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MULTI CHANNEL NON-EQUAL CHANNEL ANGLULAR EXTRUSION

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У даній статті представлено аналіз існуючих методів інтенсивної пластичної деформації, що забезпечує високу якість мікроструктури, яка забезпечує високі механічні властивості. Крім того, у статті представлений новий метод інтенсивної пластичної деформації, який був розроблений на основі попередників. Новий метод позбавлений недоліків своїх попередників, і це дозволяє отримати практично готову деталь за 1 деформаційний перехід. Перші дослідження нового процесу були пов'язані з потоком металу всередині інструменту. Експерименти проводилися на пластиліні і свинці. Всі отримані результати представлені у відповідних розділах роботи.
Ключові слова: *РККП, НРККП, мікроструктура, деформація, екструзія, інтенсивна пластична деформація.*

This study presents an analysis of existing methods of intense plastic deformation that provides a high-quality microstructure that provides high mechanical properties. also, the article presents a new method of intensive plastic deformation, which was developed on the basis of the presented ones. The new method is devoid of the shortcomings of its predecessors, and it allows to obtain a practically finished part for 1 deformation transition. The first study of the new process was carried out to understand the flow of metal inside the instrument. The experiments were carried out on clay and lead. All the results obtained are presented in the corresponding sections of the paper.
Key word: *ECAE, NECAE, microstructure, deformation, extrusion, intensive deformation.*

The main competitive advantage of steel products produced using the processes of metal forming, is a combination of high strength with sufficiently high level of impact toughness. The metal structure elaboration that after appropriate heat treatment provides the uniform fine-grained structure of the metal, takes place exactly in the processes of metal forming [1]. This structure is a necessary condition to achieve the required combination of product strength and plastic properties [2]. The analysis of the standards requirements for steel products shows that with the decrease of the conditional thickness of the product the relation between the tensile strength and yield strength usually increases for most known materials [3, 4]. This is due to the fact that the increase of the deformation degree leads to the decrease of the grain size for the most of the technological processes of metals forming.

The problem of obtaining the fine-grained structure of the products with relatively large thickness (cross sectional area) inspired the development of methods of severe plastic deformation (SPD). Such methods due to creation of conditions for the plastic shear in the deformation zone lead to intensive elaboration of the structure without significant change of the cross sectional area at the exit of the deformation zone.

The most common methods of the severe plastic deformation are asymmetric rolling [5] and angular pressing [6]. This work is concerned with the development of the latter.

Angular pressing can be performed with decrease of the cross sectional area in the deformation zone, and without it. In this case it referrers to equal-channel angular pressing (ECAP). ECAP is one of the methods of severe plastic deformation [7]. Unlike other methods of SPD, ECAP sufficiently uniformly refines the grains and changes their shape. [6] This method is used to produce ultrafine-grained [8] plastically deformable metals. The intensification of the processes of the plastic shear is caused by changing the angle β between the inlet and outlet channel of the matrix (Fig. 1).

Recently, equal-channel angular pressing has progressed from the exotic method of metals processing to the established and recognized method of producing very fine grains at the wide range of metals and alloys. Due to this, in the present time, ECAP is the most developed of all the possible methods of intensive plastic deformation. In addition, ECAP has the greatest potential for use on industrial scale [9].

The decrease of the grain during ECAP provides the occurrence of metals superplastic effect that is of great interest to modern aviation and aerospace industry [10].

The important feature of the ECAP process is the so-called additivity of grain refining with increase of deformation number. This feature allows to expose the metals and alloys with low plasticity, and considerable anisotropy of properties to the severe plastic deformation [11, 12].

Figure 2 shows the microstructure of the alloy MgCa0,8 one – and two-pass ECAP rod of the diameter of 100 mm. The images were made in cross section at the distance of 25 mm from the axis of the rod [10].

The influence of ECAP on the mechanical properties of aluminum alloy was studied in the work "Structure and mechanical properties of commercial Al–Mg 1560 alloy after equal-channel angular extrusion and annealing" [11] of V.M. Markushev, M.Yu. Murashkin from the Institute of problems of super plasticity of metals. The microcrystalline structure of the average grain size of 0.4 μm was reached as a result of severe plastic deformation by way of ECAP of the volumetric work pieces. It was established that the structure is significantly characterized by the nonequilibrium state of the internal grains, as well as asymmetrical texture of deformation. The treatment of the specified alloy using ECAP led to the increase of tensile strength and plasticity compared to more conventional methods of treatment.

