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TECHNOLOGICAL PROBLEMS OF EQUAL CHANNEL ANGULAR PRESSING

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Abstract. Equal channel angular pressing (ECAP) is an effective process to produce materials with increased mechanical properties and no change of billet size. In the present paper the experimental and finite element analysis results of ECAP investigation were obtained. The influence of die geometry and friction condition on irregularity of shear strain field in the cross section of the billet and therefore on mechanical properties distribution was studied. ECAP was shown to be always characterized by irregular shear strain distribution. Depending on die geometry and friction condition that irregularity could be reduced.

1. INTRODUCTION

Equal Channel Angular Pressing (ECAP) which is known as one of the most promising material processing techniques involves severe plastic deformation. In contrast to rolling, drawing, extrusion the main purpose of ECAP is to accumulate deformation in material without any reduction in workpiece cross-section.

There is a uniform grain structure refinement in a bulk material due to simple shear scheme. Multiple pressing provides ultra-fine grain structure. Ultra-fine grain materials typically exhibit a grain size in the range of hundreds of nanometers. This is a transition region between the coarse grained materials and nanostructured metals, where the grain boundaries play a decisive role during plastic deformation. The first few ECAP passes result in an effective grain refinement taking place in successive stages: homogeneous dislocation distribution, formation of elongated sub-cells, formation of elongated subgrains and their following break-up into equiaxed units. On the contrary, the microstructure tends to be more equiaxed as the number of passes increases. Later on, the sharpening of grain boundaries and final equiaxed ultrafine grain structure develops.

The ultra-fine grain structure produced by ECAP is sensitive to the technological details of the process, lubrication, deformation rate, dimensions of the die, etc. With no doubt, these factors influence the microstructure and finally the properties of ultra-fine grain material.

The structure received is characterized by unusual effects such as ideal plastic behavior, higher strength, enhanced ductility and toughness, and low temperature superplasticity [1-5].

Nowadays an application of ECAP to industry is the issue of the day. By the moment the only application of this method was performed by its author V.M. Segal at Honeywell Electronic Materials (USA) [6]. The method was used during processing of target billets for magnetron sputtering of thin film.

ECAP is not widely used as the researchers focus mainly on material structure. They are interested in formation of unusual structures and properties of material after ECAP while structure homogeneity, fraction of high angle grain boundaries depends on mechanics of ECAP. The last is defined

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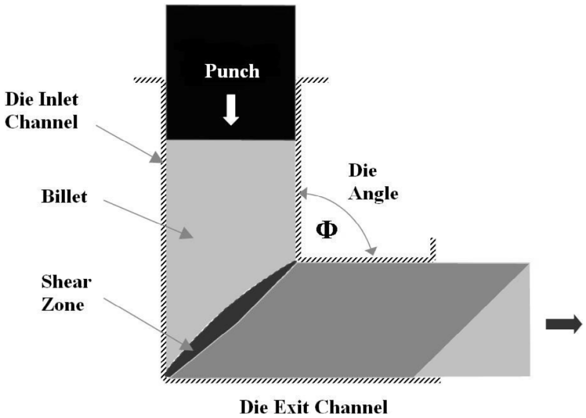

Fig. 1. Scheme of ECAP process.

by external kinematics and outside force to deformed workpiece (deformation scheme, die geometry, friction conditions). The mechanics also specifies some basic process parameters: homogeneity of stressedly-deformed state, pressing load, billet shape change, accumulative strain value and strain rate in each point.

ECAP research is performed only in laboratories, the tools used for this process consist of multi-component parts [7,8]. For example, a special die set with backpressure under computer control and measurement was designed and manufactured in Monash University [9].

In paper [10] ECAP process was carried out on INSTRON 8502 machine. The die had the exit channel closed.

There are other schemes to realize the process: the use of movable exit channel wall for friction reduction [7,11] and polishing of billet surface before each pass [12] but these approaches are complicated as well.

Let us consider ECAP more detailed. Its scheme is performed in Fig. 1. A metal billet is pressed though a die containing two channels, equal in cross-section, intersecting at an angle Φ. During the pressing, the billet undergoes severe shear deformation but retains the same cross-sectional geometry so that it is possible to repeat the pressings for a number of passes, each one refining grain size.

Basing on slide lines the mechanics of this process was described by V.M. Segal. The analytical solution was obtained for rigid-perfectly plastic material model assuming the channel is filled completely up (stationary process), the material cannot lose contact with channel walls, frictionless sliding. As that stressed and deformed states are homogenic, stress fields were obtained with the help of discontinuous solution.

Because of much scientific interest to submicron-grained and nanostructured materials during the last ten years ECAP appeared to be in the center of researchers' attention. The attempts of its industrial application revealed significant disadvantages of analytical solution obtained by V.M. Segal.

Modern approaches used to solve problems connected with plastic deformation of metals are based on numerical (finite-element) method (FEM) and allow to get rid of some assumptions and simplifications. There appeared information in works stating the possible corner gap during ECAP. For example, P.B. Prangnell et al. [13] used elastic-plastic material model to describe friction and die angle influence on shear strain inhomogeneity in bulk material. The constant of friction was equal to: $\mu = 0$ and $\mu = 0.25$. It was noticed that under frictionless conditions there was a corner gap. Under the friction influence the channel intersection is fully filled with metal and shear strain inhomogeneity increases in bulk material. Besides with reduction of die angle from 100 to 90° the inhomogeneity also increases and can result in dead zone developing in the die corner. However such situation was not analyzed due to additional computational expenses.

