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Patterns of Grain Fragmentation During Plastic Deformation of Metals at Small to Medium Strains (Brief Review)

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Abstract

The review is devoted to the phenomenon of fragmentation: the subdivision of initial grains into highly misoriented crystallites in the process of plastic deformation. The investigations performed mostly during last two decades were considered and, in doing so, the early stages of fragmented microstructure evolution were of interest. Characteristics of regular cell block structure, described repeatedly before, were specified on the basis of more recent investigations, in particular, its orientation dependence and the development of primary and secondary microbands. The large-scale manifestations of grain subdivision, zones of intense fragmentation as well as the evolution of misorientation angle distribution with increasing strain and changing deformation conditions were also considered. Finally, the modeling of fragmentation is discussed briefly.

Keywords: Plastic deformation; Microstructure; Texture; Dislocations; Electron backscatter diffraction

1. INTRODUCTION

Subdivision of grains into misoriented regions has long been known to occur in plastically deformed metallic materials, particularly not only low-angle cell boundaries but also high-angle ones were observed [1,2]. For some time, it was assumed that highly misoriented fragments evolve during gradual transformation of dislocation cells or subgrains with increasing strain [3]. The investigations by Rybin and co-workers have showed, however, that those fragments develop against the background of dislocation cell structure at considerably larger length scale and demonstrate substantially different crystallographic characteristics [4–7]. It has been suggested [6,7] that the subdivision of original grains occurs under the action of internal stresses arising from the plastic interaction of grains: these stresses lead to a different slip activity within individual fragments and different rotations of their lattice. The development of interfragment boundaries, in its turn, was described in terms of partial disclinations [7,8]. Systematic studies of strain-induced microstructures have been conducted later by Hughes, Hansen and co-workers [9–11]. In particular, based on enhanced examination of misorientation distributions, they confirmed different nature of cell and fragment boundaries. In their studies, the fragments are termed cell block, whereas the fragment boundaries separating regions with different slip system activity are termed geometrically necessary boundaries (GNBs). The cell walls formed by statistical fluctuations are termed incidental dislocation boundaries (IDBs). In their view, the fragmentation is not caused by the grain-to-grain interaction. Instead, reduction of strain hardening and, correspondingly, minimization of stored energy is assumed to stimulate activation of different combinations of less than five systems within individual cell blocks. Concerning the terminology, it is also worth noting that some researchers use the term “fragment” in relation not to a cell block but to much larger domains containing many cell blocks and highly misoriented on average towards one other [12,13]. Concurrently with above approaches, many researchers consider the evolution of the deformation substructure in terms of recrystallization, see, e.g., [14–17]. Correspondingly, the fragmented structure developing under severe deformation is considered as a result of a kind of continuous dynamic recrystallization [16].

The microstructures developed under large strains governs work hardening behavior and other properties of metals and alloys [18–20]. Besides, highly misoriented elements of the deformation microstructure serve as nuclei

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of new recrystallized grains [17,21]. Therefore, the knowledge of misoriented structures is also necessary in order to study and model physical mechanisms of recovery and recrystallization. There is extensive literature on the ultrafine-grain structures formed after very large plastic strains [22]. At the same time, there is no review of relatively recent studies devoted to the earlier stages of the fragmented microstructure development occurring at small to medium strains, up to ~1…2. The present work is intended to fill this gap. It is noteworthy that the fundamental studies of microstructure evolution mentioned above [1–11] have been carried out mostly by means of transmission electron microscopy (TEM). It turned out, however, that essential aspects of the fragmentation phenomenon manifest themselves on the scales, which are too large for the TEM technique. These scales, particularly the grain scale, correspond well to the technique of electron backscatter diffraction (EBSD). Moreover, the latter technique is ideal for examination of the orientation inhomogeneity of microstructures. It is not thus surprising that later advances in this field are highly connected with EBSD studies.

Characteristics of a regular cell block structure, which usually occupies main part of the grain volume, were described in many publications (e.g., Refs. [9–11,18]). In Section 2, those characteristics are specified on the basis of more recent investigations. In particular, the dependence of microstructure parameters on grain orientation and the development of secondary microbands against the background of primary cell blocks are considered. The main manifestations of fragmentation inhomogeneity arising at a grain scale and violating the regularity of the deformation structure are described in Section 3. The evolution of misorientation angle distribution at strain-induced boundaries is discussed in Section 4. Finally, in Section 5, modeling of fragmentation is considered briefly.

2. REGULAR CELL BLOCK STRUCTURE

Cell blocks form quite regular structure ordered in respect to alternating misorientations at GNBs. Due to this, a considerable lattice rotation does not accumulate when crossing a grain, unless grain-scale orientation inhomogeneities arise; the latter will be considered further in Section 3. At the same time, the crystal geometry of cell block structure depends on the orientation of grain.

2.1. Orientation dependence

The effect of grain orientation on the microstructure evolution was studied extensively in the case of rolling because of its practical importance. In cold-rolled metals, the morphology of cell blocks, alignment of GNBs and character of their misorientations vary between grains related to different stable components of the rolling texture [23–28]. It has also been shown by the example of cold-rolled nickel that a significant difference in the rate of the average misorientation increase exists up to strains $\varepsilon \sim 4$ in the regions related to different texture components [29].

A detailed study of the orientation dependence of microstructure evolution was performed for face-centered cubic (FCC) metals deformed by tension [30–33]. In this case, the occurrence of two-component fiber texture makes it possible to obtain significantly more representative data than in the case of rolling. Three types of the microstructure were identified. In the grains having orientations of tensile axis in the middle part of stereographic triangle, a band-like structure forms with the one set of extended planar cell block boundaries (GNBs), which traces are approximately parallel (~5°) to a slip plane traces (Type 1). Differently arranged structures form in the grains with nearly stable orientations: the cell structure with very rare GNBs (Type 2) in the grains oriented in a small area near the [100] corner of triangle, and the complex structure with two sets of GNBs lying far from slip planes (Type 3) in the grains oriented close to [111] corner. One general conclusion, which can be drawn from above-mentioned and some other investigations [23–39], is that one set of cell block bands form inside most of grains, whereas more complex structures form in those grains who find themselves near stable symmetrical orientations already at the beginning of deformation.

The investigations of Cizek and co-workers [35–38] give insight into the orientation dependence of microstructure evolution during hot deformation. The substructures formed in hot rolled austenitic Fe−30wt.%Ni model alloy within the grains corresponding to various texture components at strain up to 0.8 were relatively homogeneous and appeared to display a similar general character, though quantitative substructure characteristics differed between individual components [36]. Only the substructure of cube-oriented grains was found to be qualitatively different in comparison with the rest of the main components [36,38]: these grains were characterized by pronounced subdivision into grain-scale deformation bands separated by high-angle boundaries and containing coarse low-misoriented subgrains.