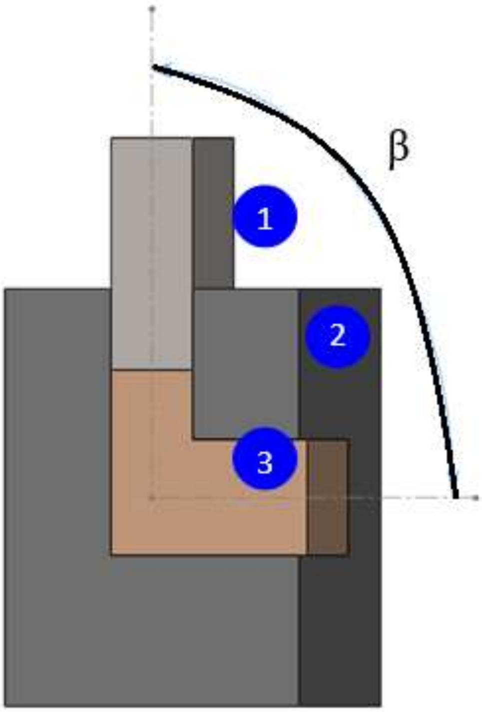
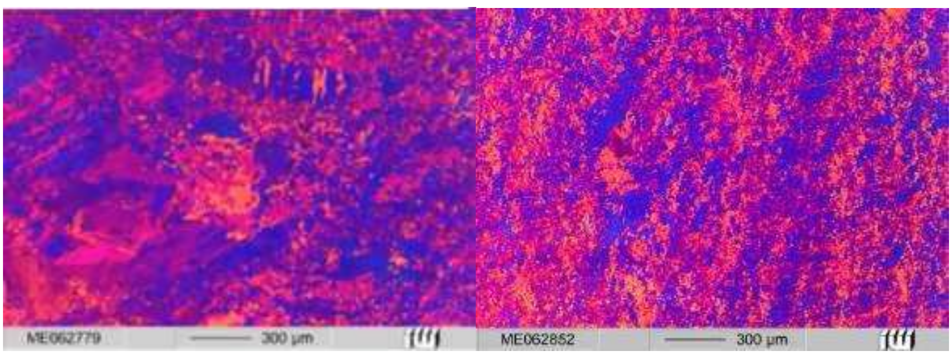


Figure 1. The scheme of equal-channel angular pressing: 1 – punch, 2 – matrix, 3 – work piece



a *b*

Figure 2. Photos of the structure of the alloy MgCa0,8 after the first (a) and the second (b) pass of ECAP [10]

The studies of M.H. Shaeri [12] from the international Institute of Imam Khomeini dedicated to the microstructural and textural evolution of aluminum alloy EN AW 7075 in the process of ECAP showed that the texture of the alloy with the initially strong fiber texture that developed in the process of ECAP strongly depended on the ECAP route and the number of passes. Having analyzed the work, it was concluded that after 1 pass, the structure strength greatly increases and then due to increase of passes up to 4, the structure strength significantly decreases. Thus, the structure after the first pass of ECAP strongly depends on the initial structure of the alloy. The initial average grain size of the alloy 7075 was 40 µm, and after the 4th ECAP pass – 600-900 nm.

As a result of ECAP development a new direction of non-equal-channel angular pressing (NECAP). Arman Hasani was one of the first who spoke of this process in his work "Principles of Non-equal Channel Angular Pressing" [13]. The essence of this process is in the reduction of the diameter of the outlet channel compared to the inlet channel. The analysis of the deformation mode during the process was performed for the case when the angle of the channels intersecting was 90 degrees. The authors determined that in this case the main mechanism of deformation was still simple shear, and so the work piece received the same fine-grained structure, as in ECAP. One of the main goals of this work was to predict the evolution of crystallographic structure in the extrusion process. The main peculiarity of the deformation mode in NECAP is that the shear plane approaches the plane of the process contributing the emergence and development of shearing textures, which have higher plasticity. Another important aspect of the process of NECAP P associated with hydrostatic pressure. The application of back pressure, carried out with the support in the outlet channel [14], showed good results. By reducing the diameter of the outgoing channel, such a back pressure develops automatically in NECAP. The last but not the least aspect is the process of grains separation. When using NECAP it is expressed stronger than in ECAP that can make NECAP more efficient method for obtaining bulk nanostructured materials [15].