The dead zone effect was also faced by the authors [14]. They prepared alloy ingots of $Bi_{1.9}Sb_{0.1}Te_{2.7}Se_{0.3}$ by melting a mixture of each metals (>99.99%) in a sealed evacuated silica tube. Rapidly solidified foils ware prepared from alloy ingots using the single-roller melt-spinning technique in an argon atmosphere. These foils were then pulverized and sifted through 1 mm^2 sieve holes. These pulverized foils were stacked into an ECAP die made from tool steel. The die channel was a rectangular shape of 30 × 6 mm^2. The angle (Ψ) between the inlet channel and outlet channel was 90°. The ECAP process was implemented in an argon atmosphere at three separate temperatures of 693K, 733K, and 773K. Repetitive pressing was performed up to 6 passes. The repetitive extruded specimens were rotated 180° at each pass in order to apply a homogeneous and cumulative strain.

All specimens were fully densified (R.D. >98%) after passing through the ECAP process. Here, a theoretical density of 7.78 g/cm^3 is utilized for the $Bi_{1.9}Sb_{0.1}Te_{2.7}Se_{0.3}$ specimen. An inhomogeneous deformation caused by a frictional affect between the specimen and the die wall was observed lying along the portion adjacent to the inner corner in the cross-section of the single pass specimen. However, this inhomogeneity was provided in the specimen processed with 2 passes via route C. A dead-metal zone was formed in the outer corner of the specimen after ECAP processing. A metal slip appeared along the surface of the dead metal zone. The canting angle (φ) from the extrusion direction of deformed elements was plotted versus the number of passes (N). Under ideal ECAP processing, φ is given by Eq. (1) with a shear strain (γ).

$$\tan\varphi = \frac{1}{(\gamma+1)}. \quad (1)$$

The shear strain γ was also derived by Ψ in Eq. (2). In their study, Ψ is 90°.

$$\gamma = 2N\cot\frac{\Psi}{2}. \quad (2)$$

Due to the dead-metal zone and the frictional effect, the experimental φ value was larger than the theoretical value. Here, the amount of equivalent strain (ε_{eq}) imposed by the ECAP processing can be estimated by Eq. (1). Typically, an amount ε_{eq} is given by Eq. (3) under the ideal condition of Ψ = 90°.

$$\varepsilon_{eq} = \frac{2N}{\sqrt{3}}. \quad (3)$$

Measurement of the φ value reveals that both the presence of a dead-metal zone and the frictional effect may lead to shear strains which are significantly lower than their ideal values.

Sometimes there was a material destroy in the channel. Such a conclusion was drawn by the authors [15]. They studied ECAP and modified process: Cross-ECAP, T-ECAP, U-ECAP, and S-ECAP. An isothermal two-dimensional plane strain finite element simulations of the ECAP and modified ECAP processes were carried out by using commercial rigid-plastic software DEFORM 2D. All simulations were realized under ideal conditions (rigid-perfect, plastic material, with frictionless contact between the die and the workpiece of 10 × 10 mm^2 in cross sectional area.

The deformation characteristics of the various modified ECAP processes were compared with that of the conventional ECAP process in the following aspects: overall deformation/flow behavior, stress-strain variations, and strain homogeneity. The stress state of the modified deformation process was analyzed through maximum principal stress. More severe tensile stresses were generated in the Cross-ECAP and T-ECAP processes in comparison to ECAP and U-ECAP and S-ECAP processes. The more severe tensile stresses generated in the modified ECAP processes may generate cracks on the surface of the workpiece during multiple passes.

The deformation is simple almost shear and the strain rate is higher at the corner where two channels meet. In Cross-ECAP the deformation is highly localized along the shear line of 45°. The strain rate is higher at four corners and central area where four channels meet. In T-ECAP the deformation is localized along the shear line of 60°. The strain rate is higher at the corner regions where two cannels meet and at the bottom region. In U-ECAP and S-ECAP the deformation is almost simple shear. However, the strain rate is very high at the inner corners and low at the outer corners with U-ECAP. In S-ECAP the strain rate is higher at both corners where two channels meet, similar to ECAP.

The deformation behavior is more complicated in modified ECAP processes than that of the ECAP process. The induced strain is also higher in modified ECAP processes. However, the strain homogeneity is possible only through ECAP and S-ECAP processes.

In another work [16], the plastic deformation behavior of forward extrusion, ECAP and a combination of the forward extrusion and ECAP processes were analyzed by the finite element method. The FEM simulations were carried out similarly: isothermal two-dimensional plane-strain, commercial rigit-plasic finite element code, DEFORM 2D. The strain hardening material properties of aluminum and friction factor were considered for these simulations. A workpiece measuring 45 × 13.3 × 13.3 (L × B × T) mm^3 and an ECAP die with a channel angle of φ = 0° and an outer corner angle of ψ = 0° was used in the simulations. An extrusion ratio of 7 : 1 along with a radius of curvature of 3 mm was also used.

The flow and strain homogeneity of the forward extrusion and ECAP combined processes were analyzed through the stress-strain contours and the load history. The values were then compared with those of the individual forward extrusion and ECAP processes.

The deformation behavior is more complicated in the forward extrusion + ECAP and ECAP + forward extrusion processes in comparison to the forward extrusion and ECAP processes. The predominant formation of a corner gap was not observed in the forward extrusion + ECAP and ECAP + forward extrusion processes. Nonetheless, it is impossible to achieve strain homogeneity in these processes. For strain homogeneity forward extrusion is a determining process.