EBSD investigations of cold rolled aluminium and its single-phase alloy conducted by Hurly, Bate and Humphreys [40–42] brought certain corrections to the picture obtained using TEM analysis. The EBSD examination confirmed that cell block bands of alternating misorientation (referred to as primary bands of cells in those studies) usually form at small strains. Based on significant statistics, it has been shown that mean misorientations at the boundaries of primary bands retain low-angle, they do not exceed ~3°

up to rolling reduction of 90%. At the same time, no evidence was found for the low-angle GNBs alignment with slip planes. It turned out that, although the bands were aligned with the traces of {111} planes when viewed in the longitudinal plane, they did not align with these planes in the rolling plane. The cell bands aligned at approximately 35–40° to the rolling direction were observed at rolling reductions of 20% and above. What is especially significant, these bands do not follow the sample shape change (correspondingly, do not undergo a rigid body rotation) at reductions up to 75%. Therefore, they are transient microstructural features, which alignment dynamically adapts to the external loading. The boundaries of these bands, in other words, continuously rearrange themselves during deformation.

It is worth noting that at the grain boundary region the cell block structures may differ from that observed in the interior of the grain. According to early studies [43,44], a reduction in the cell block size and in the cell size is usually observed as the boundary is approached, while the level of misorientation between both cells and cell blocks near grains boundaries is larger on average than within the grain interior. Therefore, the experiments demonstrate that the interaction between neighboring grains can have a considerable effect on the characteristics of cell block structure in the vicinity of grain boundaries. A research should be also mentioned, in which the orientation dependence of dislocation structure in surface grain of pure copper deformed in tension was investigated and compared with that in bulk grain [45].

2.2. Secondary bands

TEM studies of rolled FCC [9,18] and body-centered cubic (BCC) [46,47] metals showed that at a certain stage of deformation (usually at rolling reductions about 50%) secondary bands, which were called S-bands, appear that intersect primary ones. Judging by a distortion of primary GNBs at their intersections by S-bands, a considerable shear is localized in the latter. Nevertheless, they are not macroscopic shear bands [47], since their length is generally shorter than a grain diameter. Similar secondary banding was observed in the above-mentioned EBSD studies of aluminium [40–42] (the term “microshear band” was used in those studies instead of “S-band”). In contrast to low-angle primary bands, high-angle misorientations develop across their boundaries; mean misorientation angle ~20° was reported at true strain of 1.8 [40]. With further increasing strain, the bands evolve into lamellae aligned approximately parallel to the rolling plane.

The effect of deformation temperature on the banding was investigated in Ref. [42]. It has been shown that primary bands of low angle boundaries are formed at all temperatures, and their alignment to the sample axes is a function of strain and temperature, but not grain orientation. By contrast, the frequency of occurrence of the secondary bands decreases with increasing temperature; they were not observed under condition of hot deformation.

A special kind of microbands was observed to form in cold-rolled interstitial free steel, in grains with orientations near {111}<110> [48], as well as in tensile strained iron with the development of <110> fiber texture [49,50]. Bands of this kind cannot be attributed to “secondary bands”, strictly speaking, since their alignment and internal substructure coincide with those of primary bands. However, unlike primary bands, which almost always remain low-angle, they exhibit much greater misorientations. In addition to the alignment and high-angle misorientations, such microbands share another common characteristic—they form a transition zone between parts of a grain rotated toward different end orientations.

3. GRAIN-SCALE INHOMOGENEITY OF GRAINS FRAGMENTATION

According to the theory of polycrystal plasticity [51,52], a combination of slip systems operating in a grain is governed by a constraint from adjacent grains. Therefore, the influence of grain environment on the grain lattice rotation and evolution of in-grain microstructure is a fact beyond doubt. It turned out, however, that Taylor model or its later modifications cannot account for this influence. The XRD [53,54] and EBSD [55,56] studies showed that the evolution of grain microtexture (in-grain orientation distribution function) depends not only on the initial grain orientation but also on the specific local neighborhood of the grain. As a result, grains of close orientation, but different neighbours, may demonstrate mean rotations and fragmentation patterns that vary significantly. There are also several other studies, whose authors convincingly affirmed the effect of local grain neighborhood on the in-grain subdivision [26,57–62].

Note that before appearance of distinct fragments, orientation gradients in regions, which sizes significantly exceed the mean size of cell block, appear from the very beginning of deformation [60–64]. It has been detected that misorientation decreased linearly from the grain boundary into the inner part of the grain in interstitial-free steel [60] and copper [63] subjected to uniaxial tension. An examination of orientation gradients parallel to and perpendicular to boundaries suggested that the latter tend to be considerably larger of the two [63]. Detailed examination of orientation spread within individual grains in interstitial-free steel using 3DXRD supplemented by crystal plasticity simulations has been presented in Ref. [61]. The authors

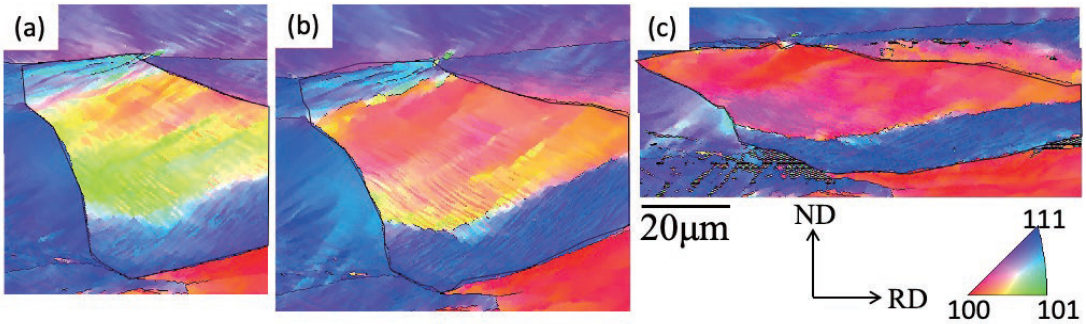

Fig. 1. Change in the orientation map (inverse pole maps for ND direction are shown) of the same grain with rolling: (a) 50%, (b) 60%, and (c) 70% reduction. High-angle boundaries (> 15°) are black. Reprinted from Ref. [68], © 2022 The Iron and Steel Institute of Japan. Available under the terms of the CC-BY-NC-ND 4.0 license.

concluded that the orientation of the grains controls the identity of the most active slip systems. At the same time, they confirmed that the relative variations in the activity of these systems are too big to be explained by the effect of Taylor ambiguity (the ambiguity in slip system selection from equally favorable slip combinations predicted by the Taylor theory). Thus, it must be, again, attributed to grain interactions. With this in mind, let us continue consideration of the fragmentation phenomenon.

3.1. Deformation banding

A long-known phenomenon related to the large-scale orientation subdivision of grains is the so-called *deformation banding*. It should be note that term "deformation band (DB)" is often used by different authors with reference to completely different band-like features formed in the course of deformation. Here we use it as it has been suggested in early studies [65,66], concerning the subdivision of grain into several large domains whose orientations rapidly diverge during deformation. A regular cell block structure (see Section 2) evolves within every domain depending on the orientation of the latter. Large size of initial grains seems to promote formation of the DBs. Theoretical consideration showed that formation of DBs might be a consequence of an intrinsic instability of the deformed grained, in particular, a product of Taylor ambiguity [66]. However, further analysis indicated the role of grains interaction with their nearest neighbors [67].

The difference of orientations arising between DBs is usually accommodated within the narrow "transition bands" [65–67]. These zones of large orientation gradient play an important role during recrystallization, and for this reason attracted attention of many researchers [17]. In early studies, the transition bands were considered only as sets of low-angle sub-boundaries. Recent studies of low-carbon steel under cold rolling [68] and iron under compression [69] showed that these sets might transform to the high-angle boundaries with increase of strain. One can see an example of such a transformation in Fig. 1. It has been shown [68] that slip deviating from the Taylor model is activated within the DBs.