In the work of La´szlo´ S. To´th, A., Rimma Lapovok, Arman Hasania and Chengfan Gub "Non-equal channel angular pressing of aluminum alloy" [16] it is shown that NECAP is a potentially productive process, but as the process itself it has not been studied experimentally. In this work, the scientists presented a comparative experimental study of the processes of ECAP and NECAP. As samples they used aluminum alloy AA2124 processed for 1 pass by each of the methods. For NECAP the matrix modernized in such a way that the ratio of the diameters of the inlet and outlet channels was equal to 2. All tests were performed at the room temperature and the constant pressing speed of 1 s^{-1}. The optical studies of the structure of the samples (Fig. 2) showed that after one pass of NECAP (Fig. 3b), the grains were very elongated compared to the grains of the sample processed with ECAP (Fig. 3c).

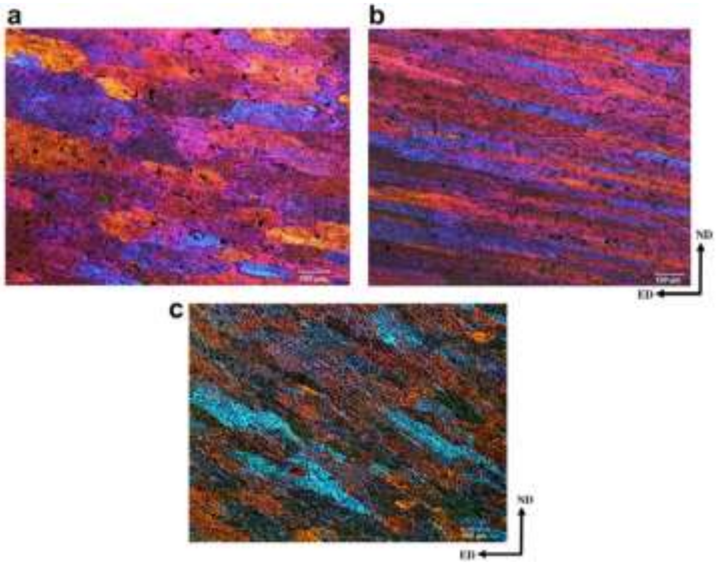


Figure 3. The microstructure of the aluminum alloy AA2124: a – original; b – after NECAP; c – after ECAP; ED – extrusion direction, ND – normal direction [16]

The results presented in this work show that NECAP leads to obtaining finer microstructure in a single pass than ECAP.

Thus, it can be concluded that the methods ECAP and NECAP excellently manage with the formation and development of fine-grained structure of the metal and significantly increase the metal strength, ductility and impact toughness due to shear deformation. However, the known methods have one great disadvantage. The result of these processes is semi-finished product (rod, strip) that requires additional treatment to obtain the finished product. However, thermal or deformational impact on the metal in the processes of such further treatment can negatively affect the structure of the metal. Therefore, the task of using SPD as finishing deformation operation in the production of the finished product is actual. The purpose of this article is to develop the method of obtaining the details of the hub type using the method of severe plastic deformation.

However, as it will be shown below the considerable nonuniformity of stresses and strains in the crimping part of the plastic zone (CPPS) under pressing is typical for the processes of NECAP. Thus evaluating the obtained microstructure it is necessary to consider the position of the collected sample relative to the zones CPPS.

Multi-channel NECAP (hereinafter MNECAP) can become a fundamentally new direction in the production of fine-grained metals and alloys. As in all reviewed methods, the core is in the punching of the work piece through the matrix that has 2 and more outlet channels located at the angle of 90° to the axis of pressing. This configuration of the matrix allows to provide shear deformations required for grain refining, as well as sufficient hydrostatic support necessary for the intensification of the processes of twinning [14]. The advantage of MNECAP in this case as well is that unlike classical methods of SPD, the finished product is obtained, for example a hub with spokes (Fig. 4). At that, the product is obtained from a relatively cheap round work piece that can have the original cast structure.

For the development of the method of MNECAP the tool for pressing of the parts of the hub type using the method of angular pressing was designed and manufactured at the department of metal forming of the National Metallurgical Academy (Fig. 5).