To solve the problem of material destroy during ECAP the authors of [9,17] suggest using back pressure. Brittle cast alloy Al-5%Fe destroying after two ECAP passes without back pressure was successfully deformed after 16 passes with a back pressure of 275 MPa.

Stressedly-deformed state during ECAP with different back pressures and frictionless condition for aluminum alloy 2024 was analyzed using the metal forming code Q-form. It is noticed the hydrostatic stress along the internal channel wall changes its value from “-” to “+” after deformation zone. This fact is the reason of surface cracks on the billet.

Thus strain homogeneity is an important parameter of ECAP analysis.

Calculated-experimental research described in paper [12] is devoted to the influence of die geometry, friction condition between the die and workpiece on the distribution of plastic deformation during ECAP for Al-alloys. Five typical zones were chosen to investigate plastic strain distribution irregularity. Basing on equivalent plastic strain value in each zone distribution of the deformation in the workpiece cross-section was analyzed. The analysis showed that scatter of equivalent plastic strain values becomes wider for the zones chosen when friction coefficient increases from 0.01 to 0.14. Besides the maximal deformation irregularity occurs in the narrow zone located near the billet center. This effect is more intense with die angle Φ decrease.

The influence of many parameters on the state of material strain was estimated in the work [18] during ECAP. Three values of die angle (Φ = 90°, 105°, 120°), different outer radius of the channel and friction conditions (μ = 0.1; 0.3; 0.5) were studied. For frictionless conditions the equivalent plastic strain values were obtained both by finite element code MARK and analytical solution. The results had a good agreement. The authors came to the conclusion: “friction condition does not affect the resulting strain distribution”.

Another work was carried out to predict deformation behavior and to investigate the deformation flow for pure copper along the die during ECAP using ANSYS V12 [19]. The die for ECAP was designed with three different angles of 90°, 110°, and 120° for five different hydrostatic pressure conditions. It was observed that deformation along the die during pressing is inhomogeneous for various channel angles under different hydrostatic pressure conditions. Total deformation of sample during pressing decreases with increase of channel angle.

Some mechanical aspects of ECAP for a channel with die angle 90° were analyzed in the paper [20]. Finite element analysis was carried out for two hypothetical materials: elastic-perfectly plastic and elastic-plastic. The influence of die corner angle, strain hardening and friction on metal deformation behavior, plastic deformation zone and working load was estimated. The possible gap formation for each material was studied. This gap always appears for frictionless pressing and small corner angle irrespective of material properties. The gap can also occur in the exit part of the channel. For elastic-plastic materials the billet looses less contact with channel surface than in case of perfectly-plastic material. Deformation zone form depends more on corner angle than on friction. At the same time the deformation inhomogeneity index increases with corner angle, strain hardening and friction coefficient.

Thus the application of ECAP to industry is delayed because the problems connected with mechanical aspect of the process are not solved enough. However the studies differ from one another and even contradict. That’s why there are no sound recommendations for tools design and lubrication.

To solve the problem mentioned above it was necessary to carry out a complex study of ECAP mechanics: estimate the influence of basic technological parameters on flow nature and stressedly-deformed state of metals during ECAP. Die geometry and contact friction are the basic technological parameters of ECAP. The length of the billets was assigned to be limited. The billets were put into the channel one after another. It’s assumed the back pressure is created only due to the previous billet.

2. FINITE ELEMENT ANALYSIS OF ECAP PROCESS

Numerical solution of lateral metal pressing task for square section channel was obtained using FEM [21].

The following admissions were made: material model – elasto-plastic hardenable body, deformation model – plain strain condition. The choice of material model was explained by deformation condition: small part of plastic deformation zone and the rest – resilient zone.

The basic geometry parameters of the channel are: die angle Φ, corner angle Ψ defined by outer coupling radius R, inner coupling radius r and channel width b (Fig. 2).

The angle Φ varied in the range 90°-120° at the interval 15°. This choice was determined by the possibility to realize the process on the one hand and its best efficiency on the other hand. The ratios of outer radius to channel width R/b were the following: 1:4, 1:2, 3:4, 1:1. The inner radius r was equal to 5 mm and the channel width was 20 mm. Fric-

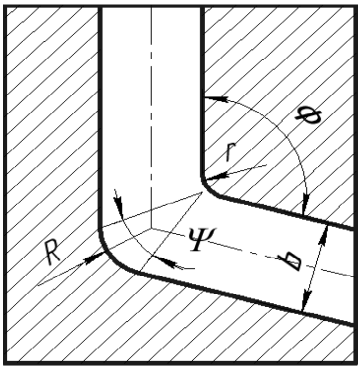

Fig. 2. Die geometry.

tion characteristic values on the surface of contact between die and workpiece were as follows: $\mu = 0$; 0.1; 0.2; 0.25; 0.3. Commercial Al was used as a model material.

First it was studied how the metal filled the channel turning part (unsteady stage of the process). Friction condition on the surface of contact between die and workpiece: $\mu = 0.1$.

In the inlet part of the channel there is a compression of the billet and forming of its forepart as shown in Fig. 3, Δh means ram displacement.

The forepart shape depends on die angle Φ. For rectangular channel ($\Phi = 90°$) the shape is close to initial, the more die angle is, the more complicated it becomes. This stage is characterized by intense rise of pressing load.

As the metal fills plastic deformation zone the hydrostatic pressure distribution becomes irregular. By the end of unsteady stage of the process the normal contact stress increases and reaches its maximal value (Fig. 4). At that the channel has heavily loaded places: at the exit from plastic deformation zone along the outer channel wall and before the entry to plastic deformation zone.