The DBs may not have a pronounced band-like shape, as can be seen, for example, from Fig. 1. At the same time, true grain-scale bands arise in many cases. In particular, this happens during shear deformation under condition of equal channel angular pressing [69–72]. Detailed investigation of such banding has been carries out by example of large-grained Nb polycrystal deformed by compression [73]. After each deformation step, one grain was characterized using EBSD. It has been shown that the appearance of orientation gradient after 5% reduction precedes the generation of DB after 11.5%. The latter involves the splitting of the band, in which an orientation gradient is concentrated, into two "rotation fronts" moving in opposite directions. A mechanism for the initiation of a band is suggested in [73], which is associated with the long-range internal stresses developed in the regions of orientation gradient.

Another investigation of the early stage of fragmentation is worth noting. The examination of polycrystalline copper deformed by tension to a strain of ~ 0.25 [74,75] showed that lattice rotations within some coarse domains of original grains are consistent with the prediction by the full-constraint Taylor model. At the same time, finer domains were also observed in this study near original grain boundaries. Analysis of lattice rotations showed that the grain interaction plays determining role in their formation.

3.2. Regions of intensive fragmentation

Concurrently with the formation of regular cell block structure and grain-scale deformation banding, rather fine and highly misoriented fragments form in certain areas of deformed grains. Although these regions of intensive (severe) fragmentation may occupy quite small fraction of the area of a grain at medium strains, they give major contribution to the accumulation of strain-induced high-angle boundaries.

Depending on the material and deformation conditions, the inhomogeneity of fragmentation may take various forms. Among them are the following:

1) Isolated fragments, which, as a rule, are adjacent to grain boundaries and extended along them; these features have been described in detail by example of cold rolled interstitial-free steel [77], and also were observed in tensile strained iron [50].

2) The sets of microbands described in Section 2.2.

3) Regions of severe fragmentation, which are clusters of fine fragments formed predominantly near original grain boundaries; they were observed, for example, in austenitic steel deformed by warm rolling [77] and in tensile-strained copper, both after cold and warm deformation [78].

4) The transition zones formed between DBs in tensile strained iron [50,79].

Concerning the latter, transition zones of three different types have been described in Ref. [49]. The first are the ordinary transition bands (see Section 3.1) accommodating a high orientation misfit by a set of low-angle boundaries, which can transform further into a high-angle boundary. Two other types are (i) zones with pronounced crystal fragmentation (Fig. 2a), and (ii) the families of parallel alternatively misoriented microbands (Fig. 2b). In both cases, these zones provide accommodation of the large orientation difference between the grain-scale DBs marked by I and II in Fig. 2.

Probability of occurrence and character of the fragmentation inhomogeneity depend on the material and the deformation conditions [78,79]. For example, the intensive development of DBs observed in tensile-strained iron having <110> fiber texture is probably due to the well-known peculiarity of BCC crystals deformed by uniaxial extension along <111> axis [80]. In this case, the same longitudinal deformation of constitutive grains is accompanied by different strains in the transversal plane, which causes strongly inhomogeneous deformation of the grains, including their bending.

4. EVOLUTION OF MISORIENTATIONS AT STRAIN-INDUCED BOUNDARIES

The distributions of IDB and GNB misorientation angles become wider and their average angles increase with increasing strain. At relatively small strains, when scaled by the average angles, they come to a single gamma distribution for each boundary type, f_1 for IDBs and f_2 for GNBs [10,81]. The IDB misorientation distribution retains the scaling in the whole strain range. In contrast, the GNB distribution does not scale at strains of larger than ~ 1 because high angle strain-induced boundaries develop, whose misorientation angles fall far beyond the range of f_2 [11,82,83]. Concerning the case of rolling, it was suggested that boundaries of this type develop when adjoining fragments rotate towards different preferred final orientations [11]. However, it turned out that such boundaries develop as well when a one-component texture forms, for example, in copper deformed by compression [84]. It has been shown by examples of

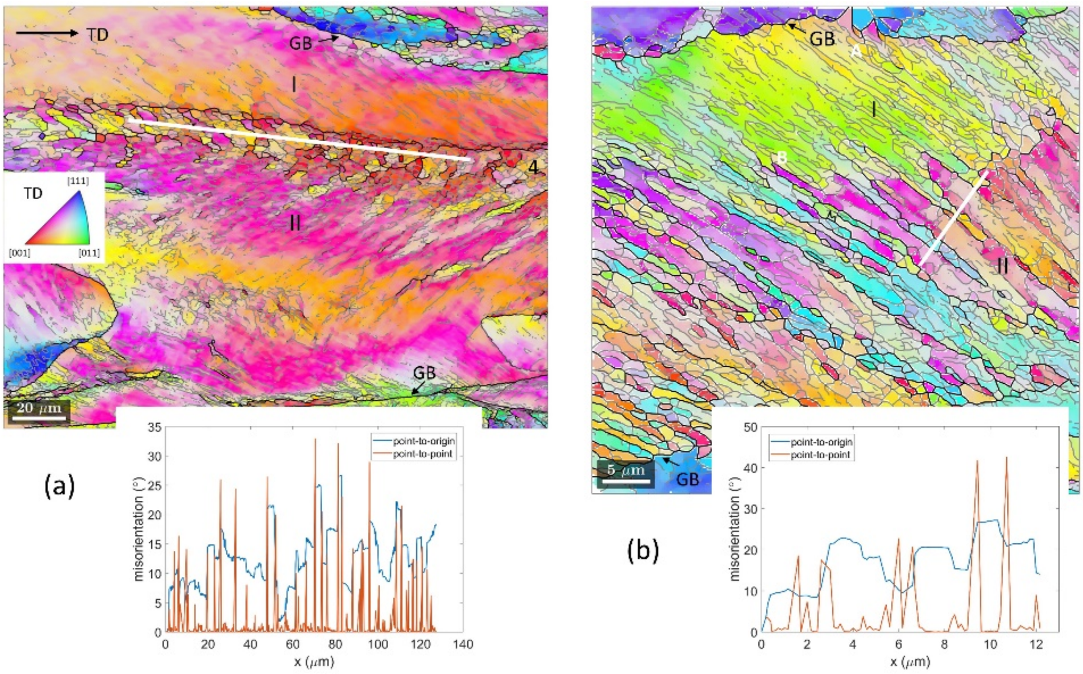

Fig. 2. EBSD maps of two areas of iron specimen deformed by tension to true strains 0.95 (a) and 1.15 (b). Longitudinal section of the specimen is shown. The maps are colored according to orientation of tensile direction (TD) on the inverse pole figure; initial grain boundaries (GB) are indicated by arrows. Misorientation distributions along white line segments are inserted below the maps. Reprinted with permission from Ref. [50], © 2022 Elsevier Ltd.

compressed copper [84] and iron [85] that the high-angle strain-induced boundaries with misorientations falling beyond the range of f_2 can be described using another gamma distribution, f_3 (Fig. 3). A relative contribution of f_2 remains approximately constant or becomes even smaller with increasing strain, whereas a contribution of f_3 increases gradually [84]. Therefore, the most significant feature of the misorientation evolution at strains $\varepsilon > 1$ is an accelerated development of partial distribution f_3. The boundaries producing f_3 seem to result from an increasing divergence of orientations of neighboring fragments. When this divergence reaches a certain point, significantly different slip patterns may be activated on both sides of the boundary. At this instant, its misorientation begins to rise with a much higher speed than before, and thereby this boundary passes from distribution f_2 to f_3.

