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# THE INFLUENCE OF TECHNOLOGICAL CONDITIONS OF THE PROCESS OF COGGING IN FLAT DIES ON THE QUALITY OF TWO-PHASE TITANIUM ALLOYS

To create a rational technology of cogging process and to determinate the optimal values of the angles of tilt and single reduction the stress-strain state (SSS) of the blank during cogging in the flat dies was analyzed. By using the finite element method and program MSC.SuperForge quantitative data are obtained and the basic patterns of distribution of SSS, the temperature during the simulation of tilting in flat dies with different angles of tilting and the amount of reduction were established. Sustainable experimental-industrial technology of forging of two-phase titanium alloys was developed and tested.

*Keywords*: cogging, flat dies, stress-strain state, effective stresses and strains, tilting, reduction

## 1. Introduction

The progress of aviation, engineering and other industries to large extent is provided by the development of new materials and manufacturing techniques of parts [1,2,3,4]. Today's magnitude of specific density of aircraft engines was achieved through the use of titanium alloys of high strength, low density and high corrosion resistance. Titanium alloys are widely used in car engines compressor vanes, compressor disks, shafts, casings and shells parts. Application of titanium alloys in the industry has been made possible due to the development of technology of parts manufacturing by forging and stamping.

The forging process is currently existing technology to produce a product with fine grained structure from ingots of the titanium alloys which is characterized by high labor intensity, low productivity and high material costs.

Technology of forging ingots from titanium alloys involves several steps [5]. The first heating of the ingot is carried out up to temperature of β-region 1200-1250°C. After heating the ingot is subjected to stretch forging in flat dies by scheme of "circle - square - circle" with relative feed 0.6-0.8, tilting angles of 90° and single reduction 20-30 % to an intermediate size. Next heating is performed to a temperature of 1100-1150°C (β-region). Cogging of resulting preform during this stage is carried out by above-described mode of deformation. Forgings are cut to cut-to-length sections and each cut preform is heated to a temperature of 1100-1120°C and comprehensive forging is carried out by mean of two - three times upsetting and cogging. A single reduction in the upsetting is 30-32%. Forging preforms in β-region with flat dies does not provide obtaining recrystallized fine grain structure throughout the volume of the preform due to uneven distribution of strain in the deforming preform in given dies. After the first three heating in order to intensify the processes of recrystallization of primary β-grains preform is deformed in the temperature range 960 - 980°C ((α+β)-region) by mean of single upsetting and cogging on the original size of the preform with a single reduction at upsetting of 20 - 25%. Then heating up to temperatures of 1100 - 1150°C and comprehensive forging by a single upsetting and cogging is carried out.

Thus, to obtain forgings with the whole cross section recrystallized grain should be used at least five heating and pre-heats with preliminary cogging in flat dies at temperatures of β-region, by multiple alternating operation of upsetting and cogging in (α+β)- and β-region. A single reduction at multiple upsetting in β-region does not exceed 32%, while at upsetting in (α+β)-region – 25%.

Upsetting and cogging in flat dies is conducted in conditions of non-uniform flow of metal throughout the height of deformed preforms due to the presence of friction forces at the contact surface of the deformed metal with tool [6,7]. Deformation with small reduction helps to preserve the structure of the initial ingot in zones of constrained deformation adjoining to the contact surface of the deformed metal with tool. Therefore, obtaining a uniform structure throughout the cross section of the forging requires multiple upsetting and cogging.

Consequently, one of the main factors affecting the level and anisotropy of the material properties of products, forged by mean of existing technology using multiple operations of upsetting and cogging is uneven strain accumulated in different parts of the workpiece. Therefore, to create science-based modes of deformation of titanium alloys labor-consuming operation of upsetting should be excluded from the process and accumulated deformation in cogging should be calculated.

However, in contrast to the well-studied metal forming processes (rolling, pressing, etc.), in case of cogging until now there is no algorithm that can guide to the optimum process

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parameters to ensure the required deforming and structure formation [8,9]. In most cases, the development of technology with a particular type of cogging is a unique in-kind process, the results of which are largely dependent on the skill of the technologist. Traditional methods of designing, debugging and development of technologies involve testing a variety of options using the "trial and error" approach. Moreover, each variant requires experimental testing and, thus, manufacturing tool, which results in additional time and cost consuming.

It should be noted that the level and stability properties of the material of forging depends on value of accumulated deformation, calculation of which in the prior publications is not cited. The optimization criterion of tilting angles for different researchers is different [10]. As a result, these values of tilting angle of preform in flat die are rather contradictory and need to be clarified.