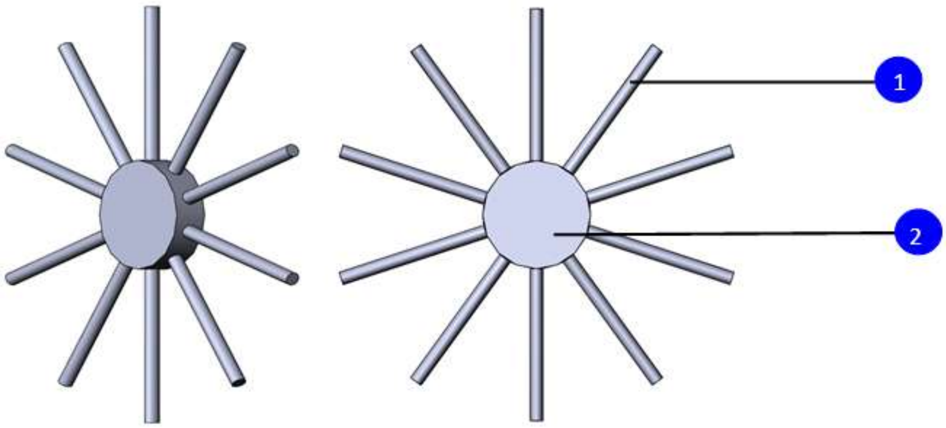


Figure 4. A hub with spokes: 1 – spokes; 2 – hub part

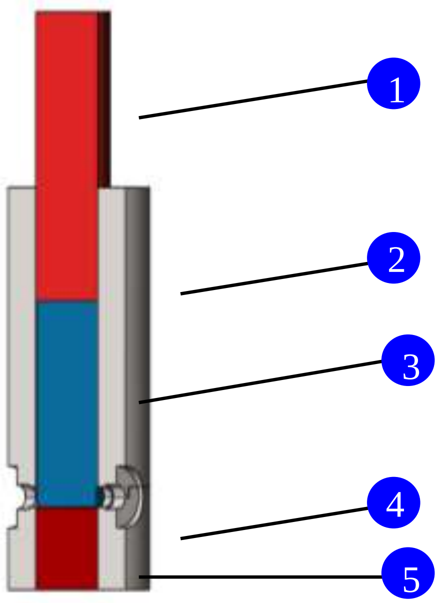


Figure 5. The tool for MNECAP as an assembly: 1 – punch; 2 – upper part of the container; 3 – work piece; 4 – lower part of the container; 5 – support

The peculiarity of the developed tool is that its matrix is integrated with the container and is performed dismountable. It provides the extraction of the finished pressed part after pressing. Thus, the tool consists of two main parts: the container for the work piece with a half of the outlet channel of the matrix and the support with the second half of the outlet channel of the matrix. To prevent undesired separation of the tool parts, a lock which can be tightened by screws is provided at the place of their junction. The process of multi-channel angular pressing is practically not studied; therefore, first it is necessary to investigate the metal flow inside the tool, as well as the capabilities of managing the geometric parameters. This will allow in future to study the microstructure of the metal, as well as to develop the technology of composite materials pressing.

Experimental study of metal flow inside the tool

To check the tool performance and analyze the metal flow in the first approach, the experiment was conducted on the plasticine pressing. The workpiece for the pressing consisted of concentric layers of the plasticine of the circles light and dark colors (Fig. 6). The layer thickness was 3 mm. Total diameter of the work piece was 42, and length was 100 mm.

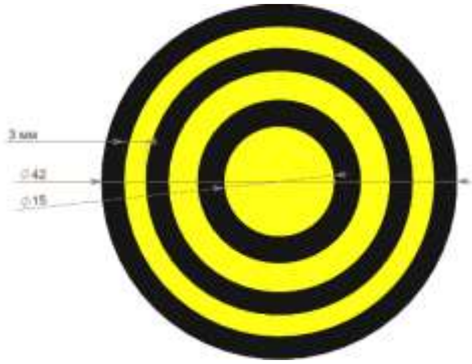


Figure 6. Schematic view of the cross section of the plasticine work piece

The experiment consisted in measuring the thickness of layers of light and dark plasticine at the distance of 10 and 30 mm from the surface of the undeformed work piece (Fig. 7).

Figure 8 shows the products of the type "hub with spokes" after MNECAP with the partial reduction ratio equal to 12.

