Effect of Severe Plastic Deformation on the Structure and Properties of Aluminum Alloys

S.A. Mashekov[1], E.A. Tusupkalieva[1], A.S. Mashekova[2*], M.M. Akimbekova[1], A.M. Alshynova[1], N.S. Sembayev[1]

[1]Institute of Industrial Engeneering, Kazakh National Research Technical University, Almaty, Republic of Kazakhstan

[2]School of Engeneering, Nazarbayev University, Astana, Republic of Kazakhstan.

[*]Corresponding author: e-mail mashekovaaigerim@mail.ru

Abstract

This article presents the results of studies of the effect of number of passes while pressing workpieces in the cross shaped tool on the stress-strain state and introduces the parameters of the microstructure of the pressed workpiece made of D16 aluminum alloy. A comparative evaluation of the size of grains of ultrafine structures after pressing the workpieces in the cross shaped tool with various stages of deformation at temperature of 350 °C is provided. The characteristic parameters of grain and defect structure are presented. It is shown that the blank of D16 aluminum alloy ensures uniform formation of an ultrafine grain structure with a size of grain of about 600 - 900 *nm*, which results an improved strength properties of the alloy and preserves good ductility.

Keywords: D16 aluminum alloy, pressing, cross shaped tool, severe plastic deformation, electron microscopy, submicrocrystalline state, mechanisms of formation and evolution of the microstructure, grain size, a single reduction.

Introduction

Grinding of grains is a well-known method and widely used way of producing semi-finished products with fine-grained structure for subsequent stamping, pressing, rolling, etc. (Kolachev et al, 2001; Kaybyshev et al, 2002). Preshaping with a fine-grained structure is the basis of a fundamental change in the properties of the products and attainment such characteristics as very high strength with significant ductility, high fatigue resistance and durability, wear resistance, superplasticity and other.

Consequently, the solution of problems associated with quality, physic-technical and technological properties of a wide application products remains to be actual every time. Such products are used in space technology, in the aircraft industry, in mechanical engineering, and so on, by using the preforms with a fine-grained structure.

Well-known studies (Valiev et al, 2000) have clearly demonstrated the great potential of severe plastic deformation methods for producing the workpieces with fine-grained structure. Therefore, among fundamental and applied scientific works of scholars of foreign countries a plastic deformation of metal materials with an aim of microstructural refinement is received the greatest development.

Currently, in order to obtain high-quality materials with ultra-fine structure (nanostructure), without significant changes in their size, the methods of severe plastic deformation (SPD) is used, mainly realizing macro shifting deformations with the total level of more than 2 - 3 (Maydanyuk et al, 2008*a*; Maydanyuk et al, 2008*b*; Valiev, 2006; Yunussova, 2004; Beygelzimer et al, 2003; Valiev et al, 2000; Segal et al, 1994;): torsion under quasi-hydrostatic high pressure, equal channel angular pressing, comprehensive isothermal forging and radial-shear rolling, etc. Macro shifting deformations cause changes in the structure of the metal due to slip transmission of grain, which does not depend on the orientation of the crystal grains. The result of these changes occurs due to increase of the level and uniformity of mechanical properties of metal, as well as reducing their anisotropy.

Paper (Nayzabekov et al, 2005) proposes to use an intensive plastic deformation for creating the materials with improved mechanical properties and with fine-grained structure, i.e., pressing of billets in equal channel step matrix with rollers in an inclined section of the channel. In the paper (Valiev et al, 2000) is widely studied the process of semi-finished products production with a fine-grained structure by using an intense plastic deformation, or another words by using pressing in equal-channel angular matrices differed in design. It should be noted that pressing of workpieces in equal channel step matrix with or without rollers in an inclined section of the channel is one of the method which is not radically different from the equal channel angle pressing (ECA-pressing).

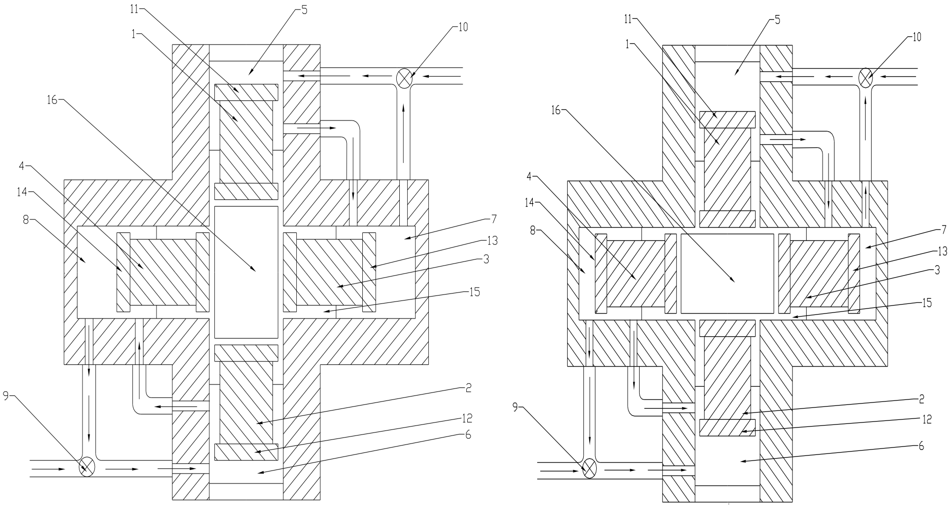
It is known that plastic deformation of crystalline bodies is carried out by micro shifting strain. However, in the proposed methods of works (Valiev et al, 2000; Yunussova, 2004; Valiev, 2006) the summation of elementary shifts of some of the crystals occurs unevenly along the volume of the deformed blank. Due to uneven summation of elementary shifts, the shear deformations are concentrated and localized in some parts of the deformed workpiece, manifesting as macroshift of its volume. In these localized areas of the workpiece, the structure of steels and alloys is rapidly converted to a fine grain structure with a relatively small value of average draft, and relatively coarse grain structure is kept in the remaining areas. Therefore, in order to obtain a fine-grained structure of the entire volume of the workpiece, it is necessary to build process of deformation, so the sufficient shear deformation can pass through all deformed volume. Application of the localization zones of shear deformations can be useful for transformation of the structure to a fine-grained structure in the separate sections of the deformation zone. However, other parts of the structure cannot be transformed into a fine-grained structure.