Economically inexpedience of this approach is most evident in the case of small batch production of forgings, when the costs of development of the technology will make production unprofitable. [11] Competitiveness in modern conditions is only mobile technology that can be quickly and optimally rebuild in depending on the changing technology parameters, preform material, etc.

Intensification the process of developing technological forging operations (cogging) requires information about the stress-strain state (SSS) of the preform material, of semi-finished products and forgings, as well as information about the dies system response of appropriate configuration - deformed preform to change the technological parameters [7, 9, 10] .

Goal of work is development of rational technology of forging titanium alloys by calculating the accumulated deformation in cogging in the flat die and its uniform distribution in terms of the metal blank.

## 2. Materials and methods of the experiment

Developing technological process to evenly distributed the accumulated strain, which means production of titanium forgings with high quality, as well as to determine the optimal value of tilting angles, relative feed and single reduction, SSS was investigated during cogging the preform in the flat dies.

Specialized standard program MSC.Super Forge was used to calculate the stress-strain state [11]. A three-dimensional geometric model of the preform and the die was built in the CAD program Inventor and were imported into CAE to program MSC.SuperForge. To create a finite-element model of the preform and the die a three-dimensional volume element CTETRA (four-junctional tetrahedron) was used, which is using to simulate three-dimensional bodies. For the model of the preform 4146 elements and 6360 assembly are required. Calculation time of the process was 20-30 minutes on a computer Pentium Duo with clock frequency of 3.4 GHz and 2 GB RAM.

The cylindrical sample with size of Ø60x300 mm was used for calculations. The material of preform - Ti6Al2Cr3Mo with deformation temperature range of 900 - 1250°C was assigned from a database of materials. To simulate the plasticity of the preform material the elastoplastic Johnson-Cook model was chosen. In MSC.SuperForge tools are made absolutely rigid and the properties taken into account are only thermal conductivity and heat transfer – specific thermal conductivity, specific heat and density, but mechanical properties are ignored. As the material of the die by default it is the steel instrument, which density and thermal properties assigned as the default also.

Interaction between the rigid die and deformable material of preform is modeled by means of contact surfaces which describe the contact conditions between the surfaces of the dies and the preform surface. In the process of modeling the contact conditions are constantly updated, reflecting the movement of the dies and the deformation of the material, which allows to simulate the slip between the die and the material of the processing preform. The contact between the die and the preform is modeled by Coulomb friction; the friction coefficient was assumed 0.3.

Operating temperature at cogging consists of heat exchange between die, preform and environment, as well as the thermal effect due to the deformation of the metal. Heat transfer is carried out by convective and radiative exchange with the environment and at contact of die with preform. The process of cogging takes place at room temperature, so the initial temperature of die is assumed 20°C.

As the initial material the Ti6Al2Cr3Mo industrial alloy ingots with size of ∅750x 1875 mm was used.

Polished specimens were prepared for metallographic investigation by the traditional method on grinding and polishing circles. The concentrated nitric acid solution in ethanol was used for etching of the samples. Metallographic analysis was conducted using a microscope "METAM LV-32".

## 3. Results and discussion

To create rational technology of forging and defining the optimal value of tilting angles, relative feed and single reduction the SSS during preform cogging in the flat dies was investigated.

Figures 1 and 2 show the distribution pattern of the effective stresses and strains by cross-section of preform at a cogging in the flat dies with a single reduction 30% (single reduction was equal to 15, 20, 25 and 30 percent).

Based on the numerical modeling results it was established that:

- at cogging the circular preform on flat dies with a relative feed $S = l/D = 1.0$ (where $l$ - length of the deformation zone; $D$ - diameter of the preform, respectively) the most intensities of stress and strain are localized in the initial stage of the first reduction in the surface areas of preform, but with an increasing reduction due to the occurrence of the friction force the intensity of stress and deformation are localized in forging cross (Figures 1, a and 2, a), and transferred to the center of preform;
- at the first cogging in tool adjacent areas of the forging the effective stress and strain get the maximum value, but in the central contact zones of the flat tool with the preform effective stress and strain get, conversely, the minimum (Figures 1a and 2a);