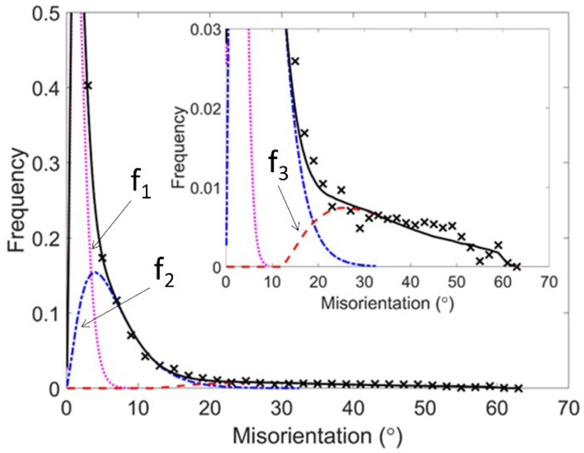

Fig. 3. Representation of misorientation angle distribution across strain-induced boundaries in copper deformed by compression to $\varepsilon = 1.3$ (crosses) together with the results of modelling partial distributions f_1, f_2 and f_3 (colored lines). Black line indicates the sum of the partial distributions. Enlarged image of part of the plot is inserted. Reprinted from Ref. [84] with permission, © 2018 Elsevier Inc.

The scaling behavior of strain-induced misorientations has a physical significance, since it indicates that a physical mechanism remains unchanged when changing conditions of plastic deformation. With this in mind, the misorientation distribution of strain-induced boundaries were examined recently [78,86]. Note that the scaling of GNBs has been proved using TEM through their visual separation from IDBs. The EBSD technique does not allow one to make such a separation and, for this reason, an approximate solution of this problem based on crystallographic characteristics of GNBs has been used. A tensile experiment was conducted with polycrystalline copper deformed under three different conditions: at a constant strain rate at room temperature and at 400 °C [78] as well as at a constant stress at 400 °C [86]. Appropriately normalized angle distributions are shown in Fig. 4. It is seen that a scaling of misorientations remains for three conditions studied. This suggests that, in spite of recovery and recrystallization occurring at 400 °C, the mechanism of strain-induced boundary evolution within non-recrystallized part of the material remains the same as it was under cold deformation.

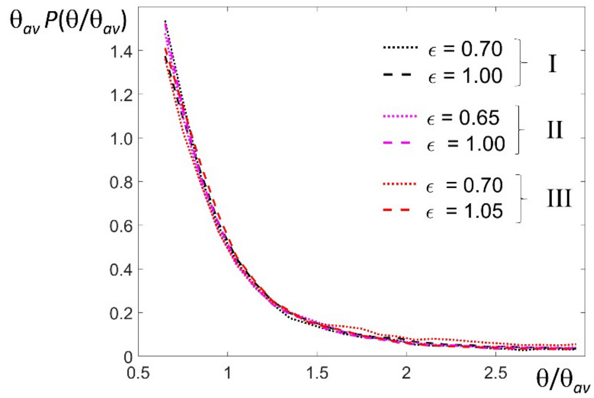

Fig. 4. Scaling behavior of misorientations across GNBs for copper deformed under different conditions: at a constant strain rate at room temperature (I) and at 400 °C (II), at a constant stress at 400 °C (III). The graph shows probability density $p(\theta/\theta_{av})$ calculated for angular range 4°…25° as function of normalized misorientation; θ_{av} is the average misorientation angle over the given angular interval. Reprinted from Ref. [86], © 2024 The Authors. Available under the terms of the CC-BY-NC 4.0 license.

One more peculiarity of the misorientation at the boundaries developed in plastically deformed materials should be mentioned: a substantial variation of misorientation along an individual boundary [84,87]. Such a variation can be described, in particular, as a distribution of disclination density on the boundary surface. A method for the recovery of components of the disclination density tensor from EBSD maps was suggested [88,89], and extensive presence of disclination densities has been revealed in various materials at low and high-angle boundaries as well as at triple junctions [88–90]. At the same time, the numerical approximation method applied in those studies to the mapped orientation data remains the subject of debate [91].

A calculation of the strength of triple junction disclinations from the EBSD data was developed recently [92]. The authors fulfil these calculations based on the mean orientations of reconstructed "grains" (the elements of deformation substructure with a misorientation that exceeds a given critical value). It is thereby assumed that a misfit of boundary misorientations is concentrated in the triple junctions. However, in reality, as indicated above, this misfit is distributed along the boundaries.

5. MODELING OF GRAIN FRAGMENTATION

In conclusion, let us review very briefly the current state of the mathematical modeling of the fragmentation process.

The first attempts to develop a theory were connected with a consideration of partial disclinations associated with broken (uncompleted) sub-boundaries [7,8,93]. Indeed, the displacement of such disclinations across a crystal results in the subdivision of the latter into misoriented parts. The nucleation of the broken low-angle boundaries was suggested to take place near corresponding stress concentrators, in particular, at the "junction disclinations" [6] proved to be a result of inevitable incompatibility of plastic strain at grain boundaries. Using the disclinations, a model has been later developed by Seefeldt et al. [94] for the modeling of the initial stage of grain subdivision and texture development. The above-mentioned idea on the role of junction disclinations has been realized in the model of Orlova, Nazarov et al. [96,97], where accumulation of disclinations at junctions of a grain embedded in a homogeneous effective medium was calculated by the viscoplastic self-consistent model. These disclinations then relax by the formation of sub-boundaries, which further subdivide the grain into fragments. The predicted evolution of misorientation angles at the fragment boundaries with strain reasonably agrees with experiment [97].

The disclination-based approach is undoubtedly useful when applied to the propagation of microbands [93,95]. However, in general it is not very efficient for modelling of grain subdivision, because the internal stress field that controls the grain subdivision seems to depend largely on the incompatibility appearing at facets of grain boundaries rather than at their junctions [104–106].

A model of Tóth et al. should be mentioned [98]. It comes from the fact that the rotations of crystallographic planes are impeded near the grain boundaries, so the rotations are significantly smaller there than in the middle part of the grain. This can actually take place as a result of the distribution of geometrically necessary dislocations inside relatively soft grains adjacent to harder grains [17]. However, in general, such a pattern of crystal rotations does not agree with experiment [99–101]. Recently, the model has been suggested [102], which considers the process of grain refinement in terms of dynamic recrystallization [13]. This approach seems to contradict, however, the experimental results presented in Section 4, which show that physical mechanism of fragmentation does not change with the increase of deformation temperature from ~ 0.2 to 0.5 of melting point.