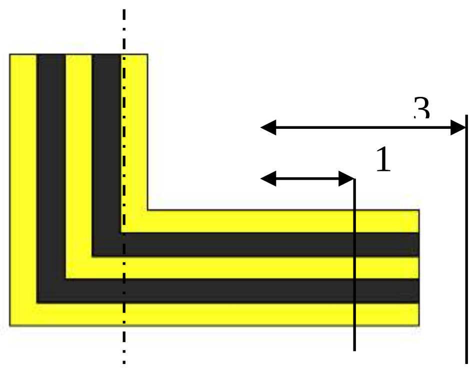


Figure 7. The scheme of measurements of the deformed plasticine

Figure 8. The view of the part of the type "hub with spokes" obtained as a result of MNECAP of the layered plasticine work piece and the numbers of the layers that were measured (table 1)

In the study of MNECAP the following deformation indexes are used:

Partial reduction ratio μ_i:

$$\mu_i = A_c / A_i \quad (1)$$

where: Ac is the area of the container cross section equal to the area of the work piece cross section after its pressing-out; Ai is the cross section area of one outlet channel of the matrix.

The total reduction ratio μ_Σ:

$$\mu_\Sigma = \frac{A_c}{\sum_{i=1}^{n} A_i} \quad (2)$$

where: n is the number of outlet channels of the matrix.

Relative deformation of the plasticine layer ε_l:

$$\varepsilon_l = \frac{h_0 - h_1}{h_0} \quad (3)$$

where: h_0 is the initial thickness of the layer (in the performed experiment h_0 =3 mm) h_1 is the thickness of the plasticine layer after pressing.

The values obtained by the formulas 1 to 3 of the parameters are presented in table 1.

Table 1. The deformation indexes at MNECAP of the layered plasticine work piece (Fig. 7 and 8)

	Layer number			
	1	2	3	4
10 mm from the inner surface of the container				
h_0, mm	3 mm	3 mm	3 mm	3 mm
h_1, mm	2,3 mm	1,5 mm	1,5 mm	1,85 mm
ε %	23 %	50%	50%	38%
30 mm from the inner surface of the container				
h_0, mm	3	3	3	3
h_1, mm	2,5	1,5	1,5	2
ε %	17 %	50%	50%	33%

As a result of the experiment, the data of unhomogeneity of the deformation of the plasticine layers were obtained. It is established so that the inner layers of material (layers 2 and 3) have the maximum deformation. The flow of the layer 1 is decelerated by changing the direction of the metal flow and contact friction. The layer 4 is decelerated by the residual effect of the contact friction of other layers that lie below it and, unfortunately, were not measured. At that the deceleration of the layer 1 was stronger that led to the spoke bending up.

Thus, as a result of the plasticine pressing the qualitative results of irregularity of the material flow during MNECAP were obtained. It is established that the central layers of the material are deformed easier and the layers the flow of which is decelerated due to peculiarities of the tool design, are deformed less. In addition, this experiment was necessary to verify the efficiency of the tool and pressing technology. As a negative result of the experiment with plasticine the following should be noted: plasticine pickup in the tool, as well as significant non-uniformity of deformation resistance associated with heating of the material in the deformation process. Probably the significant difference in the layers thicknesses after pressing is caused by this fact.

In order to avoid these drawbacks of plasticine, lead of C1 grade was also used as a model material for MNECAP. The experiment with this material was the following:

- Five cylindrical work pieces of the diameter of 42 mm and the length of 100 mm were previously cut lengthwise.
- The coordinate grid with cell size of 2x2 mm was applied with a steel needle on the jointing plane.
- MNECAP was conducted at the laboratory press of the nominal force of 160t of the Department of metal forming of the National Metallurgical Academy of Ukraine.
- The pressing temperature was room temperature.
- The tool design was similar to the one of experiments with plasticine (see Fig. 9).