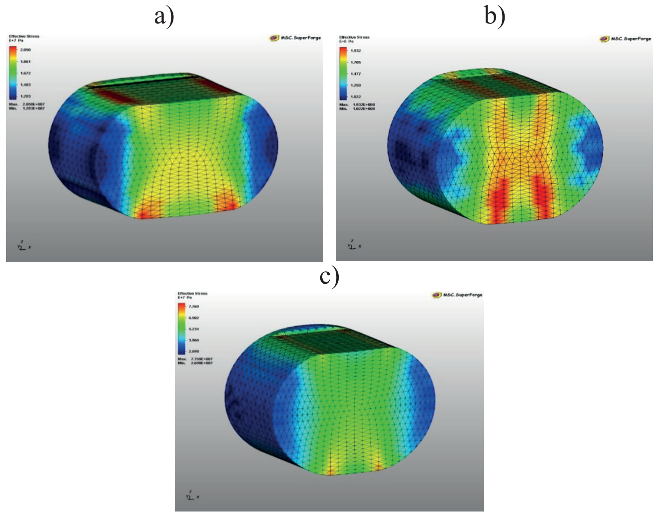

Figure 1. The distribution of the effective stresses in the preform during cogging in the flat dies with a single reduction of 30%, t = 1250°C; *a)* $S = 1.0$; *b)* $S = 0.8$; *c)* $S = 0.6$

- during cogging with relative feed of 0.8 and 0.6 the effective stress and strain are localized in the initial stage of the first reduction in the surface areas of preform, and with an increase of reduction the intensity of stress and stain are localized in forging cross (Figure 1, b, c and 2, b, c), wherein the maximum value of effective stress and strain are concentrated in the middle ($S = l/D = 0.8$) or in the surface ($S = l/D = 0.6$) zone of preform;

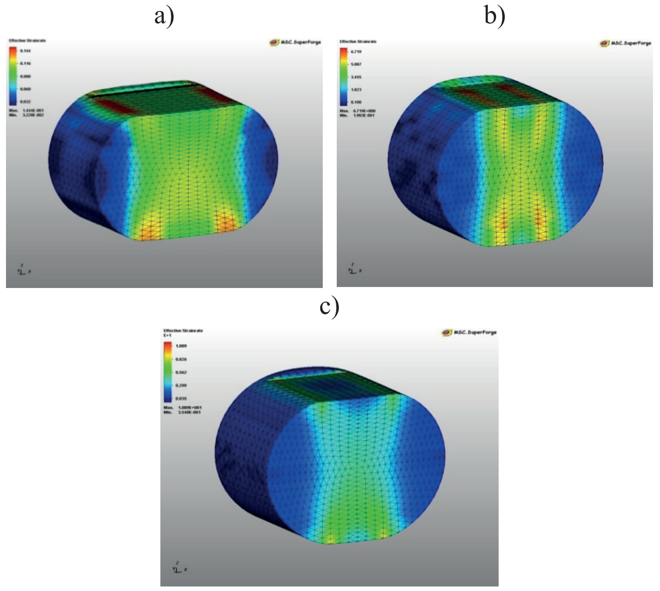

Fig. 2. The distribution of the effective strain rate in the preform during cogging in a flat dies with a single reduction of 30%, t = 1250°C; *a)* $S = 1.0$; *b)* $S = 0.8$; *c)* $S = 0.6$

- consequence of appearance of zones of hindered strain is localization of preferential flow of metal in the form of forging cross and intensive strains in the central part of preform (Figure 2);
- on the one hand localization of strain in the area of the forging cross leads to increas heat generation and the risk of collapse of the metal in these areas, on the other hand it leads to the lack of deformation of the structure in the remaining volume of preform and to inequigranular structure by section;
- during cogging in the first pass with relative feed of 0.8, 0.6 and single reduction of 15, 20, 25 and 30%, a small fraction of the volume of the geometric deformation zone appears hindered strain zones (Figure 2, b, c);
- during cogging in flat dies with an increase of single reduction the effective stresses and strains are concentrated in the areas of transition from deformable to non-deformable part of the preform (Figures 1 and 2). Such concentration of stress and strain can also lead to inequigranular structure, which impairs the quality of the metal;
- in the process of cogging in a flat dies in the areas of localization of stress the temperature rises.

Cogging of circular cross-section preforms in the flat dies, to keep its shape is, performed by small tilting angles, continuously tumbling preforms after each reduction. Therefore, the tilting angle chosen equal to: 30°, 60°, 90°, 120°, 150° and 180°.

