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ANALYSIS OF SHEAR DEFORMATION SCHEME EFFICIENCY IN PLASTIC STRUCTURE FORMATION PROCESSES

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The paper is devoted to the analysis of such an important factor as deformation behavior in the simple shear conditions. It is shown that non-monotonous character of material plastic flow exerts significant influence on the intensity of initial structure refinement. Induced non-monotonous character that ensures formation of equiaxed structural states plays an important role in the process.

Key words: plastic deformation, simple shear, equal-channel angular pressing (ECAP), non-monotony, severe and large plastic deformations.

Severe plastic deformation (SPD) techniques have been recently widely used to fabricate nanostructured and ultrafine-grained states in a wide range of metal materials [1-3]. Development of SPD techniques was inspired by theoretical works of Prof. V.M. Segal and his colleagues (Minsk) on analysis of mechanics of shear deformation schemes. In these works simple shear features were thoroughly studied. The simple shear is the most promising technique from the authors'point of view.

Its features are [4]:

- stability of the section perpendicular to the flow plane during straining. This makes possible processing of billets with large cross sections;
- orientation of spatial development of deformation is determined by one system of slip lines, which is important for control over texture formation processes;
- possibility of multiple cyclic deformation of one billet and achievement of as high levels of accumulated strain as desired.

For simple shear implementation, V.M. Segal developed a processing technique in intersecting channels further referred to as equal channel angular pressing (ECAP). First experimental works on ECAP application were aimed at strengthening of materials. At the beginning of 90 s of the past century use of the scheme moved to the sphere of creating new structural states in metals, namely in ultrafine-grained and nanostructured grain size ranges. Research teams under the direction of Prof. R.Z. Valiev, Ufa State Aviation Technical University, and Prof. S.V. Dobatkin, MISIS, IMET RAS have been successively developing this technique in Russia. The technique has been also widely used in a number of leading physical metallurgy centers all over the world [2].

It should be noted that simplicity of a laboratory die-set and high efficiency in forming new structural states in studied materials contributed to such development.

Another two advantages of the ECAP technique worth paying attention to are considered below. They are high localization of deformation and non-monotonic character of deformation through the simple shear scheme.

Theoretical analysis of deformation processes in polycrystalline metals shows that strain rate discontinuity lines appear in the deformation zone, in which the strained state changes stepwise [5, 6]. Only the tangential rate undergoes the discontinuity. It has been stated that "straight strain rate discontinuity lines are of special interest for settling the problems of plastic structure formation, as homogeneous stress and strained states are formed along these lines" [7] (Figure 1). The intensity of shear strain in the infinitely thin layer δ tending to 0 is determined from the ratio $\Gamma = |V\tau| / |V_n|$, the intensity of shear strain rates H and shear strain rate tend to the maximum values close to ∞ (Figure 1).

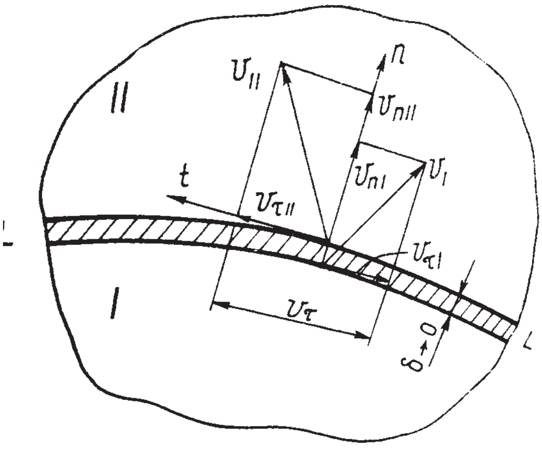

Figure 1 Simple shear in the strain rate discontinuity line, where δ – the band width, V_1 and V_{11} – the rates of billet parts I and II on the rate discontinuity lines

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One may assume that enhancement of the density of rate discontinuity lines in the conditions of large localization and strain degrees during ECAP contributes to much higher intensity of structure refinement, as it is known that large single strains actively fragment the initial structure [8] and as a rule are extremely non-monotonous. Thus, during multi-cycle ECAP processing of billets, with different single strains per 1 processing cycle and an equal total accumulated strain of $e_{\Sigma} \sim 4{,}4$, the highest efficiency of structure refinement, formation of equi-axed grains and enhanced fraction of high-angle boundaries is achieved for the maximum value of a single strain per a processing cycle. The angle of channels intersection is 90 ° (true strain e = 1,1). The processing regime is with billet rotation about its longitudinal axis by 90 ° before each processing cycle (route B) [9].