As a result of the experiment, the product samples of the type "hub with spokes" were obtained. The peculiarity of the products obtained in the experiment was the split along the axis of two opposite spokes. Thus, the transformation of the grid cells in the pressing process is clearly seen on the jointing plane after pressing. Further investigation of the metal flow was performed with simulation by the finite element method implemented in the software package QForm V8, kindly provided by the company Micas Simulations Ltd (Dr. N. Biba). The main objective of the study at this stage was obtaining of geometric similarity of the process and the end product of the type "hub with spokes" to the results of the experiment on the following criteria:

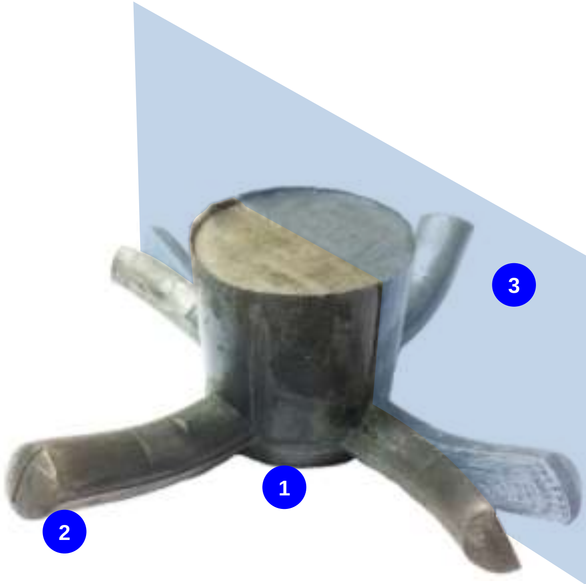


Figure 9. Split along the axis of two opposite spokes

1. The nature of the metal outflow from the matrix over time. The direction of the spokes bending.

2. The nature of changes of the virtual coordinate grid, similar to the experiment.

Pressure and temperature conditions of the process as well as friction were also estimated in the simulation process. The simulation process was as follows:

1. The creation of a two-dimensional drawing of the tool and work piece in the editor QDraft integrated in the software product QForm. Also, the drawing can be created in another editor.

2. Development of the geometric model of the tool and work piece to the drawing and its segmentation into finite elements grid was performed using the module QShape (Fig. 10). In this simulation process, the grid is automatically rebuilt into finer one, improving the accuracy of the results.

3. The task of boundary conditions, which include the coefficient of friction between the tool and the work piece, the material of the work piece and the tool, the movement direction and the force affecting the punch, as well as the condition of the process stop.

4. The calculation of the process.

Verification of the model adequacy. When specifying the boundary conditions the data obtained by the experiment were used, therefore, the verification of the model adequacy was performed by comparison of the simulation and experiment results.

The evaluation of the results of the experiment and simulation

*The analysis of the nature of the metal outflow from the matrix over time and the direction of the spokes bend***.** The sample obtained in result of simulation is similar to the experimental one according to the nature and size of the spokes bend. Also in the modeling process, it was evident that the nature of the metal outflow over time was identical to the experimental one. The main difference is less bend of the spokes. This is probably caused by friction conditions and rheological properties of the material. The study of these parameters is a subject for further research.

The analysis of the nature of the coordinate grid change. Pressing of the sample with grid proved that the coordinate grid change was qualitative and conformed the experiment (Fig. 11). Quantitative comparison of changes of the coordinate grid was not carried out in this work. Having sized the model sample grid and compared with the sizes of the experimental sample grid, the boundary deviation was 4.5% that is high for FEM models. Thus, the software package QForm V8 is well suited for studying the process of MNECAP as well as for studying the possibility of using this type of pressing at the production of a part of the type "hub with spokes". However, the condition of metal fracture remained not entirely clear from the simulation results.

The analysis of the jointing plane of the sample allows to separate a few main areas on it (Fig. 12):

1. All-around compression area. Compression without strain zone

2. Area of the outer surface of the work piece, which was not deformed, and was extruded by the inner layers of the metal during pressing. Punched external layers

3. Area of the established process, this zone contains sites that received different ratio of shearing deformation and drawing.

4. Pressing part of the plastic zone (PPPZ) is characterized by a smooth transition from the main shear stresses through compressive to tensile.