Based on the numerical modeling results it is established that:
- tilting of the preform on 30°, 60°, 90°, 120°, 150°, 180° and deformation with a reduction of 15, 20 percent, regardless of value of the relative feed leads to localization of the stresses and strains on the surface of preform, and an increase of reduction up to 25 and 30 percent allows to concentrate effective stress and strain rate from the surface to the center (figures 3 and 4), whereas with increasing reduction, turning of part with a maximum stress and strain by section of preform occurs;

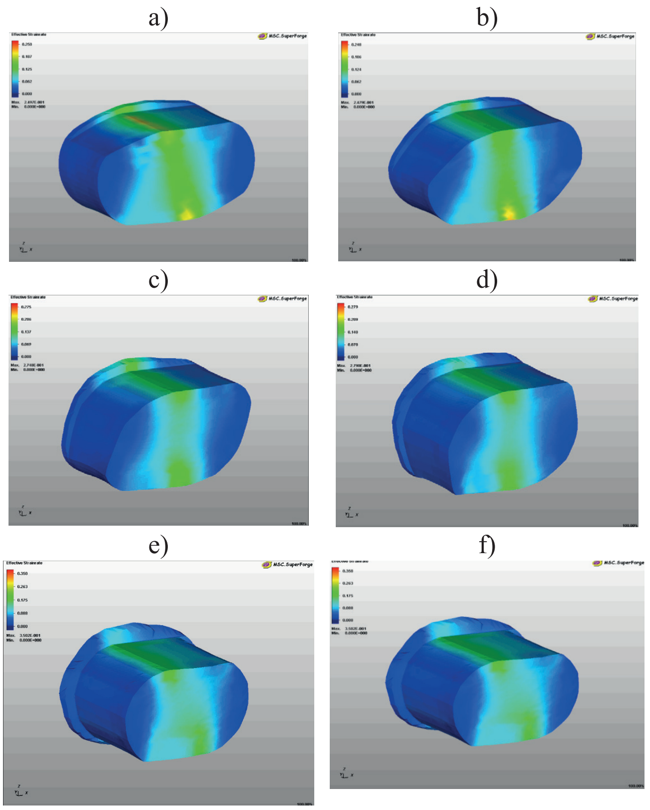

Fig. 3. The distribution of the effective strain rate in the preform during cogging in flat dies with unit reduction of 80% and a tilting 30° (*a*) and 60° (*b*), 90° (*c*) and 120° (*d*), 150° (*e*) and 180° (*f*), t = 1250 °C

- during cogging in flat dies the temperature of the metal in the areas of localization of stress is increased, but in zones of contact of the tool with the preform decrease to 1100°C;
- at forging round preform in the flat dies with tilting 30°, 60°, 90°, 120°, 150° and 180° because of turning of zones with a maximum strain in the cross section of preform macro-shear strains being intensively developed over the deformation zone that will induce profound changes in the structure of metal by grinding the original metal structure;
- the result of uniform grinding of the initial metal structure is increasing level and the uniformity of mechanical properties of the metal over the section of preform, as well as reducing the anisotropy of their properties.

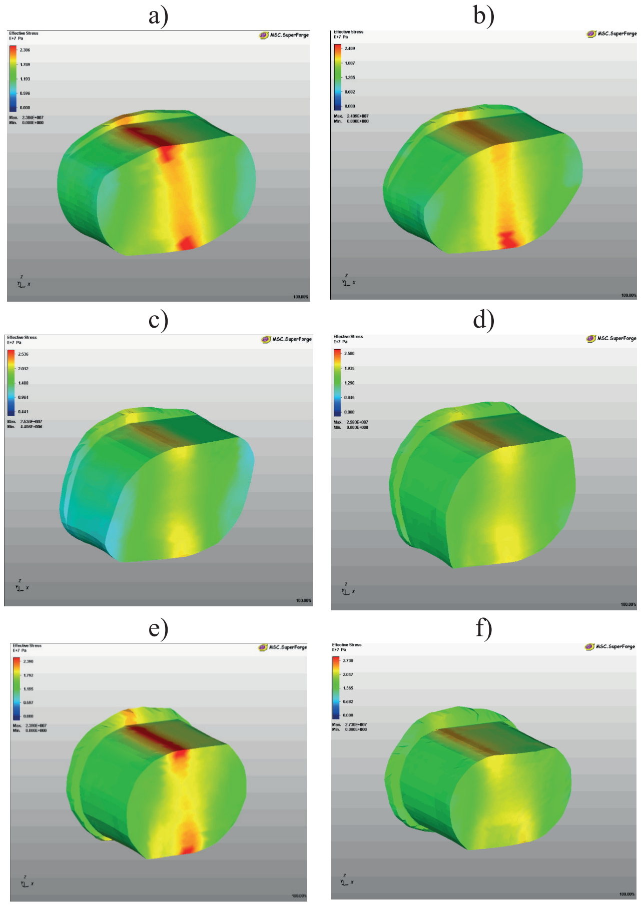

Fig. 4. The distribution of the effective stresses in the preform during cogging in the flat dies with unit reduction of 80% and a tilting 30° (*a*) and 60° (*b*), 90° (*c*) and 120° (*d*), 150° (*e*) and 180° (*f*), t = 1250°C

