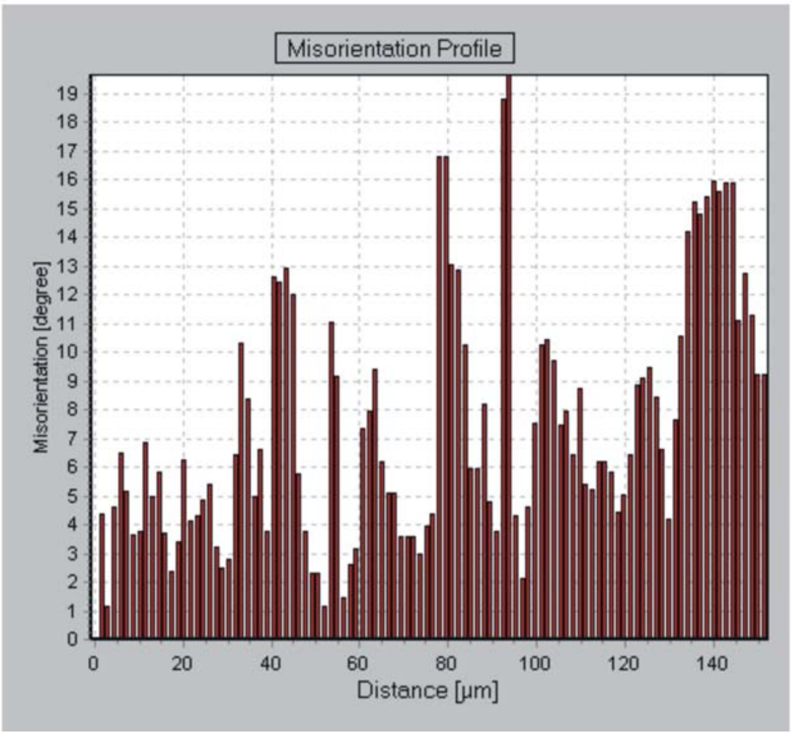


Figure 3. Distribution of misorientation angles along secant line (a), distribution of misorientation angles along secant line with respect to the fixed point 1 (b).

4. Conclusions

Zones of sample maximum bending are considered to be preferable zones of folding formation. The zone of maximum bending is the boundary of zones with different schemes of primary stresses.

Folding formation in the zone of macro-bending reflects periodic behavior of the spatial process of reorientation development. The value of period varies within 10…30 µm. Schmid factor increases in the zone of folded structure formation. Every period includes two zones, each of them having its preferable orientation, generally [221] and [120].

Alteration of orientation between neighboring zones correlates with the earlier obtained data of transmission electron microscopy.

The value of reorientation corresponds with reorientation in elements of dislocation structure inside deformation band and with significant alteration of orientation while transition from one deformation band to the other.

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