Based on the information written above, it can be noted that for the plastic deformation of the entire volume of semi fine structure it is necessary to reduce the shear strain localization, i.e. shearing deformation should be evenly distributed in the volume of deformable semi-finished product. In order to realize this, a design of a new device should be developed which allows to distribute the shear deformation evenly in the deformable volume of the workpiece.

The aim of the paper is to develop a new device construction for uniform grinding of metal structures and to study the stress-strain state (SSS), besides to evaluate the structure of billet made of D16 aluminum alloy while deforming it in this device.

Equipment, materials and methods of the experiment

A device for deformation metals and alloys was proposed in order to get ultrafine grained structure along the entire volume of the billet by using a severe plastic deformation (Mashekov et al, 2011). This device consists (Figure 1) of the matrix 15 of a cross shape, four punches 1, 2, 3 and 4, four cylinders 5, 6, 7 and 8, two valves 9 and 10, four pistons 11, 12, 13 and 14. The upper, lower, left and right punches are located in the channels of matrix, and the relevant pistons are located in the cylinders connected with matrix. It should be noted that the punches are secured to the respective pistons.



a) *b*)

Figure 1. Initial (*a*) and final (*b*) position of the details and the workpiece in the tool

Production of semi-finished products with ultrafine structure is as follows. The preform 16 through a side loading device is placed between the punches 1, 2, 3 and 4. When a source of energy passes through the control valve 9 and 10 into the upper part of the upper 5 and lower part 6 of the lower cylinder, the reciprocal movement occurs relative to each other in pairs fixed to the upper punch piston (1, 11) and the lower punch-piston (2, 12). At the same time the displacement of the energy carrier from the bottom of the top 5 and top of the lower cylinder 6 and feed them to the left side of the right 7 and right side of left 8 of the cylinder. This leads to a divergent movement relative to each other in pairs enshrined the right of the punch-piston (3, 13) and a left punch-piston (4, 14). Plastic deformation in the vertical direction of the workpiece occurs while driving the upper 1 and lower 2 punches in the opposite direction. The reciprocal movement relative to each other in pairs, fixed to the right punch piston (3, 13) and left-punch piston (4, 14) occurs while applying energy source through the control valve 9 and 10 to the right side of the right 7 and left side 8 of the left cylinders. Thus there is a displacement of the energy carrier to the left side of the right 7 and left-right side of the cylinder 8 and feed them in the lower part of the top 5 and the upper part 6 of the lower cylinder. This leads to a divergent movement relative to each other in pairs, fixed to the upper punch piston (1, 11) and the lower punch-piston (2, 12). While moving the right 3 and left 4, the punches in the opposite direction of the plastic deformation occurs in the horizontal direction of the workpiece.

Appliance of equal channel stepped matrix with a cross-shaped form allows to deform the workpiece inside the matrix repeatedly, and as a result to obtain the semi-finished products with fine-grained structure. Alternating metal deformation occurs with the change of the axis of the workpiece. Changing the workpiece axis facilitates changing of constrained deformation zones, which arises between the dies and the workpiece. Zone of constrained deformation occurs in one cycle of deformation, i.e. a cycle is consisted of a deformation in the vertical and horizontal directions, begining from the end surface to the side surface of the workpiece. This case, as well as multiple interlace of deformation in the horizontal and vertical directions results in ultrafine structure over the entire section of the deformable preform. Implementation of the alternating deformation in the matrix without removing the workpiece from the tool allows to increase the productivity of obtaining semis with ultrafine grained structure.

One of the most important tasks of metal processing theory is the analysis of the power mode pressing, the definition of existing hotbeds of tension in the deformation. A study of SSS of the blank during the pressing process in the proposed device in terms of mathematical modeling is a complicated process because of the very large number of defining parameters and ambiguous nature of their impact. Therefore, CAE program MSC.SuperForge was used for the mathematical modeling.

A three-dimensional geometric model of the instrument was built in CAD Inventor program and imported into the CAE program MSC.SuperForge. A three-dimensional volume element CTETRA was used to create a finite element model of the workpiece and the tool. The element is applied for modeling the three-dimensional bodies.

The samples of cylindrical shape with dimensions of Ø50 × 100 *mm* were used to investigate SSS of the blanks. Aluminum alloy was chaosen as a material of the blank. The temperature range of the alloy is 300 – 450 °C, and the mechanical properties of the material are equal to: elasticity modulus of 75 *GPa*, punch coefficient of 0.3 and density of 3800 kg/m^3. The elastoplastic model of Johnson-Cook was chosen in order to simulate the plasticity of the workpiece.

SSS and the temperature field of the metal of the blank were calculated for the double stroke of punches in opposite directions. At the same time pressing the workpiece was performed at the rate of $1.5*10^{-3}$ m/s. Absolute reduction while pressing and time of deforming was 25 *mm* and 6.67 *s*, respectively.

In MSC.SuperForge the tools are absolutely rigid and provide only the properties of thermal conductivity and heat transfer, i.e., thermal conductivity, specific heat and density are taken into consideration, while mechanical properties are ignored. The material of the tool is assigned to the tool steel H13 by default.

Also the density and thermal properties for this material will be assigned by default.

Interaction between the rigid tool and the deformable material of the workpiece is modeled using contact surfaces, the contact conditions that describe the surfaces between the tool and the workpiece surface. In the process of modeling the contact conditions are constantly updated to reflect the movement of the tool and the deformation of the material, which allows us to simulate the slip between the tool and the workpiece material. The contact between the tool and the workpiece is modeled by Coulomb friction, where the friction coefficient was adopted as 0.3.