It is known that the use of the macro-shear strains of cast metal allows obtaining a reduction only for 8 - 10% to provide high quality macrostructure of metal from steels and alloys [12]. The effectiveness of impact of macro-shear strains on the structure of the metal is due to the phenomena occurring in the planes (surfaces) of macro-shear at the micro level. Slip lines that are in bands of macro-shear, penetrate through the whole grain. It has been found [12] that during plastic deformation process with additional macro-shear appears trans-grain slip occurring on the surface of macro-shear of displacement. When this micro-slip occurs in all grains located on these surfaces, in one direction, independent of the orientation of slip planes in grains of metal and grains boundaries.

So, macro-non-dilatational strain cause profound changes in the structure of the metal due to the trans-grain slip, independent of crystal orientation of grains; the result of these changes is increasing level and uniformity of the mechanical properties of the metal, as well as reducing their anisotropy.

In this paper, by summing the strain intensity the value of non-dilatational strain Λ (total strains) for a number of technological modes of forging in flat dies was calculated.

Analysis of Epirus changes Λ in the cross section of preform during cogging with tilting 30°, 60°, 90°, 120°, 150° and 180° and relative feed $S = l/D = 1.0$ indicates that non-dilatational strains have most values in the preform zones surrounding the tool areas (figure 5), and in central layers of preform. In this case in the surface sections it has the lowest values.

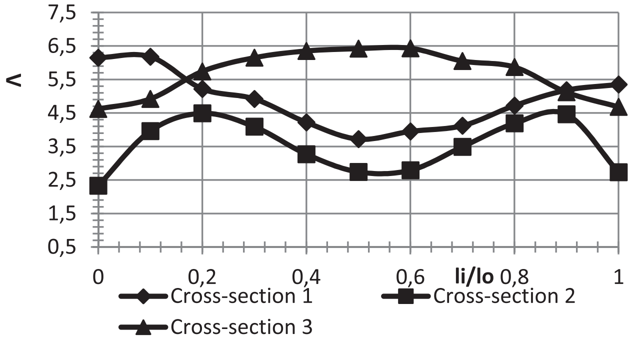

Fig. 5. Distribution of Λ in the longitudinal cross section of preform during cogging in flat dies with relative feed 1.0 (cross-section 1 - $D_i/D_0 = 0.9$; cross section 2 - $D_i/D_0 = 0.75$; cross section 3 - $D_i/D_0 = 0.5$; li and Di – the distance to investigated point by length and diameter; $l_0$ and $D_0$ – length and diameter of the deformation zone, respectively)

At cogging in flat dies with tilting angles 30°, 60°, 90°, 120°, 150° and 180° and relative feed $S = l/D = 0.8$ the non-dilatational strains have most values in the surrounding to the tool areas of preform (Figure 6), and in the layers of the preform being positioned between the center and surface areas of the preform. In this case in the surface sections it has the lowest values.

Tilting the preform on 30°, 60°, 90°, 120°, 150° and 180° after cogging with relative feed $S = l/D = 0.6$ leads to increase the value of non-dilatational strain in the surface areas of preform (Figure 7). Here Λ has the minimum value in the central layers of the preform.

The results of calculating the value of non-dilatational strain showed that a uniform distribution Λ over the cross section of the deformed preform can be achieved by cogging with tilting angle 30°, 60°, 90°, 120°, 150° and 180° and the relative feed of 1.0 in the first stage, 0.8 in the second stage and 0.6 in the third stage of cogging (Figure 8).

It was investigated the possibility of obtaining a fine-grained structure by cogging in the flat dies with the elimination of time-consuming upsetting operation (Table 1). As an initial material industrial ingot of Ti6Al2Cr3Mo alloy with size of ∅750x1875 mm was used.