One should also pay attention to the non-monotonic character of simple shear strain [10] (Figure 2), which ensures continuous change of main strain components directions in the deformation zone. This contributes to appearance of new directions of rate discontinuity lines and their intersections, and therefore higher intensity of initial structure refinement.

In case of monotonous deformation this graph should coincide with a direct line (φ_{13} - φ_{11} = $\pi/2$).

Another important factor for enhancing efficiency of refinement during ECAP is change of direction of slip lines by 90 or 180 degrees via rotation of a billet about its longitudinal axis in the multicycle processing conditions. This effect should be qualified as induced non-monotony. Such effectiveness is confirmed by formation of a homogeneous structural state in Al after 4 ECAP cycles (Figure 3).The structure with equiaxed UFG grains is formed. It is characterized by enhanced fraction of high-angle boundaries testifying to formation of a grain-type structure for the minimally possible number of processing cycles.

Analysis of finer processes of structure formation occurring on the dislocation level in the conditions of monotonous and non-monotonous deformation is also of special interest.

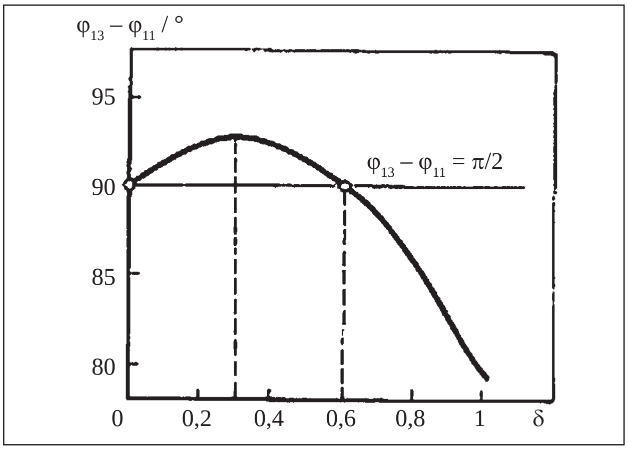
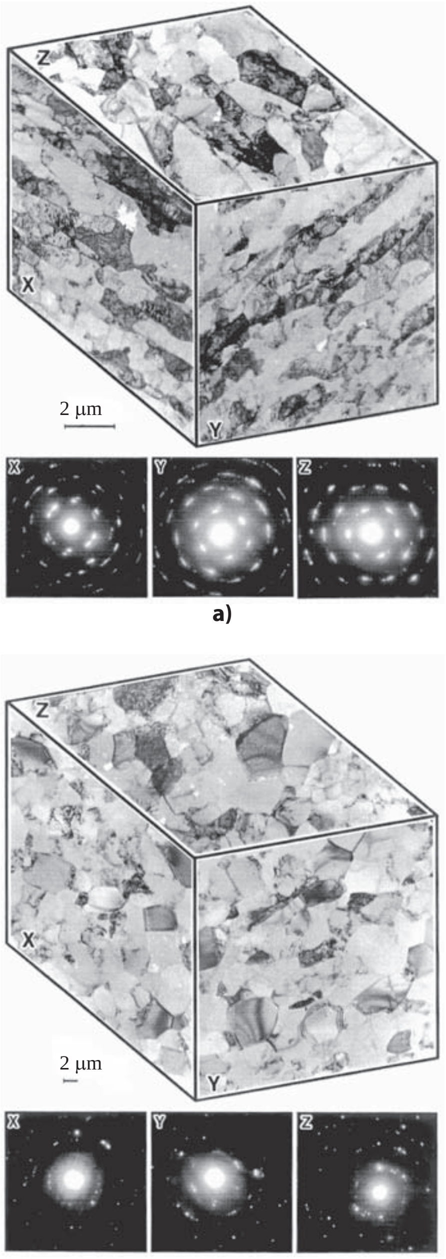


Figure 2 Graph of angle change (φ_{13}-φ_{11}) between figure axis and main strain axis with increase of the relative shear value δ. Non-monotonous deformation



a)

b)

Figure 3 Microstructure and diffraction patterns of pure Al after 4 ECAP passes without billet rotation about the longitudinal axis (a) and with rotation by 90 ° before each pressing cycle (b). Electron microscopy [11]

It is known [3] that absorption of lattice dislocations by boundaries leads to significant misorientation angle increase in case the following ratio is fulfilled

$$J_{ent}\, b_S >> J_{leav}\, b_{S,}$$

where the product of the Burgers vector and the dislocations flow entering a boundary is given to the left of the non-equality sign, the similar product for dislocations leaving a boundary is given to the right of the non-equality sign. The flow directions of dislocations and their parts remaining in boundaries depend on the direction of external stress.