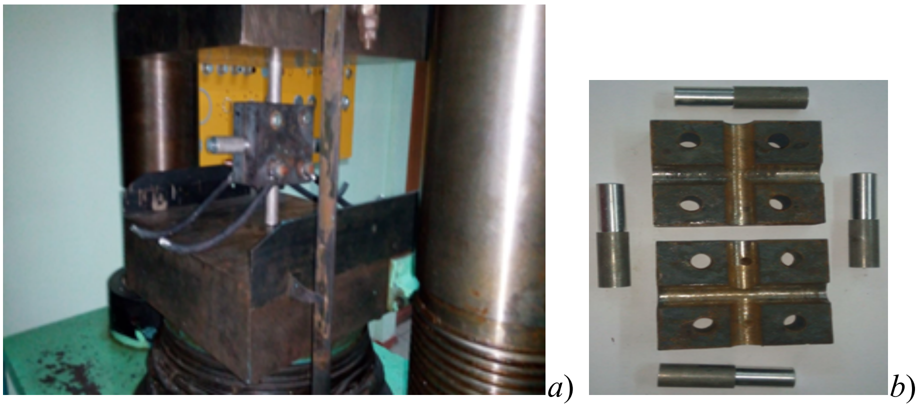
Temperature conditions during the pressing include the heat exchange between the tool, the workpiece and the environment, as well as a thermal effect due to metal deformation. Heat transfer is carried out by convective and radiative exchange with the environment and tool contact with the workpiece. The pressing process takes place at a temperature of 350 °C. The initial temperature of the tool was adopted as 20 °C.

2518 elements and 3180 assembly were required for the model of the workpiece and the tool. Time calculation process was 24 minutes on the computer PentiumDuo with the clock frequency of 3.4 *GHz* and 2 *GB*.

Pressing process in the present device can be divided into stages of deformation as a percentage of the total time of deformation. While analyzing the data we selected the following compression stage: 40, 60, 80 and 100 percent of full-time deformation.

D16 aluminum alloy was selected as the workpiece material while providing laboratory experiments. Workpieces with the size of Ø50 × 100 *mm* was heated at 350 °C for 2 hours and deformed in the cross shaped tool with two, four and six passages (Figure 2). The cross shaped tool was heated until it reached the deformation temperature.

Metallographic analysis was performed by using a spectrometer JNCAENERGY (England), mounted on electron probe microanalyzer JEOL (Dzheol) at an accelerating voltage of 25 *kV*. Range of increases of JEOL instrument is from 40 to 40,000 times. The principle of the microprobe: high-energy (25 *kV*) narrow (1 micron) beam of electrons is directed onto the sample, which is set in the screen (frame) by scanning the sample with the recorded secondary electrons emitted by the sample. The resulting picture is very similar to the optical photo, but due to the fact that the electron beam is very thin (≈ 1-2 microns), the depth of focus is much higher than that of optical photo and used increase is much higher, respectively, it is possible to distinguish between the smaller structural componential samples.



a - pressing on the laboratory extruder; *b* - cross-shaped tool
Figure 2. Deformation of the workpiece in a cross-shaped tool

Quantitative analysis of the parameters of the defect substructure was carried out by standard methods (Utevsky, 1973). Microsections for metallographic study were prepared according to traditional methods in the grinding and polishing circles. Concentrated nitric acid solution in ethanol was used for etching samples. Grain size (D_g, microns) was determined by secants (measuring ~ 300 grains) on the assumption that the grains are spherical, the average value was based on the chord (X) by the formula: $D_g = 4/\pi \cdot X_{average}$.

Mechanical testing on the flat samples with the size of working part of 1.5 × 3 × 6 *mm* was performed on a universal testing machine “Instron 5882”. According to testing results of samples at room temperature, the followings were evaluated: yield strength ($\sigma_{0.2}$), ductility range (σ_d) and elongation (δ) by the procedures described in GOST 1497-84 and GOST 9651-84, respectively.

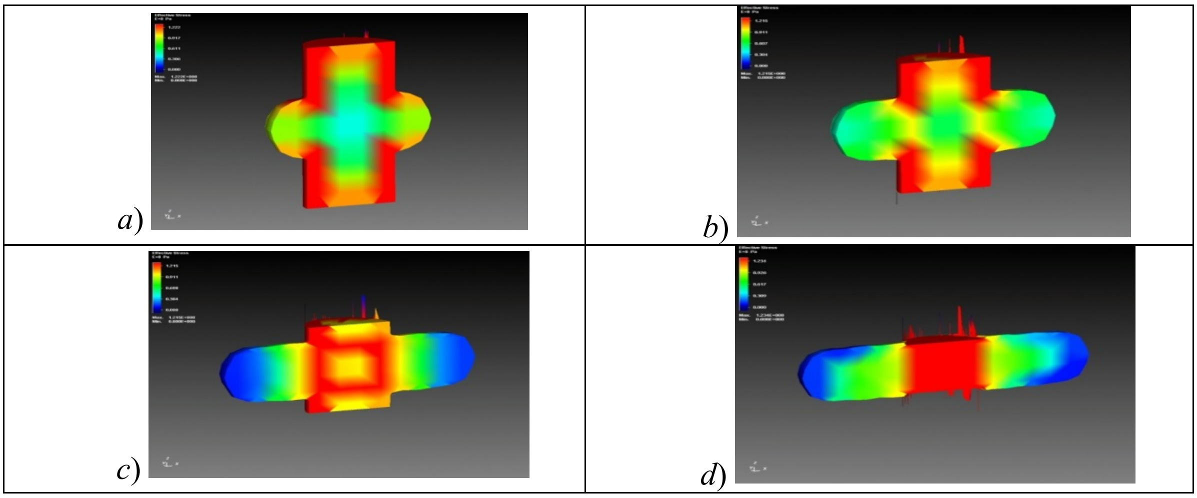
Before testing, the samples were subjected to tensile thermal procedure (TP) consisting of a hardening and subsequent aging. The heating temperature for quenching was 450 ^{o}C, keeping time at this temperature is 2 hours, cooling in oil. Aging was conducted at the temperature of 120 ^{o}C for 5 hours.