In both cases it is the place where the motion path of contact point changes. In mechanics it is a stress concentrator. When the process becomes steady the normal contact stress values decrease in the indicated points.

On the outer channel wall before the entry to plastic deformation zone the metal looses contact with tool surface and a gap forms. The less outer coupling radius is, the more gap size forms.

The strained state of the billet forepart does not correspond to simple shear.

As while the practical realization of ECAP process the billets were put one after another into the inlet part of the channel it was necessary to estimate the influence of the previous workpiece. Obviously this influence is caused by the force of friction in the channel. So numerical modeling of ECAP of two billets was carried out for different friction conditions in the channel. Fig. 5 illustrates the position of billets at the final stage of the process.

ECAP process was observed on 60 forming steps where the ram displacement was $\Delta h = 1$ mm for each step. By this moment in both cases the forming of forepart and back part of the first billet and forepart of the second billet had finished. To solve contact task a layer of elements (see the shaded layer in Fig. 5) was assigned between the billets. The properties of the layer differed from those of the billets. From Fig. 5 it results that forming of the contact surfaces between the billets (forepart and back part shape) depends on friction conditions. For less friction (Fig. 5b) the previous workpiece doesn't practically impede forming of the forepart of the next

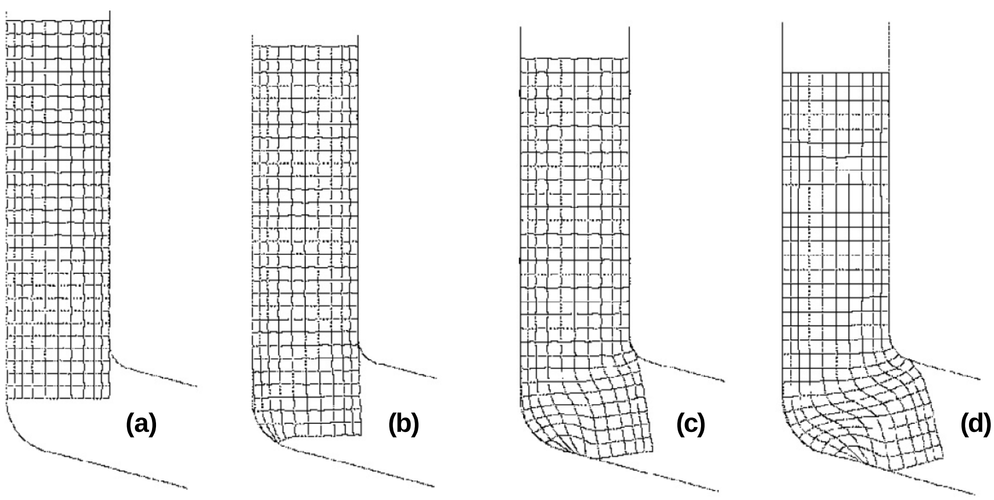

Fig. 3. Position of the billet in the channel at $\Phi = 105°$: a) $\Delta h = 0$ mm; b) $\Delta h = 8$ mm; c) $\Delta h = 13$ mm; d) $\Delta h = 18$ mm.

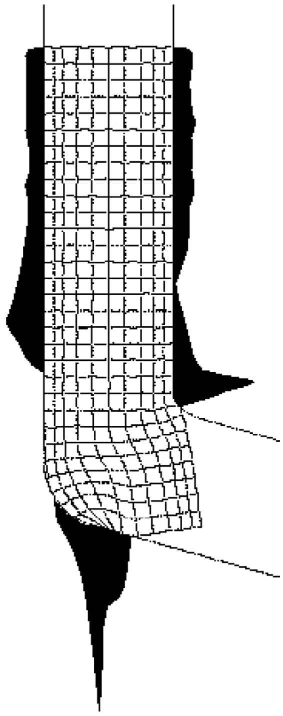

Fig. 4. Normal contact stress distribution along channel walls at the moment of its maximum for Φ = 105°, *R/b* = 1:2.

one. There is a free turning of the billet in the channel. With more friction the contact area of the neighboring billets increases (Fig. 5a) and the next workpiece has to push the previous one out. Contact surfaces form according to the direction of material plastic flow.

To analyze the steady stage of the process the model with the turning part of the channel filled previously with metal was taken. Validity of this assumption was confirmed by corresponding comparative analyses of strain fields. Due to the fact that contact friction stress (at μ = 0.1) was not enough to fill the channel completely the numerical analysis was carried out with back pressure. ECAP process was observed also on 60 forming steps. As a result metal filled the exit part of the channel and the process came to steady (quasistationary) stage.

Basing on calculation results for all die geometry options the diagrams of flow velocity during ECAP along the longitudinal section of the workpiece were obtained (Fig. 6).

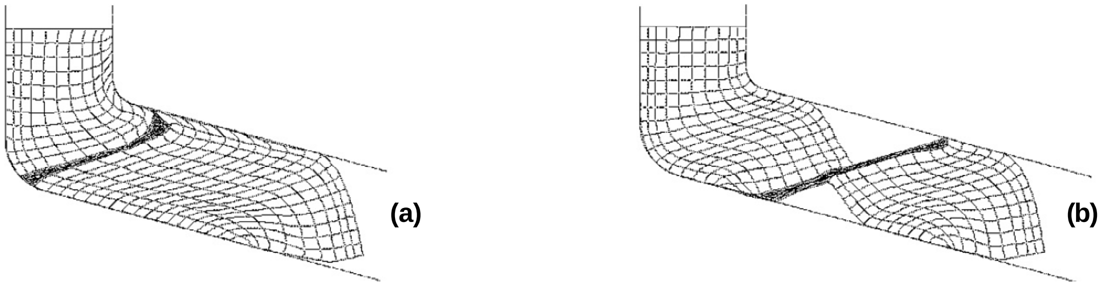

Fig. 5. The position of billets in the channel during ECAP for different friction conditions: a) μ = 0.3; b) μ = 0.15.