Given all complexities involved in phenomenon of fragmentations, the modeling by means of crystal plasticity finite element (CPFE) technique is the most promising now [19–21,107]. At the present stage of development, even this approach seems unable to reproduce key features of the fragmentation patterns, which were considered in the review. At the same time, together with ex-situ and in-situ observations of crystal rotations inside individual grains (e.g., Ref. [62]) providing validation of the calculation results, the CPFE modeling can be already used for reproducing an early stage of grain fragmentation.

6. SUMMARY

The review can be summarized as follows.

Band-like regular cell block structure developed within grains is orientation dependent: the alignment of GNBs, the level of misorientations, the cell size and shape vary between grains related to different texture components. At the same time, above parameters differ at the grain boundary regions and in the grain interior due to the interaction between neighboring grains. EBSD investigations of cold rolled aluminum showed that primary cell block bands retain low-angle up to large rolling reductions and do not undergo a rigid body rotation. Therefore, their alignment dynamically adapts to the external loading. In contrast, the boundaries of secondary bands become high-angle with increasing strain and undergo rigid body rotation. With increasing temperature, the frequency of occurrence of the secondary bands decreases.

The subdivision of grains into several large domains, the so called "deformation bands", whose orientations rapidly diverge during deformation, is observed. Such a grain-scale fragmentation and corresponding development of grain microtexture usually cannot be explained by the effect of Taylor ambiguity and must be attributed to the interaction of neighboring grains. The difference of orientations arising between the deformation bands is accommodated within the transition zones of various types. Strain-induced high-angle boundaries form predominantly inside these zones. The regions of intensive fragmentation, where fine and highly misoriented fragments are concentrated, may also take other forms. Although these regions occupy small fraction of grain volume, they give major contribution to the accumulation of high-angle boundaries.

At relatively small strains, the distribution of misorientation angles at GNBs, when scaled by the average angle, is described by a single distribution. However, at strains ~ 1 and larger the high-angle boundaries develop, whose misorientation angles fall beyond the range of those distribution. The misorientation angles at such boundaries are described using another unique gamma distribution. By example of tensile strained copper, the scaling of misorientations was demonstrated to occur not only with increasing strain but also with changing conditions of deformation, including the increase of deformation temperature from ~ 0.2 to 0.5 of the melting point. This suggests that the mechanism of strain-induced boundary evolution remains the same within this temperature range.

Concerning computer simulation of the fragmentation process, the CPFE modeling coupled with experimental observations of crystal rotations inside individual grains seems to be the most promising.

REFERENCES

[1] G. Taylor & J. W. Christian, Experiments on the deformation of niobium single crystals. II. Electron microscope study of dislocation structures, *Philos. Mag.*, 1967, vol. 15, no. 137, pp. 893–929.

[2] G. Landford, M. Cohen, Microstructural analysis by high-voltage electron diffraction of severely drawn iron wires, *Metall. Trans. A*, 1975, vol. 6A, pp. 901–910.

[3] V.I. Trefilov, Yu.V. Milman, S.A. Firstov, *Physical fundamentals of refractory metals strength*, Naukova Dumka, Kiev, 1975 (in Russian).

[4] A.N. Vergazov, V.A. Likhachev, V.V. Rybin, Study of fragmented structure formed in molybdenum under active plastic deformation, *Phys. Met. Metalloved.*, 1976, vol. 42, no. 7, pp. 1241–1246 (in Russian).

[5] A.S. Rubtsov, V.V. Rybin, Structural features of plastic deformation at the stage of localized flow, *Phys. Met. Metalloved.*, 1977, vol. 44, no. 3, pp. 611–622 (in Russian).

[6] V.V. Rybin, A.A. Zisman, N.Yu. Zolotorevsky, Junction disclinations in plastically deformed crystals, *Acta Metall. Mater.*, 1993, vol. 41, no. 7, pp. 2211–2217.

[7] V.V. Rybin, *Large plastic deformations and fracture of metals*, Metallurgy, Moscow, 1986 (in Russian).

[8] V.I. Vladimirov, A.E. Romanov, *Disclinations in Crystals*, Nauka, Leningrad, 1986.

[9] [9] B. Bay, N. Hansen, D.A. Hughes, D. Kuhlmann-Wilsdorf, Overview no. 96 evolution of f.c.c. deformation structures in polyslip, *Acta Metall. Mater.*, 1992, vol. 40, no. 2, pp. 205–219.

[10] D.A. Hughes, Q. Liu, D.C. Chrzan, N. Hansen, Scaling of microsructural parameters: misorientations of deformation induced boundaries, *Acta Mater.*, 1997, vol. 45, pp. 105–112.

[11] D.A. Hughes, N. Hansen, High angle boundaries formed by grain subdivision mechanisms, *Acta Mater.*, 1997, vol. 45, no. 9, pp. 3871–3886.

[12] R. Quey, P.R. Dawson, J.H. Driver, Grain orientation fragmentation in hot-deformed aluminium: Experiment and simulation, *J. Mech. Phys. Sol.*, 2012, vol. 60, no 3, pp. 509–524.

[13] R. Quey, J.H. Driver, P.R. Dawson, Intra-grain orientation distributions in hot-deformed aluminium: Orientation dependence and relation to deformation mechanisms, *J. Mech. Phys. Sol.*, 2015, vol. 84, pp. 506–527.

[14] A. Belyakov, T. Sakai , H. Miura, K. Tsuzaki, Grain refinement in copper under large strain deformation, *Philos. Mag. A*, 2001, vol. 81, no. 11, pp. 2629–2643.

[15] A. Belykov, K. Tsuzaki, Y. Kimura, Regularities of deformation microstructures in ferritic stainless steels during large strain cold working, *ISIJ International*, 2008, vol. 48, no. 8, pp. 1071–1079.

[16] T. Sakai, A. Belyakov, R. Kaibyshev, H. Miura, J.J. Jonas, Dynamic and post-dynamic recrystallization under hot, cold and severe plastic deformation conditions, Prog. Mater. Sci., 2014, vol. 60, pp. 130–207.

[17] F.J. Humphreys, M. Hatherly, *Recrystallization and related annealing phenomena*, Elsevier Science Ltd., Pergamon, Oxford, 2004.

[18] D.A. Hughes, N. Hansen, The microstructural origin of work hardening stages, *Acta Mater.*, 2018, vol. 148, pp. 374–383.

[19] H. Hallberg, S.K. As, B. Skallerud, Crystal plasticity modeling of microstructure influence on fatigue crack initiation in extruded Al6082-T6 with surface irregularities, *Int. J. Fatigue*, 2018, vol. 111, pp. 16–32.

[20] K. Sedighiani, K. Traka, F. Roters, J. Sietsma, D. Raabe, M. Diehl, Crystal plasticity simulation of in-grain microstructural evolution during large deformation of IF-steel, *Acta Mater.*, 2022, vol. 237, art. no. 118167.

[21] K.K. Alaneme, E.A. Okotete, Recrystallization mechanisms and microstructure development in emerging metallic materials: A review, *Journal of Science: Advanced Materials and Devices*, 2019, vol. 4, no 1, pp. 19–33.

[22] Y. Estrin, A. Vinogradov, Extreme grain refinement by severe plastic deformation: a wealth of challenging science, *Acta Mater.*, 2013, vol. 61, no. 3, pp. 782–817.