Results and discussion

Figures 3, 4 and 5 show the intensity distribution of pattern of stresses and strains, the temperature field in the first stage of deformation.

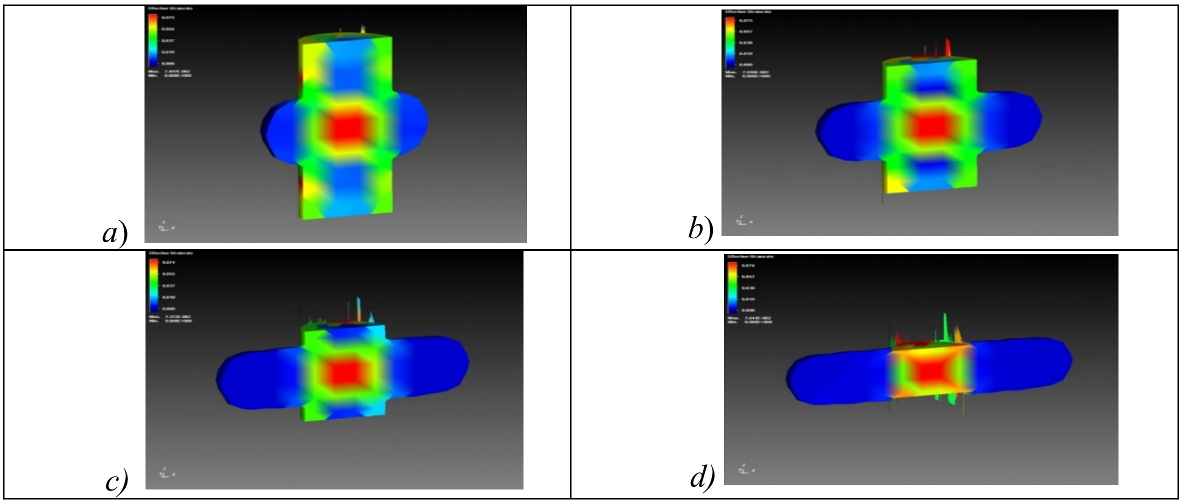
On the basis of numerical simulation results it is revealed that:

- in the first pass of pressing and at the initial moment of deformation the maximum value of the stress intensity are located in the upper and lower sides of the surfaces of the workpiece, i.e. it is detected on the adjacent to the upper and lower cylinders of the preform zones (Figure 3, *a*, *b*);
- with the increasing draft the intensity localization is transferred from the side surface to a central portion of the preform (Figure 3, *b*); and finally at the end of the draft the intensity is completely concentrated under the upper and lower punch (Figure 3, *d*);



a – 40%; *b* – 60%; *c* – 80%; *d* – 100%

Figure 3. Stress intensity distribution pattern in the workpiece during pressing in the first pass



a – 40%; *b* – 60%; *c* – 80%; *d* – 100%

Figure 4. Deformation intensity distribution in the preform during pressing in the first pass

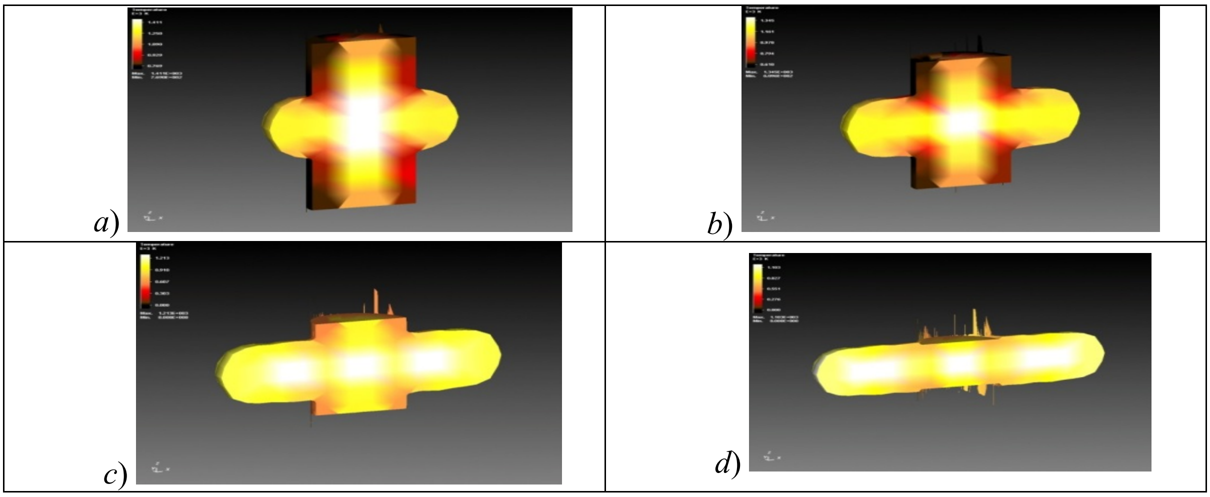
- in the first passage of pressing and during the initial deformation moment, the maximum intensity value of deformations are localized in the central portion of the preform, as well as the upper and lower side surfaces of the workpiece, (Figure 4, *a*, *b*).

- with the increase of compression, the stress strain localization intensity is transferred from the side of surfaces to a central portion of the preform (Figure 4, *b*) and finally the compression is completely concentrated under the upper and lower punch (Figure 4, *d*);

- in the first passage of pressing and during the initial deformation moment, the temperature decreases in the upper and lower sides of the workpiece, i.e.

adjacent to the cylinder device blank areas, and the temperature rises in the central portion of the preform (Figure 5, *a*, *b*).