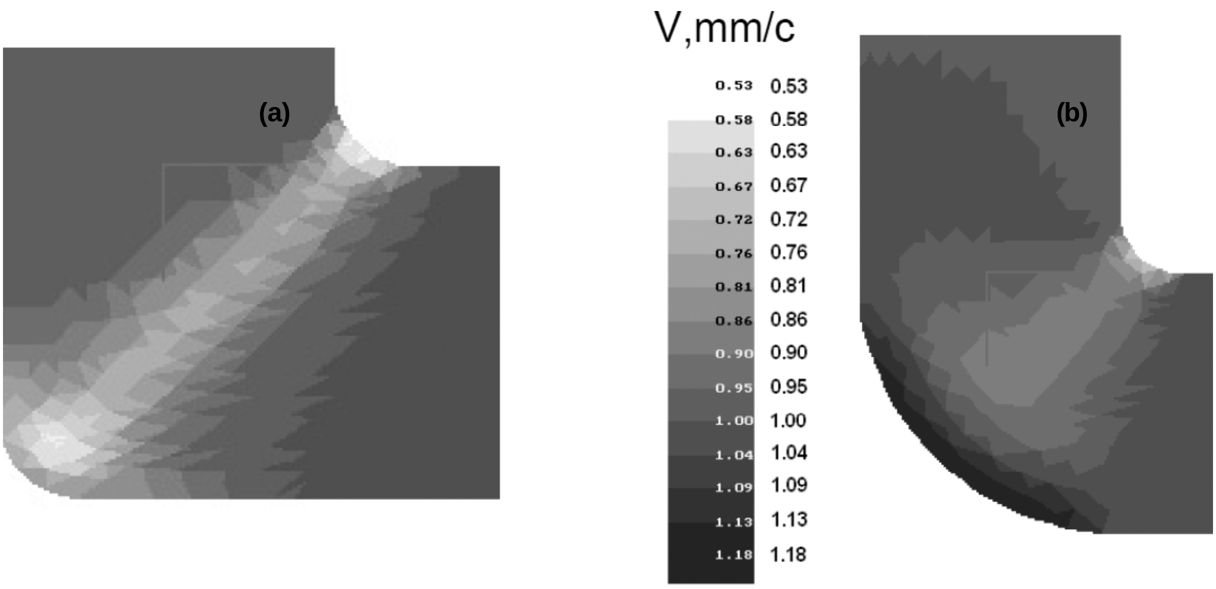

Fig. 6. Distribution of flow velocity along the longitudinal section of rectangular channel during ECAP for different ratios *R/b*: a) 1:4; b) 1:1.

The character of flow velocity diagram is defined by the ratio *R/b*. The main deformation zone has a retarded flow area for the channel with the least ratio *R/b* (Fig. 6a). Under back pressure conditions the metal fills the outer corner of the channel. With increase of the ratio *R/b* the retarded flow area disappears. In the radial channel (Fig. 6b) along the outer coupling radius the metal layers move at more velocity compared to others. At the same time along the inner radius the metal moves slower. Such behavior is explained by the difference in distances the neighboring metal layers have to pass. The initial regular field of velocities becomes irregular since the condition of constant metal volume per second along the cross-section is fulfilled. With die angle decrease the velocity gradient rises.

Due to the fact that during ECAP strained state is provided mainly by intense shear (mixed) component of tensor deformation, the invariant characteristic – shear strain intensity Γ was used to estimate that state.

Shear strain intensity distributions received for different die geometry has revealed an irregularity of this characteristic. It's advisable to investigate value Γ distribution irregularity behavior in the cross-section of the billet under steady stage of the process. Fig. 7 shows shear strain intensity distributions in the cross-section of the billet for different die geometry at the steady stage of ECAP process.

Irregularity of shear strain intensity distribution is the consequence of irregularity of metal flow in the main deformation zone.