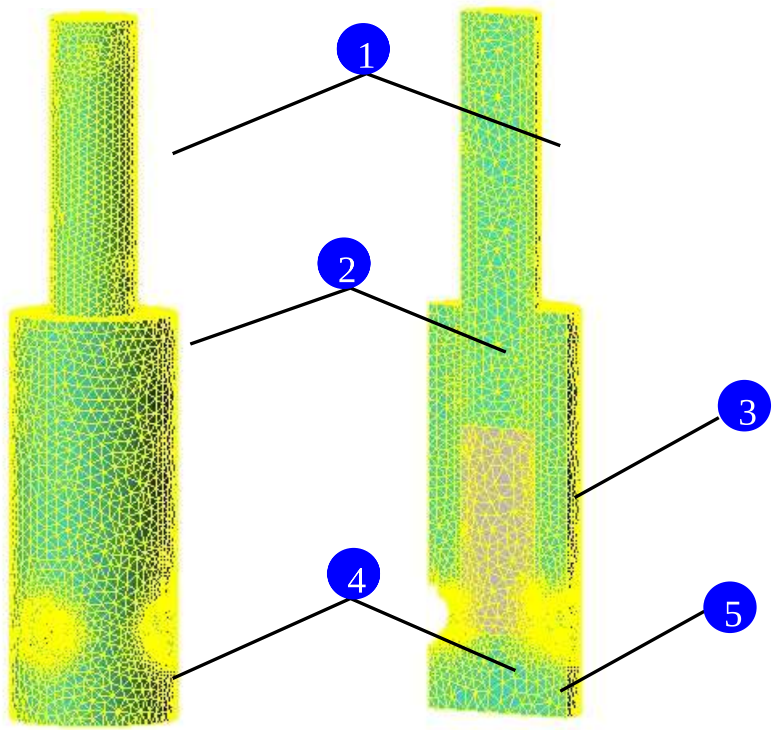


Figure 10. The original grid of finite-element model: 1 – punch; 2 – upper part of the container; 3 – work piece; 4 – lower part of the container; 5 – support

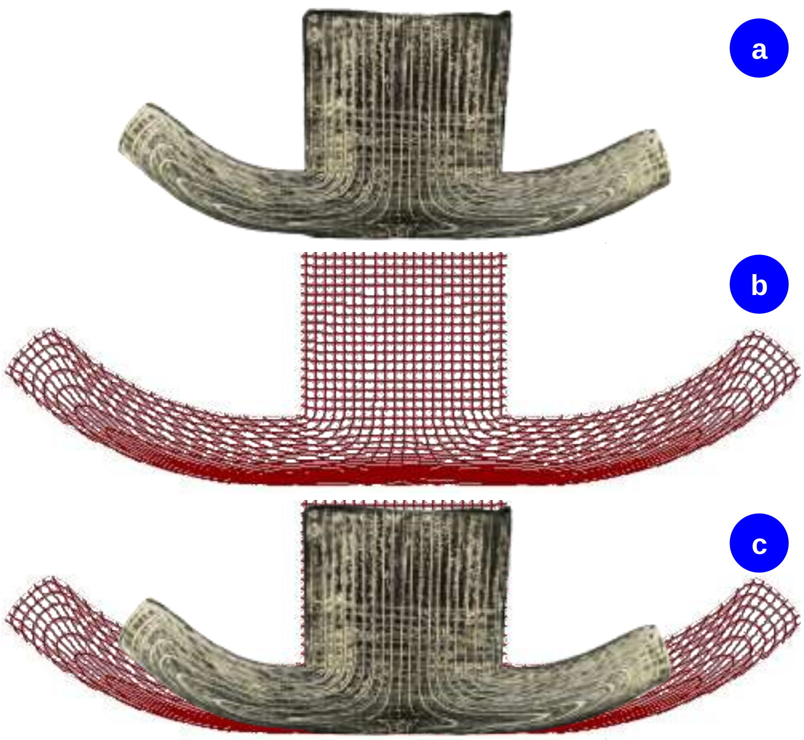


Figure 11. The jointing plane of the sample after MNECAP: a – experiment (lead S1); b– simulation in the program QForm V8; c – overlay of the images a and b

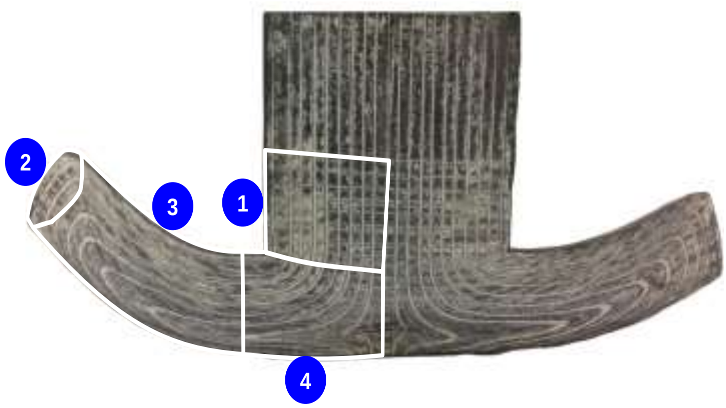


Figure 12. Location of the typical areas on the jointing plane of the sample

The analysis of the pressing part of the plastic zone (PPPZ) proved that it consists of certain zones, and is classified on the basis of the prevalence of the shear, compression or tension. Thus, PPPZ consists of the following (Fig. 13):