- with the increase of reduction, the temperature of the cross section of the workpiece is aligned (Figure 5, *b*, *d*), but the largest zones in terms of the temperature are focused at the upper and lower punch, also in the areas of preform which is perpendicular to the pressing axis of the shaft (Figure 5, *d*);



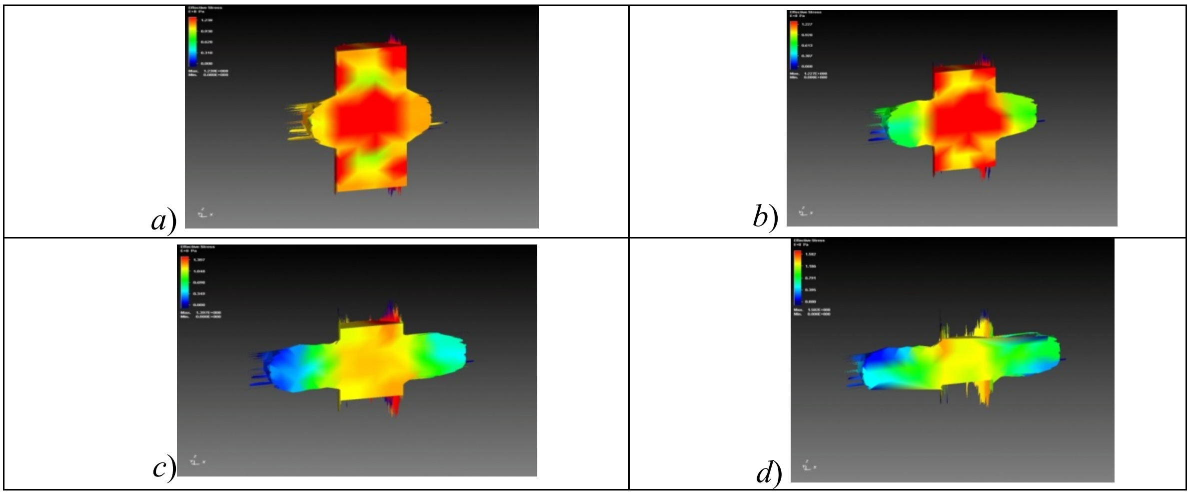
a – 40%; *b* – 60%; *c* – 80%; *d* – 100%

Figure 5. Distribution pattern of the temperature field in the billet while pressing in the first pass

Figures 6, 7 and 8 present the intensity distribution pattern of stresses and strains, the temperature field in the second deformation pass (Figures 6, 7 and 8 are rotated by 90°).

On the basis of numerical simulation results it is revealed that:

1. In the second pass of pressing and during initial deformation moment, the stress intensity is localized in the left and right sides of the surfaces of the workpiece, i.e. adjacent to the left and right cylinder devices of billet zones, as well as in the central zone of the workpiece (Figure 6, *a*, *b*).



a – 40%; *b* – 60%; *c* – 80%; *d* – 100%

Figure 6. Stress intensity distribution pattern in the workpiece during pressing in the second passage

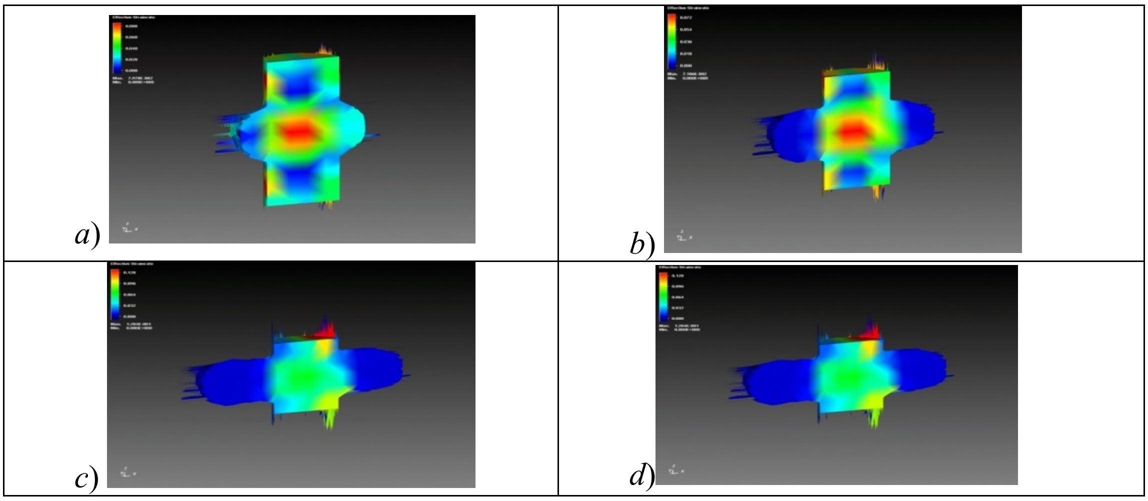

a) *b*) *c*) *d*)

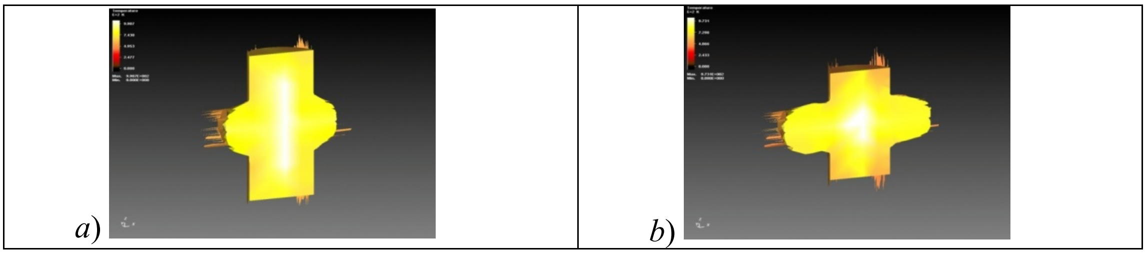
Figure 7. Deformation intensity distribution in the preform during pressing in the second passage

2. With increasing emphasis, the compression stress intensity localization is transferred from the side of surface to the central portion of the preform (Figure 6, *b*) and finally the reduction is completely concentrated under left and right punch (Figure 6, *d*);