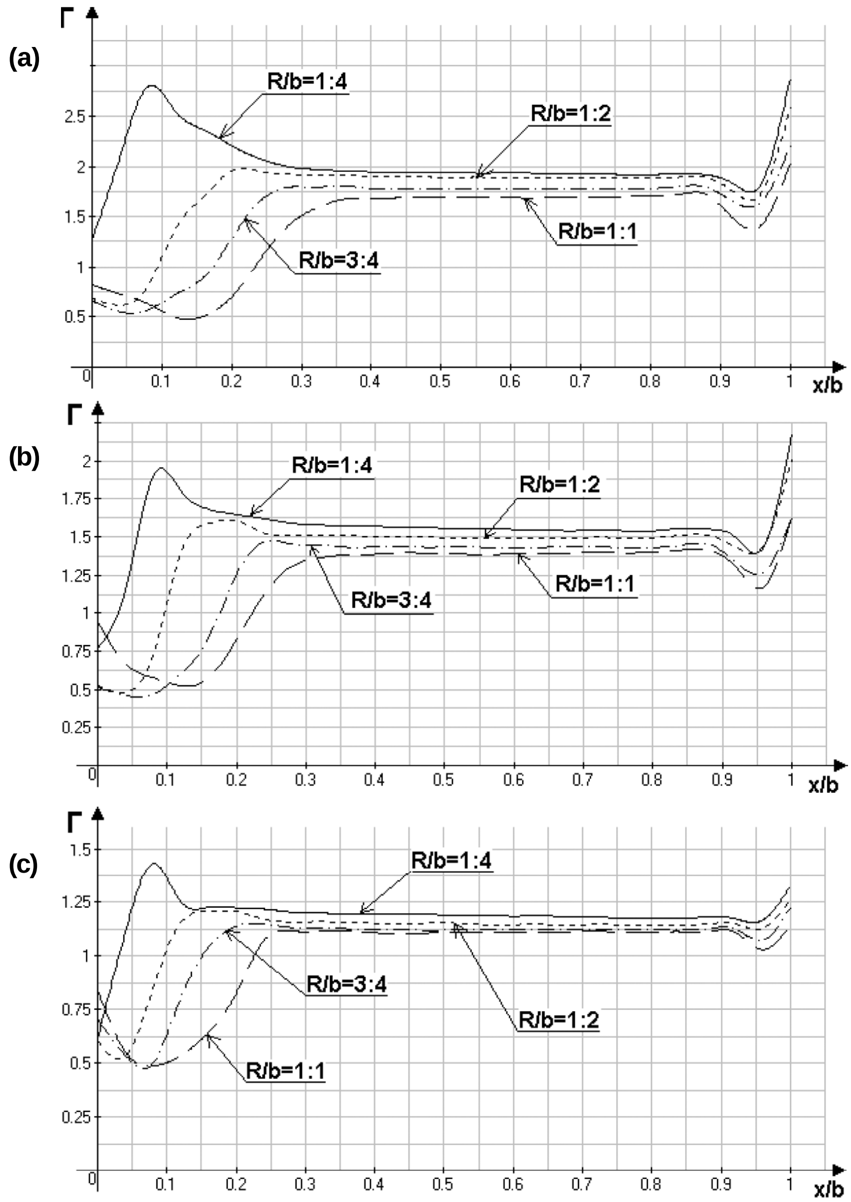

Fig. 7. Shear strain intensity distributions in the cross-section of the billet for different die geometry: a) Φ = 90°; b) Φ = 105°; c) Φ = 120°.

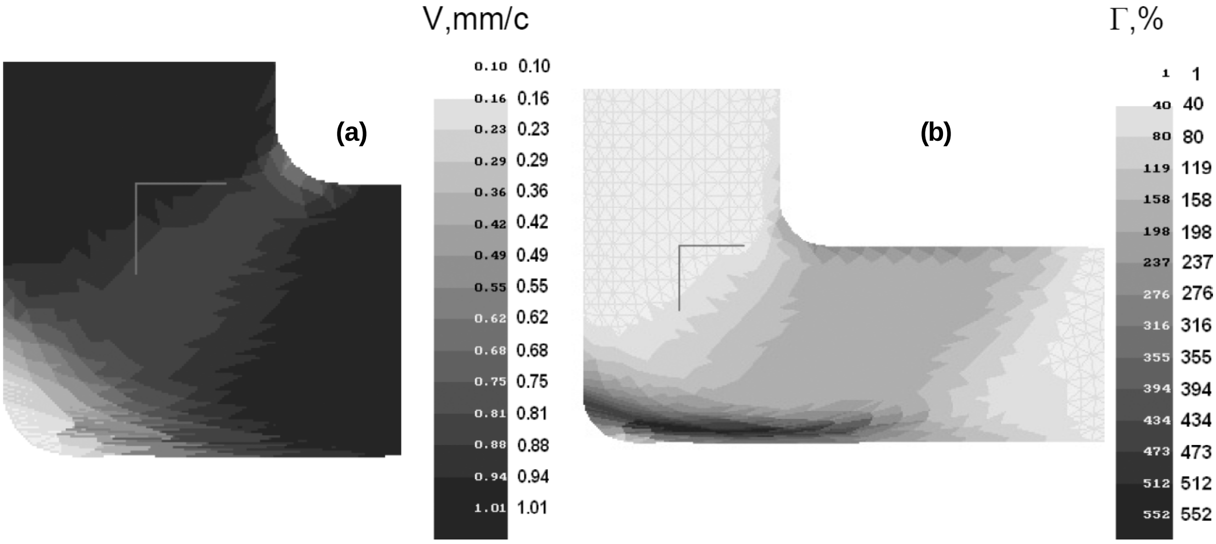

Fig. 8. Distribution of flow velocity during ECAP (a) and shear strain intensity (b) along the longitudinal section of the workpiece for Φ = 90°, *R/b* = 1:4, μ = 0.25.

For the numerical estimation of the level of irregularity a parameter *q* was used [22]:

$$q = \frac{\sum_{i=1}^{n} \sqrt{\left(\Gamma_{ave} - \Gamma_i\right)^2} p_i}{\Gamma_{ave} \cdot 100}, \tag{4}$$

where Γ_{ave} – is the average value of shear strain intensity in the workpiece cross-section; Γ_i – is the mean strain of the i^{th} area of the workpiece which belongs to the given strain range; p_i – is the percentage of the mentioned area. When the strain of the workpiece is regular the irregularity parameter *q* is zero. In other cases more value of parameter means more irregularity of the strain fields. Table 1 contains parameters of the dies and corresponding values of *q*.

The closer channel shape to the radial is, the more irregular shear strain intensity distribution in the workpiece cross-section appears. With die angle increase the shear strain field becomes more regular.