[23] Q. Liu, D. Juul Jensen, N. Hansen, Effect of grain orientation on deformation structure in cold-rolled polycrystalline aluminium, *Acta Mater.*, 1998, vol. 46, no. 16, pp. 5819–5838.

[24] X. Huang, G. Winther, Dislocation structures. Part I. Grain orientation dependence, *Philos. Mag.*, 2007, vol. 87, no. 33, pp. 5189–5214.

[25] G. Winther, X. Huang, Dislocation structures. Part II. Slip system dependence, *Philos. Mag.*, 2007, vol. 87, no. 33, pp. 5215–5235.

[26] N. Hansen, X. Huang, G. Winther, Effect of grain boundaries and grain orientation on structure and properties, *Metall. Mater. Trans. A*, 2011, vol. 42, pp. 613–625.

[27] C. Hong, X. Huang, G. Winther, Dislocation content of geometrically necessary boundaries aligned with slip planes in rolled aluminium, *Philos. Mag.*, 2013, vol. 93, no. 23, pp. 3118–3141.

[28] A. Haldar, X. Huang, T. Leffers, N. Hansen, R.K. Ray, Grain orientation dependence of microstructures in a warm rolled IF steel, *Acta Mater.*, 2004, vol. 52, no. 18, pp. 5405–5418.

[29] H.S. Chen, A. Godfrey, N. Hansen, J.X. Xie, Q. Liu, Microstructure–grain orientation relationship in coarse grain nickel cold-rolled to large strain, *Mater. Sci. Eng. A*, 2008, vol. 483–484, pp. 157–160.

[30] X. Huang, N. Hansen, Grain orientation dependence of microstructure in aluminium deformed in tension, *Scr. Mater.*, 1997, vol. 37, no. 1, pp. 1–7.

[31] X. Huang, Grain orientation effect on microstructure in tensile strained copper, *Scr. Mater.*, 1998, vol. 38, no. 11, pp. 1697–1703.

[32] X. Huang, A. Borrego, W. Pantleon, Polycrystal deformation and single crystal deformation: dislocation structure and flow stress in copper, *Mater. Sci. Eng. A*, 2001, vol. 319–321, pp. 237–241.

[33] N. Hansen X. Huang, W. Pantleon, G. Winther, Grain orientation and dislocation patterns, *Philos. Mag.*, 2006, vol. 86, no. 25–26, pp. 3981–3994.

[34] G.M. Le, A. Godfrey, C.S. Hong, X. Huang and G. Winther, Orientation dependence of the deformation microstructure in compressed aluminum, *Scr. Mater.*, 2012, vol. 66, no. 6, pp. 359–362.

[35] P. Cizek, Dislocation boundaries and disclinations formed within the cube-oriented grains during tensile deformation of aluminium, *Acta Mater.*, 2010, vol. 58, no. 17, pp. 5820–5833.

[36] P. Cizek, F. Bai, E.J. Palmiere, W.M. Rainforth, EBSD study of the orientation dependence of substructure characteristics in a model Fe–30wt%Ni alloy subjected to hot deformation, *J. Microsc.*, 2005, vol. 217, no. 2, pp. 138–151.
[37] A.S. Taylor, P. Cizek, P.D. Hodgson, Orientation dependence of the substructure characteristics in a Ni–30Fe austenitic model alloy deformed in hot plane strain compression, *Acta Mater.*, 2012, vol. 60, no. 4, pp. 1548–1569.
[38] D. Poddar, P. Cizek, H. Beladi, P.D. Hodgson, Orientation dependence of the deformation microstructure in a Fe-30Ni-Nb model austenitic steel subjected to hot uniaxial compression, *Metall. Mater. Trans. A*, 2015, vol. 46, pp. 5933–5951.
[39] J. Baton, W. Geslin, C. Moussa, Orientation and deformation conditions dependence of dislocation substructures in cold deformed pure tantalum, *Mater. Charact.*, 2021, vol. 171, art. no. 110789.
[40] P.J. Hurley, F.J. Humphreys, The application of EBSD to the study of substructural development in a cold rolled single-phase aluminium alloy, *Acta Mater.*, 2003, vol. 51, no. 4, pp. 1087–1102.
[41] P.J. Hurley, P.S. Bate, F.J. Humphreys, An objective study of substructural boundary alignment in aluminium, *Acta Mater.*, 2003, vol. 51, no. 16, pp. 4737–4750.
[42] F.J. Humphreys, P.S. Bate, The microstructures of polycrystalline Al–0.1Mg after hot plane strain compression, *Acta Mater.*, 2007, vol. 55, no. 16, pp. 5630–5645.
[43] V. Randle, N. Hansen, D. Juul Jensen, The deformation behaviour of grain boundary regions in polycrystalline aluminium, *Philos. Mag. A*, 1996, vol. 73, no. 2, pp. 265–282.
[44] Q. Liu, N. Hansen, Microstructural study of deformation in grain boundary region during plastic deformation of polycrystalline aluminium, *Mater. Sci. Eng. A*, 1997, vol. 234–236, pp. 672–675.
[45] Q. Sun, Y. Ni, S. Wang, Orientation dependence of dislocation structure in surface grain of pure copper deformed in tension, *Acta Mater.*, 2021, vol. 203, art. no. 116474.
[46] B.L. Li, A. Godfrey, Q.C. Meng, Q. Liu, N. Hansen, Microstructural evolution of IF-steel during cold rolling, *Acta Mater.*, 2004, vol. 52, no 4, pp. 1069–1081.
[47] G. Ma, D.A. Hughes, A.W. Godfrey, Q. Chen, N. Hansen, G. Wu, Microstructure and strength of a tantalum-tungsten alloy after cold rolling from small to large strains, *J. Mater. Sci. Technol.*, 2021, vol. 83, pp. 34–48.
[48] N. Afrin, M.Z. Quadir, P.R. Munroe, M. Ferry, Unusual crystallographic aspects of microband boundaries within {111}<110> oriented grains in a cold rolled interstitial free steel, *ISIJ International*, 2014, vol. 54, no. 6, pp. 1346–1352.
[49] N. Zolotorevsky, E. Ushanova, V. Rybin, V. Perevezentsev, Characterization of fragmented structure developed during necking of iron tensile specimen, *Letters on Materials*, 2021, vol. 11, no 4, pp. 503–507.
[50] N. Zolotorevsky, V. Rybin, E. Ushanova, N. Ermakova, V. Perevezentsev, Large-scale fragmentation of grains in plastically deformed polycrystalline iron, *Mater. Today Commun.*, 2022, vol. 31, art. no. 103816.
[51] G.I. Taylor, Plastic strains in metals, *J. Inst. Metals*, 1938, vol. 62, pp. 307–324.
[52] P. Van Houtte, S. Li, M. Seefeldt, L. Delannay, Deformation texture prediction: From the Taylor model to the advanced Lamel model, *Int. J. Plast.*, 2005, vol. 21, no. 3, pp. 589–624.
[53] N.Yu. Zolotorevskii, Yu.F. Titovets, N.Yu. Ermakova, Microstructure evolution inside grains of aluminium polycrystal under compression, *The Physiscs of Metals and Metallography*, 2002, vol. 93, no. 1, pp. 86–93.
[54] N.Yu. Ermakova, N.Yu. Zolotorevsky, Yu.F. Titovets, Quantitative X-ray analysis of deformation microtexture within individual grains, *Mater. Sci. Forum*, 2005, vol. 495–497, pp. 983–988.
[55] R. Quey, D. Piot, J.H. Driver, Microtexture tracking in hot-deformed polycrystalline aluminium: Experimental results, *Acta Mater.*, 2010, vol. 58, no 5, pp. 1629–1642.
[56] R. Quey, J.H. Driver, Microtexture tracking of sub-boundary evolution during hot deformation of aluminium, *Mater. Charact.*, 2011, vol. 62, no. 12, pp. 1222–1227.
[57] D. Raabe, Z. Zhao, W. Mao, On the dependence of in-grain subdivision and deformation texture of aluminum on grain interaction, *Acta Mater.*, 2002, vol. 50, no. 17, pp. 4379–4394.
[58] D.P. Field, A. Alankar, Observation of deformation and lattice rotation in a Cu bicrystal, *Metall. Mater. Trans. A*, 2011, vol. 42A, pp. 676–683.
[59] G. Winther, J.P. Wright, S. Schmidt, J. Oddershede, Grain interaction mechanisms leading to intragranular orientation spread in tensile deformed bulk grains of interstitial-free steel, *Int. J. Plast.*, 2017, vol. 88, pp. 108–125.
[60] N. Allain-Bonasso, F. Wagner, S. Berbenni, D.P. Field, A study of the heterogeneity of plastic deformation in IF steel by EBSD, *Mater. Sci. Eng. A*, 2012, vol. 548, pp. 56–63.
[61] J. Oddershede, J.P. Wright, A. Beaudoin, G. Winther, Deformation-induced orientation spread in individual bulk grains of an interstitial-free steel, *Acta Mater.*, 2015, vol. 85, pp. 301–313.
[62] H. Pirgazi, L.A.I. Kestens, Semi in-situ observation of crystal rotation during cold rolling of commercially pure aluminum, *Mater. Charact.*, 2021, vol. 171, art. no. 110752.
[63] S. Subedi, R. Pokharel, A.D. Rollett, Orientation gradients in relation to grain boundaries at varying strain level and spatial resolution, *Mater. Sci. Eng. A*, 2015, vol. 638, pp. 348–356.
[64] N.S. De Vincentis, A. Roatta, R.E. Bolmaro, J.W. Signorelli, EBSD Analysis of orientation gradients developed near grain boundaries, *Mater. Res.*, 2019, vol. 22, no. 1, art. no. e20180412.
[65] H. Hu, Microbands in rolled Fe-Si crystals and their role in recrystallization, *Acta Metall.*, 1962, vol. 10, no. 11, pp. 1112–1116.
[66] I.L. Dillamore, P.L. Morris, C.J.E. Smith, W.B. Hutchinson, Transition bands and recrystallization in metals, *Proc. R. Soc. Lond. A*, 1972, vol. 329, no. 1579, pp. 405–420.
[67] E. Aernoudt, P. Van Houtte, T. Leffers, Deformation and textures of metals at large strains, in: R.W. Cahn, P. Haasen, E.J. Kramer (Eds.), *Materials Science and Technology*, VCH, Weinheim, 1993, pp. 89–136.
[68] T. Morikawa, R. Kurosaka, M. Tanaka, T. Ichie, K. Murakami, Grain subdivision mechanism for constructing lamellar microstructure in cold-rolled ultra-low carbon, *ISIJ International*, 2022, vol. 62, no. 2, pp. 335–342.
[69] P.B. Prangnell, J.R. Bowen, P.J. Apps, Ultra-fine grain structures in aluminium alloys by severe deformation processing, *Mater. Sci. Eng. A*, 2004, vol. 375–377, pp. 178–185.