3. In the second pass, and during the initial deformation moment, the deformation intensity is localized in the central portion of the preform, as well as the left and right sides of surfaces of the workpiece, i.e. adjacent to the left and right cylinder device of blank areas (Figure 7, *a*, *b*);

4. With increasing reduction, the compression strain localization intensity is transferred from the side of surfaces towards the central portion of the preform (Figure 7, *b*) and finally the compression is completely concentrated under left and right punch (Figure 7, *d*);

5. In the second pass of pressing and during the initial moment of deforming, the temperature decreases in the left and right sides of the surfaces of the workpiece, i.e. adjacent to the left and right areas of the blank unit cylinders, whereby the temperature rises in the central portion of the blank (Figure 8, *a*, *b*).


a) *b*)

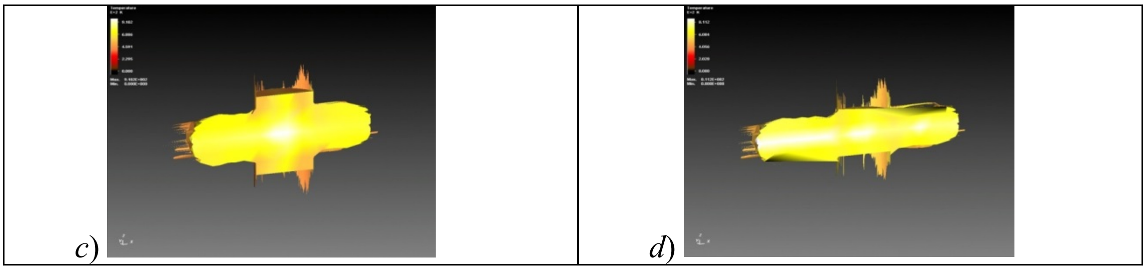


Figure 8. The temperature field distribution in the billet while pressing in the second pass

6. With increasing compression, the temperature on section of the workpiece is aligned (Figure 8, *c*, *d*), but largest in magnitude zones according to the temperature focuses below the left and right areas of the punch and the workpiece, the axis of which is perpendicular to the pressing axis (Figure 8, *d*);

7. While pressing in the offered device, the present degree of shear deformation (cumulative strain) in a few stages of deformation is distributed evenly over the cross section of the pressed billet.

In the initial state of the D16 alloy preform had non-uniform microstructure which consisted of large unrecrystallized grains having an average size of ~ 283 *μm* in the longitudinal and ~ 251 *μm* in the transverse directions located along their boundaries of small grain with the size of ~ 37 – 43 *μm* (Figure 9).

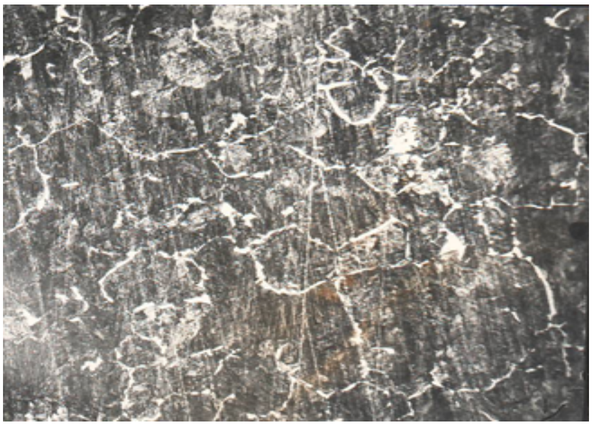
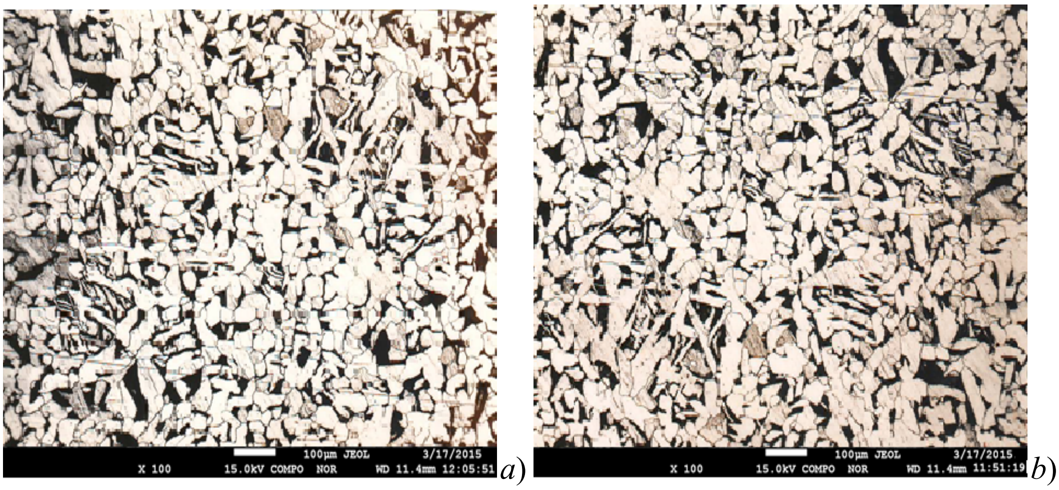