At the same time the velocity field analysis showed the possible appearance of retarded flow area of metal. Between this area and the main flow there is a very localizated zone of intense shear strain. So in spite of small value of irregularity parameter for low-plastic material it can result in its discontinuity.

Finite element analysis of friction conditions influence on stressedly-deformed state of metal was carried out for three die angles Φ = 90°, 105°, 120°. Irregularity parameter had the least value at *R/b* = 1:4 so friction influence was investigated only for this case.

The model was assumed to have the turning part of the channel filled previously with metal. ECAP process was observed on 35 forming steps.

As a result metal filled the exit part of the channel and the process came to steady (quasistationary) stage. Basing on calculation results the diagrams of flow velocity during ECAP along the longitudinal section of the workpiece were obtained (Fig. 8).

For frictionless condition the channel was not filled completely and metal passed the turning relatively easily. With friction increase metal had to fill the channel and retarded flow area mentioned above appeared. At the border with this area there was

Table 1. Values of irregularity parameter *q* for different die geometry.

Φ	*R/b*	*q*
90^0	1:4	0.074
	1:2	0.116
	3:4	0.202
	1:1	0.232
105^0	1:4	0.059
	1:2	0.087
	3:4	0.199
	1:1	0.227
120^0	1:4	0.058
	1:2	0.076
	3:4	0.124
	1:1	0.181

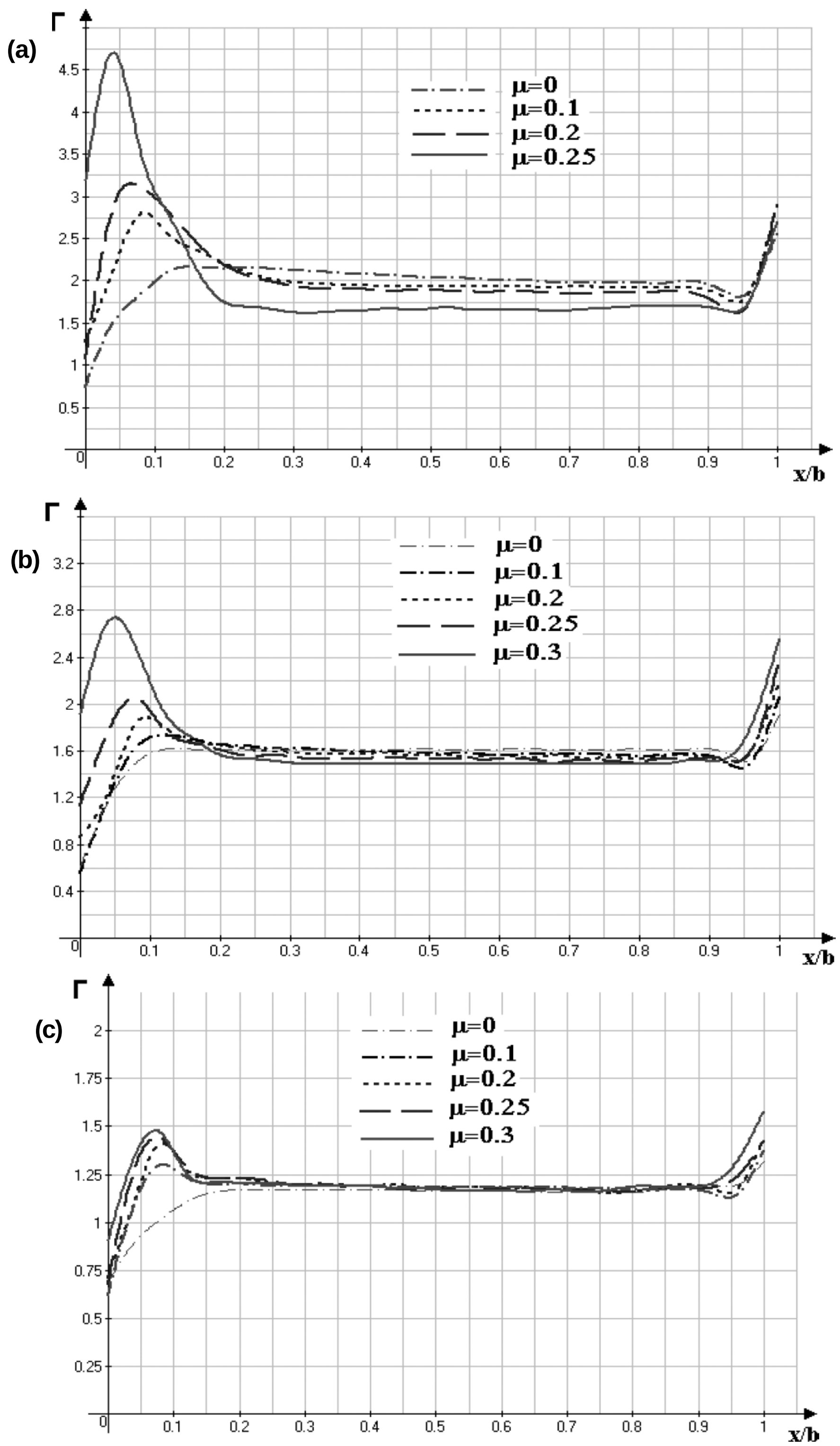

Fig. 9. Shear strain intensity distribution in the cross-section of the channel for different die angles and friction conditions: a) Φ = 90°; b) Φ = 105°; c) Φ = 120°.

greater difference of flow velocity with more friction that could result in significant irregularity of the main deformation zone.