[70] Y. Huang, P.B. Prangnell, Orientation splitting and its contribution to grain refinement during equal channel angular extrusion, *J. Mater. Sci.*, 2008, vol. 43, pp. 7273–7279.
[71] A.P. Zhilyaev, K. Oh-ishi, G.I. Raab, T.R. McNelley, Influence of ECAP processing parameters on texture and microstructure of commercially pure aluminum, *Mater. Sci. Eng. A*, 2006, vol. 441, no. 1–2, pp. 245–252.
[72] L. Zhu, M. Seefeldt, B. Verlinden, Three Nb single crystals processed by equal- channel angular pressing – Part II: Mesoscopic bands, *Acta Mater.*, 2013, vol. 61, no. 12, pp. 4504–4511.
[73] L. Zhu, M. Seefeldt, B. Verlinden, Deformation banding in a Nb polycrystal deformed by successive compression tests, *Acta Mater.*, 2012, vol. 60, no. 10, pp. 4349–4358.
[74] C. Thorning, M.A.J. Somers, J.A. Wert, Grain interaction effects in polycrystalline Cu, *Mater. Sci. Eng. A*, 2005, vol. 397, no. 1–2, pp. 215–228.
[75] J.A. Wert, C.T. Thorning, Grain subdivision in polycrystalline copper subject to tensile deformation, *Mater. Sci. Technol.*, 2005, vol. 21, no. 12, pp. 1401–1406.
[76] N. Afrin, M.Z. Quadir, M. Ferry, Formation of highly misoriented fragments at hot band grain boundaries during cold rolling of Interstitial-Free Steel, *Metall. Mater. Trans. A*, 2015, vol. 46, pp. 2956–2964.
[77] Z. Yanushkevich, A. Belyakov, R. Kaibyshev, Microstructural evolution of a 304-type austenitic stainless steel during rolling at temperatures of 773–1273 K, *Acta Mater.*, 2015, vol. 82, pp. 244–254.
[78] N.Yu. Zolotorevsky, V.V. Rybin, E.A. Ushanova, V.N. Perevezentsev, Effect of deformation temperature on the microstructure and texture evolution in copper during tension, *Letters on Materials*, 2023, vol. 13, no. 4, pp. 362–367.
[79] N.Y. Zolotorevsky, V.V. Rybin, E.A. Ushanova, A.N. Matvienko, V.N. Perevezentsev, Comparative study of grain fragmentation in iron during cold and warm deformation by uniaxial tension, *Mater. Phys. Mech.*, 2022, vol. 50, no. 2, pp. 239–251.
[80] W.F. Hosford, Microstructural changes during deformation of [110] fiber-textured metals, *Trans, Metall. Soc. AIME*, 1964, vol. 230, pp. 12–15.
[81] W. Pantleon, The evolution of disorientations for several types of boundaries, *Mater. Sci. Eng. A*, 2001, vol. 319–321, pp. 211–215.
[82] Z.P. Luo, H.W. Zhang, N. Hansen, K. Lu, Quantification of the microstructures of high purity nickel subjected to dynamic plastic deformation, *Acta Mater.*, 2012, vol. 60, no. 3, pp. 1322–1333.
[83] Z.P. Luo, O.V. Mishin, Y.B. Zhang, H.W. Zhang, K. Lu, Microstructural characterization of nickel subjected to dynamic plastic deformation, *Scr. Mater.*, 2012, vol. 66, no. 6, pp. 335–338.
[84] N.Yu. Zolotorevsky, V.V. Rybin, A.N. Matvienko, E.A. Ushanova, S.A. Philippov, Misorientation angle distribution of deformation-induced boundaries provided by their EBSD-based separation from original grain boundaries: Case study of copper deformed by compression, *Mater. Charact.*, 2019, vol. 147, pp. 184–192.
[85] N.Yu. Zolotorevsky, V.V. Rybin, A.N. Matvienko, E.A. Ushanova, S.N. Sergeev. Misorientation distribution of high angle boundaries formed by grain fragmentation: EBSD-based characterization and analysis performed on heavily deformed iron, *Letters on Materials*, 2018, vol. 8, no. 3, pp. 305–310.
[86] N.Yu. Zolotorevsky, V.V. Rybin, E.A. Ushanova, V.N. Perevezentsev, The scaling of misorientation angle distribution at strain-induced boundaries in copper deformed by tension under various conditions, *St. Petersburg State Polytechnical University Journal. Physics and Mathematics*, 2024, vol. 17, no. 1, pp. 71–80.
[87] G. Salishchev, S. Mironov, S. Zherebtsov, A. Belyakov, Changes in misorientations of grain boundaries in titanium during deformation, *Mater. Charact.*, 2010, vol. 61, no. 7, pp. 732–739.
[88] B. Beausir, C. Fressengeas, Disclination densities from EBSD orientation mapping, *Int. J. Solids Struct.*, 2013, vol. 50, no. 1, pp. 137–146.
[89] C. Fressengeas, B. Beausir, Tangential continuity of the curvature tensor at grain boundaries underpins disclination density determination from spatially mapped orientation data, *Int. J. Solids Struct.*, 2019, vol. 156–157, pp. 210–215.
[90] S. Demouchy, M. Thieme, F. Barou, B. Beausir, V. Taupin, P. Cordier, Dislocation and disclination densities in experimentally deformed polycrystalline olivine, *Eur. J. Mineral.*, 2023, vol. 35, no. 2, pp. 219–242.
[91] A.C. Leff, C.R. Weinberger, M.L. Taheri, On the accessibility of the disclination tensor from spatially mapped orientation data, *Acta Mater.*, 2017, vol. 138, pp. 161–173.
[92] S. Zhu, A.P. Jivkov, E. Borodin, A. Bodyakova, Triple junction disclinations in severely deformed Cu–0.4%Mg alloys, *Acta Mater.*, 2024, vol. 264, art. no. 119600.
[93] V.I. Vladimirov, A.E. Romanov, Partial disclination dipole motion under plastic deformation, *Sov. Phys. Solid State*, 1978, vol. 20, pp. 1795–1800.
[94] M. Seefeldt, L. Delannay, B. Peeters, E. Aernoudt, P. Van Houtte, Modelling the initial stage of grain subdivision with the help of a coupled substructure and texture evolution algorithm, 2001, *Acta Mater.*, vol. 49, no. 12, pp. 2129–2143.
[95] A. Zisman, E. Nesterova, V. Rybin, C. Teodosiu, Interfacial misorientations and underlying slip activity of a shear microband in mild steel: TEM analysis and numerical simulation, *Scr. Mater.*, 2002, vol. 46, no. 10, pp. 729–733.
[96] T.S. Orlova, A.A. Nazarov, N.A. Enikeev, I.V. Alexandrov, R.Z. Valiev, and A.E. Romanov, Grain size refinement due to relaxation of disclination junction configurations in the course of plastic deformation of polycrystals, *Phys. Solid State*, 2005, vol. 47, no. 5, pp. 845–851.
[97] A.A. Nazarov, N.A. Enikeev, A.E. Romanov, T.S. Orlova, I.V. Alexandrov, I.J. Beyerlein, R.Z. Valiev, Analysis of substructure evolution during simple shear of polycrystals by means of a combined viscoplastic self-consistent and disclination modeling approach, *Acta Mater.*, 2006, vol. 54, no. 4, pp. 985–995.
[98] L.S. Tóth, Y. Estrin, R. Lapovok, C. Gu, A model of grain fragmentation based on lattice curvature, *Acta Mater.*, 2010, vol. 58, no. 5, pp. 1782–1794.
[99] N.Y. Zolotorevsky, N.Y.Ermakova, V.S. Sizova, E.A. Ushanova, V.V. Rybin, Experimental characterization and modeling of misorientations induced by plastic deformation at boundaries of annealing twins in austenitic steel, *J. Mater. Sci.*, 2017, vol. 52, pp. 4172–4181.
[100] W.Q. Gao, C.L. Zhang, M.X. Yang, S.Q. Zhang, D. Juul Jensen, A. Godfrey, Strain distribution and lattice rotations during in-situ tension of aluminum with a transmodal grain structure, *Mater. Sci. Eng. A*, 2021, vol. 828, art. no. 142010.