Figure 9. Microstructure of D16 aluminum alloy in the initial state

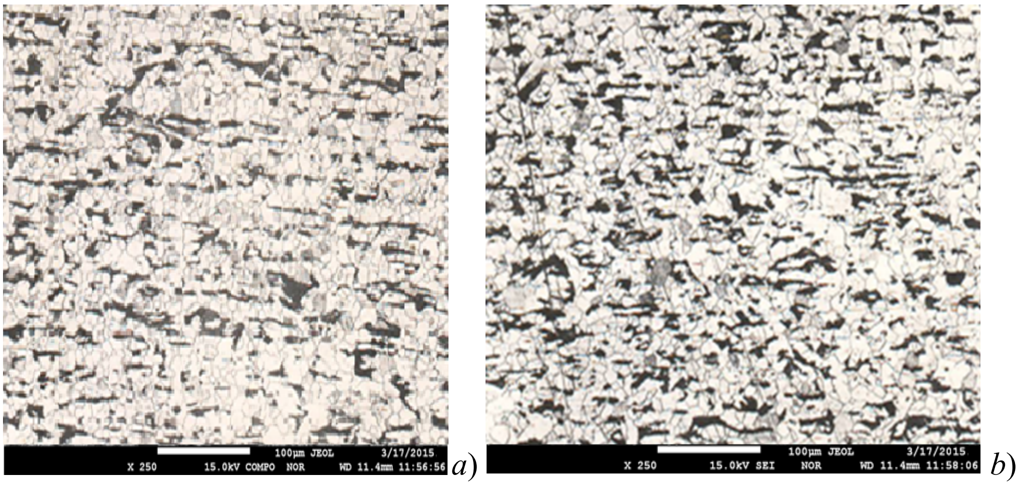
The study of the structural state of D16 aluminum alloy after pressing in the cross-shaped tool with two passages shows that micro lined structural state (Figure 10, *a*, *b*) is formed in the longitudinal and cross-sectional parts of the workpiece. At the same time, it increases the density of intragranular dislocations forming shear band width of up to 8 - 23 *μm*. Deformation of shear bands takes place mainly within the large grains with an average size of 94 *μm*. The most probable values of microbands width with angle boundaries after pressing range from 16 to 23 *μm* at the maximum (very rarely observed) values of this magnitude ~ 24 *μm* (Figure 10, *a*, *b*). Width of microbands with low-angle boundaries can vary from 5 *μm* to 8 *μm* with the most likely value of about 6 *μm*.



a - a longitudinal section; *b* - a cross-section
Figure 10. The microstructure of the D16 aluminum alloy after pressing in the cross shaped tool (second pass)

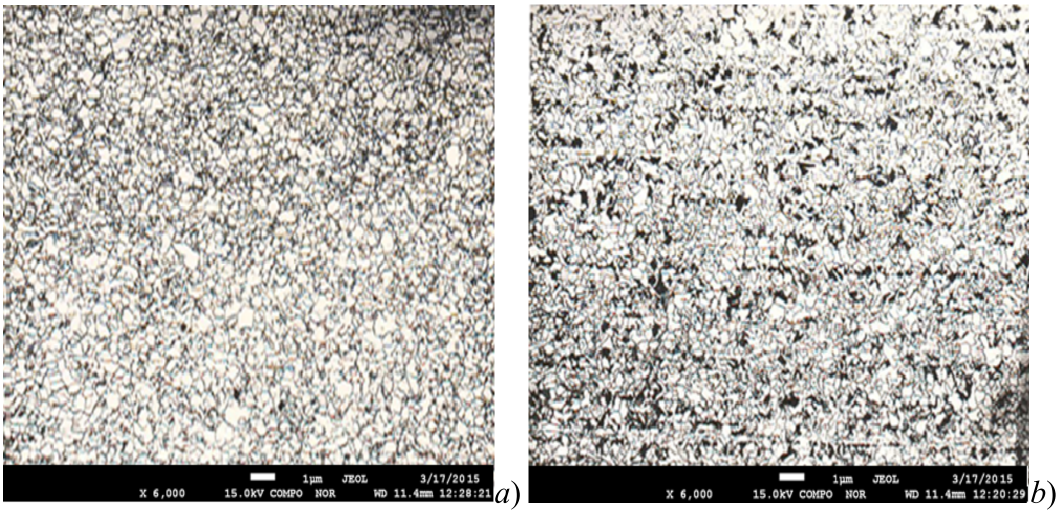
Further pressing in the cross shaped tool with four passes (Figure 11, *a*, *b*) reduces the width of microbands, and thin shear bands are formed at the boundaries of the original wide microbands. The distance between the lined structures not exceeding 3 – 7 μm at the most probable values equals to 4 – 6 μm (Figure 11, *a*, *b*). In the longitudinal aisles and cross-sectional aisles of the workpiece, grain-subgrain structures with the size of separate grains of 28 – 36 μm (Figure 11, *a*, *b*) will be formed after pressing with four passages.

Pressing in a cross-shaped tool with six passages led to the formation of the homogeneous and equiaxial structure in the longitudinal and cross-section areas of the billet (Figure 12, *a*, *b*). At the same time, it is clear that advance grinding of grain-subgrain structure occurs. As a result of the passage of softening processes in the metal blank, the polygonized or recrystallization structure is formed on the entire volume of bands with the average grain size of about 600 – 900 *nm*. The angle boundaries are formed in the border areas of the grains. The dislocation density is very high and it was not possible to calculate its value according to the picture of structures.



a - a longitudinal section; *b* - a cross-section

Figure 11. The microstructure of D16 aluminum alloy after pressing in the cross shaped tool (fourth pass)



a - a longitudinal section; *b* - a cross-section

Figure 12. The microstructure of D16 aluminum alloy after pressing in the cross shaped tool (six passes)

It can be assumed that with the increasing degree of deformation in the subsequent passes of the pressing in the cross shaped tools the grinding structure not only becomes twinning but also informing the cellular substructures as a result of slip dislocation processes. At high degrees of accumulated deformation, the borders of initial twins and subgrains are translated into a greater angle.

It is known (Ditenberg et al, 2012*a*; Ditenberg et al, 2012*b*; Tyumentcev et al, 2012) that the presence of large-borders suggests the implementation of dislocation-disclination mechanism of reorientation of the crystal lattice, which is developed in two stages: the formation of a substructure with non-zero components of the tensor density of disclinations; and its collective relaxation in the discrete boundaries of disorientation. This mechanism is one of the most universal mechanisms of fragmentation of the crystal, including the formation of submicron and nanocrystal structural conditions in a wide range of metals and alloys.

It should be noted that while pressing in the cross shaped tool the action mechanism provides alternating deformation and fragmentation of the reorientation of the crystal lattice. In this case, the transverse and longitudinal direction of the blank is formed with high angle boundaries density.