In the rectangular channel flow velocity values for various metal layers differ ten times more (Fig. 8a). As a consequence the value of accumulated deformation in various parts of the billet differs more than 2.5 times (Fig. 8b). This can result in discontinuity of material. Further increase of friction (up to μ = 0.3) for rectangular channel is limited by additional computational expense. On the opposite side of the workpiece there is unfavorable situation as well. Along the upper wall of the channel the strain of the billet is non-monotone: material undergoes compression in the inlet part of the channel and tension in the exit part. With friction increase tensile stress values rise as well. It can result in crack formation on the surface of the processed material.

Under different friction conditions in the channel an irregularity of shear strain intensity distribution value was observed. On the analogy of die geometry influence investigation let's consider value Γ distribution irregularity behavior in the cross-section of the channel. Fig. 9 shows shear strain intensity distribution in the cross-section of the channel for different die angles and friction conditions.

With the help of *q* parameter a numerical estimation of irregularity of shear strain intensity distribution in the workpiece cross-section depending on friction conditions for different dies was obtained (Table 2).

Irregularity of shear strain intensity distribution rises with less value of die angle and friction increase. Friction increase results in rise of both hydrostatic pressure in the channel and pressing load. The analysis of stress distribution under the ram showed that with μ value increase the total level of stress rises 3-3.5 times.

3. EXPERIMENTAL RESEARCH OF ECAP PROCESS

Basing on numerical modeling of ECAP process 2 variants of experimental tool were made. In the first variant the tool consisted of two parts and had a joint in the symmetry plane of the channel.

During making and operation of this tool the following disadvantages were found out: complicated final polishing of the channel work surface, difficult taking out of un-pressed material.

According to the second variant the tool consisted of more parts (Fig.10) and was used for experimental researches. Geometric parameters of the channel: die angle Φ = 105°, channel width b = 20 mm, outer coupling radius R = 10 mm, inner coupling radius r = 5 mm.

Commercial cast aluminum A7 (according to Russian Standard) was used for experiment. The lubricants on basis of: liquid vegetable fat (lubricant №1), higher fatty acids salts (lubricant №2), solidified oils (lubricant №3, 4, 5), tallow (lubricant №6, 7) were used. Graphite and zinc stearate was taken as a stuff.

Table 2. Values of irregularity parameter *q* for different die angle and friction.

Φ	m	*q*
90^0	0	0.069
	0.1	0.074
	0.2	0.141
	0.25	0.205
105^0	0	0.058
	0.1	0.059
	0.2	0.066
	0.25	0.072
	0.3	0.099
120^0	0	0,052
	0,1	0,053
	0.2	0.058
	0.25	0.061
	0.3	0.065

With the lubricant №1 and 2 ECAP process failed. Squeezing of the lubricant out and sticking of aluminum to the channel walls was observed. Lubricants №3-7 showed sufficient results. Fig. 11 illustrates the shapes of the deformed billets after ECAP with different lubricants.

The shape of the forepart and back part of the next billet was different depending on lubricant used.

With friction increase, for example lubricant №3 (Fig. 11a), the third billet had to push out its previous one. Contact surfaces formed according to the direction of material plastic flow. If the friction remains practically the same the shape of next billets is the same either (Fig. 11b).

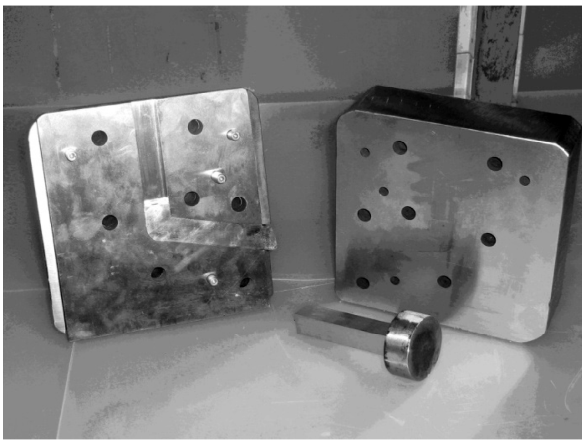

Fig. 10. Experimental tool for ECAP process.

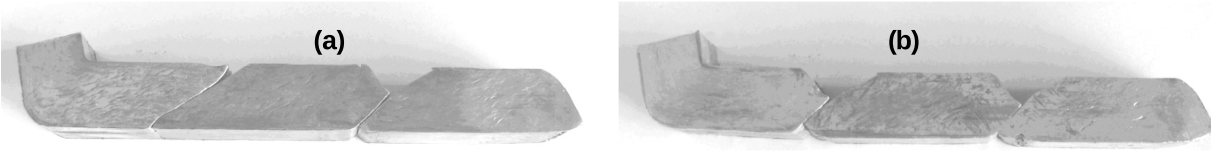

Fig. 11. The shape of the billets after ECAP process with different lubricants: a) lubricant №3; b) lubricant №6.

4. CONCLUSION

The homogeneity of structure and metal properties is provided by strain distribution regularity in the bulk material.

ECAP process is always characterized by irregular shear strain distribution. Depending on die geometry and friction condition that irregularity could be reduced. If there is a given die angle Φ and certain friction conditions it's necessary to choose the ratio *R/b* in such a way as to minimize the possible appearance of areas of retarded or accelerated flow of metal.

For designing of the tool for ECAP process it's recommended to use demountable construction that will allow making the final polishing of channel work surface easier. For higher reliability of the tool function it's advised to use a bandage.

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