1. The area of the surface layers, which are deformed by the pure shear without drawing (the area of the pure shear).
2. The area of increase of the influence of compressive stresses, it is characterized by the shear deformation and drawing.
3. The area of compressive stresses with the maximum drawing of inner layers of the work piece.
4. The area of increase of the influence of tensile stresses. In this zone, the drawing of the layers decreases.
5. The area of predominance of tensile stresses. Due to the action of tensile stresses in the central part of the work piece, extrusion defect is formed. The boundaries of this zone can be defined by the criterion of complete disappearance of the transverse surface defects (in this case, the crossing grid lines [21]).

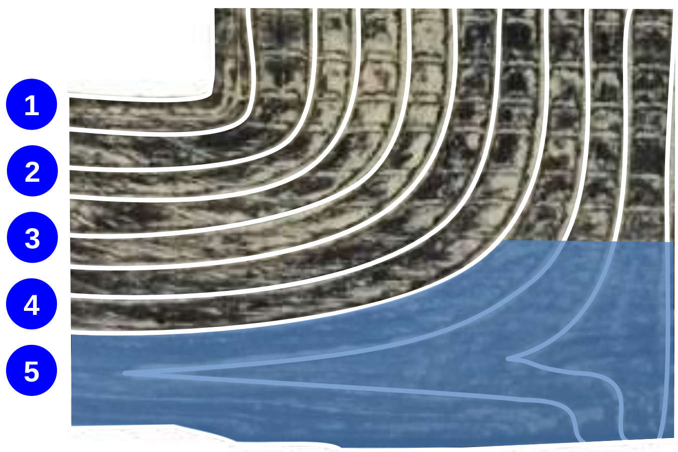


Figure 13. Typical zones of PPPZ

Thus, the experimental pressing of the sample with coordinate grid allowed to define the nature of the metal flow in the jointing plane in general and in the pressing part of the plastic zone in particular. The results of this study are necessary for further computer simulation, as well as for necessary explanation of the structure transformation in the process of MNECAP (is not provided in this work). In addition, the carried out experimental studies confirmed the efficiency of the developed design of the tool for MNECAP.

Definition of quantitative criteria of division of PPPZ zones is a task for further simulation. However, it can be already concluded that in the process of MNECAP, as in other processes of angular pressing, the zone of pure shear takes only a small part of the deformation zone. Therefore, the conclusions made in the works [12-16] should be clearly related to the place of sampling for metallographic examination, as it was done in the work [12]. Thus, a relevant objective for further research of the process MNECAP may be the determination of the optimal ratio of the private and the total (1, 2) to reduce the anisotropy of the structure and properties of the output profile. Also it is possible to reduce the stress gradient in the deformation zone by optimizing the shape of the punch and support.

CONCLUSIONS

1. The process of multi-channel pressing is a particular interest for industry as it allows to obtain almost finished part with high mechanical properties of round cast work piece for one transition.

2. Due to shear deformation and drawing, the process MNECAP has the potential to control the mechanical properties of the finished product.

3. The tool for MNECAP of the part of the type "hub with spokes", which was checked during the pressing of the plasticine and lead alloy C1, was developed.

4. As a result of the pressing the plasticine, the qualitative results of the material flow irregularity during MNECAP were obtained. It is established that the central layers of the material are deformed easier and the layers the flow of which is decelerated due to peculiarities of the tool design, are deformed less.

5. The experimental pressing of the samples made of lead of C1 grade with the coordinate grid drawn on the jointing plane of the two halves of the work piece, allowed to determine the nature of the metal flow of the jointing plane in general and in the pressing part of the plastic zone, in particular

6. The finite element model of the process of multichannel angular pressing in the software package QForm V8, kindly provided by the company Micas Simulations Ltd, was first-ever created and tested.

7. The modeling of the process MNECAP showed good convergence with the experimental results.

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