Thus, the evolution of the structure of D16 aluminum alloy during pressing in the cross shaped tool occurs in the following order:

- formation of the deformation substructure (dislocation and twin) with a band of width of about 8 - 23 *μm*;
- formation of cross borders within the strips, increased internal stresses and distortions of the original lattice;
- development of processes such as softening polygonization and primary recrystallization with the formation of ultrafine structure with the size of 600 - 900 *nm*.

The results of evaluation of the parameters of strength and ductility of D16 alloy after pressing in the cross shaped tool are shown in Table 1. It should be noted that the strength properties of the UFG materials not only affects the average size of grains, but mainly, nature, particle size and particulate distribution. Additionally provided EDS-mapping (Energy dispersive X-ray microanalysis, the elemental mapping of the surface composition) of the surface showed that in D16 alloy the *S*-phase lamellar (Al_2CuMg) is allocated on the grain boundaries. This reduces the effects of aging. According to the development of the aging process, these particles grow and the reinforcement of T-phase ($Al_{12}Mn_2Cu$), coherent particles which are distributed uniformly in the body of grains are dissolved, which leads to a drop in strength. High strength is achieved in the case if T-phase with coherent boundaries is released on the volume of the grain homogeneously.

Table 1. Mechanical properties of D16 alloy (at room temperature) after pressing in the cross shaped tool

State of D16 alloy	$\sigma_{0,2}$, MPa	$\sigma_В$, MPa	δ, %
Pressing in the cross shaped toll with 4 passes + heat treatment	287	434	10,1
Pressing in the cross shaped toll with 6 passes + heat treatment	294	474	10,5

The alloy deformed with 4 passes in the cross shaped tool, demonstrates lower levels of strength and ductility than after rolling with 6 passes in a cross shaped tool. This is due to the fact that the structure of the alloy after deformation with 4 passages in the cross shaped tool consists of larger grains and contains stringers of S-phase clusters, which are located at the angle of 45° to the axis of tension, that is, they coincide with the direction of action of maximum shear stress. Lowering the strength characteristics of D16 alloy is also associated with an increase in the volume fraction of *S*-phase.

It is shown that D16 alloy shows much higher mechanical properties after pressing in the cross-shaped tool with 6 passages. Apparently, it is due to an optimum combination of structural hardening which is closely connected to the size of grains, and precipitation strengthening, associated mainly with coherent particles of T-phase in the body of the grain.

Conclusion

Results of the study of the evolution of the microstructure of the workpiece at various stages of their production have shown the possibility of semi-finished products with ultrafine structure using intensive plastic deformation. The main role in the technological scheme belongs to the pressing treatment in a cross-shaped tool, in which the action results an intensive structure refinement. Saving enough plasticity of aluminum after pressing in the cross-shaped tool allows subsequent conductions of shaping operations on different hardware. As a result, the formation of homogeneous ultrafine structures with a grain size less than 600 - 900 *nm* is ensured in the finished products made of D16 aluminum alloy, which results in an increase of the strength properties of the alloy and the preservation of a good plasticity.

Reference

Beygelzimer, Y., Varyukhin, V., Orlov, D. (2003). *Screw Extrusion – the process of accumulation of deformation*. Donetsk Company TEAH. p.86

Ditenberg, I., Tyumentsev, A., Grinyaev, K. (2012*a*). Features of the defect substructure alloy V-4Ti-4Cr depending on the method of plastic deformation. *PAST. Ser. Fusion*, Vol. 3, pp. 27 - 35.

Ditenberg, I., Tyumentsev, A., Korznikov, A. (2012*b*). Peculiarities of submicrocrystalline structural state by plastic deformation of the alloy V - 4Ti - 4Cr on Bridgman anvils. *Physics of Metals and Metallography*, tom 113, No. 2, pp. 170 - 180.

Kaybyshev, O., Utyashev, F. (2002). *Superplasticity, microstructure grinding and processing the hard-deformed alloys*. Moscow: Nauka, p. 455.

Kolachev, B., Yelagin, V., Livanova, V. (2001). *Physical metallurgy and heat treatment of non-ferrous metals and alloys*. Moscow: MISA (Moscow Institute of Steel and Alloy), p. 416.

Mashekov, S., Nurtazaev, A., Mashekova, A., Uderbaeva, A. (2011). *An apparatus for producing nanostructured semi-finished*. RK. No. 23128. Patent Publ. 15.11.2011.

Maydanyuk, A., Stern, M., Baglyuk, G. (2008*a*). *Simulation of equal channel angular pressing of porous workpieces*. Kramatorsk: DDMA. pp. 31-36.

Maydanyuk, A., Ryabicheva, L., Stern, M., Baglyuk, G. (2008*b*). *The evolution of the density distribution at equal channel angular pressing of porous workpieces*. Kramatorsk: DDMA. Ch. 2. pp. 213-216.

Nayzabekov, A., Ashkeev, J., Lezhnev, S. and Toleuova A. (2005). A study of the deformation process the workpiece of equal channel step matrix. *Math. Universities. Ferrous metallurgy*. No. 2. pp. 16-18.

Segal, V., Reznikov, V., Kopylov, V. (1994). *Processes of plastic structure of metals*. Minsk: Science and technology. 232 p.

Tyumentsev, A., Ditenberg, I. (2011). Structural state with a high crystal lattice curvature in submicrocrystalline and nanocrystalline metallic materials. *Proceedings of the universities. Physics*, No. 9, pp. 26 - 36.

Valiev, R., Alexandrov, I. (2000). *Nanostructured materials produced by severe plastic deformation*. Moscow: Logos. 272 p.

Valiev, R. (2006). Creating nanostructured metals and alloys with unique properties, using severe plastic deformation. *Russian Nanotechnologies*, Vol. 1, pp. 208-216.

L.M. Utevsky, L. (1973). *The diffraction electron microscopy in metallurgy*. Moscow: Metallurgy, 584 p.

Yunusova, N. (2004). *Effect of severe plastic deformation on the structure and properties of aluminum alloys*. Cand. Techn. Sciences. Ufa.