[101] S. Nagarajan, R. Jain, N.P. Gurao, Microstructural characteristics governing the lattice rotation in Al-Mg alloy using in-situ EBSD, *Mater. Charact.*, 2021, vol. 180, art. no. 111405.
[102] E.N. Borodin, V. Bratov, Non-equilibrium approach to prediction of microstructure evolution for metals undergoing severe plastic deformation, *Mater. Charact.*, 2018, vol. 141, pp. 267–278.
[103] E.N. Borodin, A. Morozova, V. Bratov, A. Belyakov, A.P. Jivkov, Experimental and numerical analyses of microstructure evolution of Cu-Cr-Zr alloys during severe plastic deformation, *Mater. Charact.*, 2019, vol. 156, art. no. 109849.
[104] P. Van Houtte, S. Li, M. Seefeldt, & L. Delannay, Deformation texture prediction: From the Taylor model to the advanced Lamel model, 2005, *Int. J. Plast.*, vol. 21, no. 3, pp. 589–624.
[105] N.Y. Zolotorevsky, V.V. Rybin, Deformation of fragmented polycrystals and texture formation, *Phys. Met. Metalloved.*, 1985, vol. 59, no. 3, pp. 440–449 (in Russian).
[106] A. Zisman, Model for partitioning slip patterns at triple junctions of grains, *Int. J. Eng. Sci.*, 2017, vol. 116, pp. 155–164.
[107] A. Krishna Kanjarla, P. Van Houtte, L. Delannay, Assessment of plastic heterogeneity in grain interaction models using crystal plasticity finite element method, *Int. J. Plast.*, 2010, vol. 26, no. 8, pp. 1220–1233.

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Особенности фрагментации зерен в процессе пластического деформирования металлов при малых и средних степенях деформации

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Аннотация. Обзор посвящен явлению фрагментации: разбиению исходных зерен на сильно разориентированные кристаллиты в процессе деформации. Рассмотрены главным образом исследования, выполненные в последние двадцать лет, при этом представляли интерес относительно ранние стадии эволюции фрагментированной структуры. Характеристики неоднократно описанной ранее упорядоченной структуры, состоящей из блоков ячеек, конкретизированы на основе более поздних публикаций, в том числе, ориентационная зависимость структуры и формирование первичных и вторичных микрополос. Кроме того, рассмотрены крупномасштабные проявления фрагментации, зоны интенсивной фрагментации, а также эволюция распределения разориентаций при увеличении степени и изменении условий деформации. В заключении кратко обсуждается моделирование фрагментации.

Ключевые слова: пластическая деформация; микроструктура; текстура; дислокации; дифракция обратно рассеянных электронов.