Contribution to the fixed increase of the misorientation angle θ is made only by sessile components of grain-boundary dislocations (GBD) with the Burgers vectors normal to the boundary plane. As the modules of entering and leaving dislocations should correspond to the constant lattice, $|b_S| = |b_{S'}|$ and the Burgers vector module of the GBD sessile component is equal to:

$$|\Delta \mathrm{b}_\mathrm{n}| = |\Delta \mathrm{b}| \sin\left(\frac{\theta}{2}\right) = 2\,|\mathrm{b}_\mathrm{S}| \sin^2\left(\frac{\theta}{2}\right) \qquad (1)$$

Permeability of low-angle boundaries for lattice dislocations is high. With the constant shear direction, only a small part of dislocation flow J_B can pin on such boundaries, as the kinetic energy of dislocations ($f\ v\ \cos(\alpha)$), necessary for overcoming barriers, is low due to a small value of the Schmid factor – α angle cosine between the force vectors – *f*, acting on a dislocation and its velocity – v:

$$J_B = J - J_P \qquad (2)$$

where J – the number of mobile dislocations; J_P – flow of dislocations that moved to the external surface.

The misorientation angle between low-angle boundaries is $\theta_{\text{м}} = b/h$, where h – the distance between dislocations in a wall. Therefore, the angle increment $\Delta\theta_{\text{м}}$ is proportional to $|\Delta b_n|$ and J_B:

$$\Delta\theta_M \propto J_B\,|\Delta b_n| = 2\,J_B\,|b_S| \sin^2\frac{\theta}{2} \qquad (3)$$

In case when the external stress acting on a sample is constant in its direction, which is typical of quasimonotonous deformation, for example drawing, and the external surface area increases significantly, there occurs a condition upon which $J_{\text{в}} \to 0$ and $J_{\text{в}} << J_P$. In this case the increment $\Delta\theta_{\text{м}}$ is very small, as it is determined by the product of small values: the flow of dislocations $J_{\text{в}}$ entering a boundary and settling in it is small, the low-angle boundary angle sine square is small either. The experimental data show that during quasimonotonous deformation the increment of angle misorientations is observed mainly near band boundaries and practically does not take place in cells, blocks and subgrains located in bands. The boundaries of these misorientation areas remain low-angle [12]. One may search for the analogy of rate discontinuity lines formation and formation of band boundaries occurring in a gradient field of material flow rates. As a result, band boundaries do not practically intersect in a low-gradient field of rates (during quasimonotonous drawing, for example), which results in formation of a grain-subgrain type structure.

Another situation arises during non-monotonous deformation, when the direction of external force impact on the material changes constantly providing enhanced gradient of rates in the local areas of deformed billets and high intensity of formation and intersection of high-angle band boundaries (rate discontinuity lines). Such pattern is typical of ECAP being non-monotonous process, when the external surface of a sample does not change and dislocation flows close inside billets on the internal surfaces of the deformation zone. Nonmonotonous large deformation results in constant formation of new shear bands and therefore high-angle band boundaries. High-angle boundaries with a high value of the angle θ, as significant barriers for dislocations flow, contribute to more intensive increment of the angle $\Delta\theta_{\text{м}}$ (see Formula 1). It is evident that such conditions ensure intensive formation of a grain-type structure.

CONCLUSION

1. Thus, the performed analysis shows that during development of effective SPD processes one should adhere to the procedure that accounts the following conditions:
   - provision of a maximum high level of single accumulated strain per a processing cycle;
   - use of simple shear scheme;
   - provision of induced non-monotony.
2. Localization of deformation zone against non-monotony also enhances the effects of grain refinement and ensures formation of equi-axed structures due to high density of differently directed rate discontinuity lines, formation and intersection of band high-angle boundaries.

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Note: The responsible for English language is lecturer from Kazan Federal University, Kazan, Russia