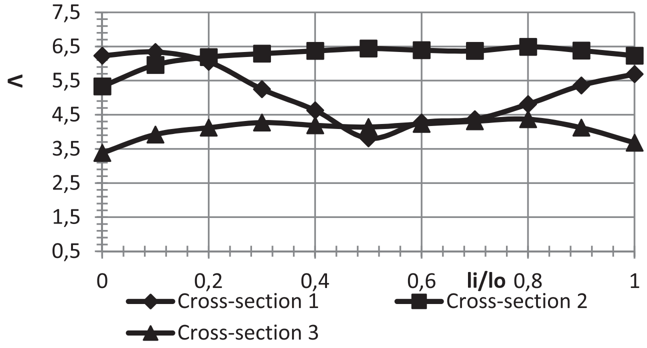

Fig. 6. Distribution Λ by longitudinal cross section of preform during cogging in flat dies with relative feed 0,8 (cross-section 1 - $D_i/ D_0$ = 0.9; cross section 2 - $D_i/ D_0$ = 0.75;cross section 3 - $D_i/ D_0$ = 0.5; $li$ and $D_i$ - the distance to investigated point by length and diameter; $l_0$ and $D_0$- length and diameter of the deformation zone, respectively)

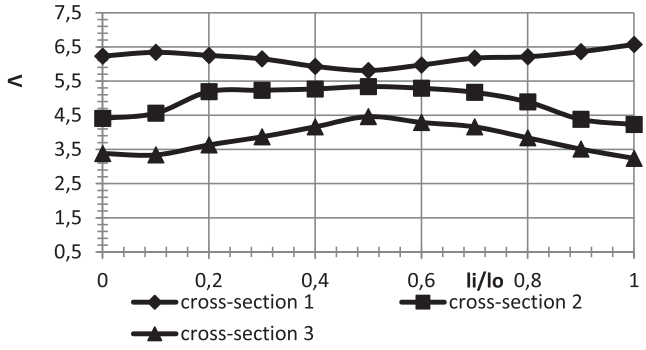

Fig. 7. Distribution Λ by longitudinal cross section of preform during cogging in flat dies with relative feed 0.6 (cross-section 1 - $D_i/ D_0$= 0.9; cross section 2 - $D_i/ D_0$ = 0.75;cross section 3 - $D_i/ D_0$ = 0.5; $l_i$ and $D_i$ - the distance to investigated point by length and diameter; $l_0$ and $D_0$ - length and diameter of the deformation zone, respectively)

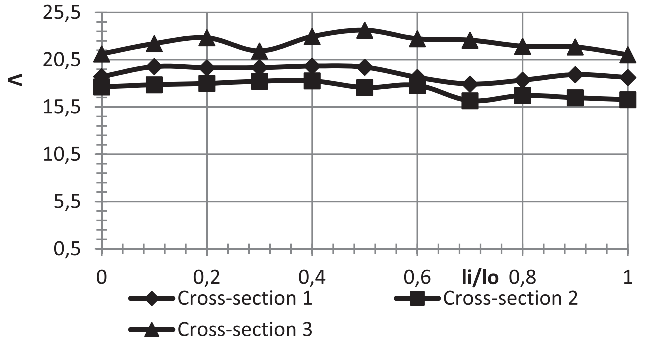

Fig. 8. Distribution Λ by longitudinal cross section of the preform during cogging in flat dies with relative feed of 1.0 in the first stage, the second stage of 0.8 and 0.6 in the third stage of cogging (cross-section 1 - $D_i/ D_0$ = 0.9; cross-section 2 - $D_i/ D_0$ = 0.75; cross-section 3 - $D_i/ D_0$ = 0.5; $l_i$ and $D_i$ - the distance to investigated point by length and diameter; $l_0$ and $D_0$ - length and diameter of the deformation zone, respectively)

The results of conducted pilot forging show that the macrostructure of forging of Ti6Al2Cr3Mo alloy, forged with intermediate deformation in (α + β) – region in flat dies, fine-grained - score 2-3 (Figure 9). In the cross-cut templates has a small amount of grains that match 3-4 score. These relatively large grains are distributed in peripheral parts of forgings.

Analysis of the microstructure indicates that after forging following structural transformations occur: transformation of sheet-like α-phase to equiaxial, recrystallization of β-phase with form grains with size of 20 - 30 microns (Figure 10).

Thus, obtained results showed that cogging in flat dies with the rational modes of forging, as the use of pre-deformation in the β-region, intermediate deformation in (α + β)-region and final deformations in β-region allows to produce recrystallized structure with fine grain corresponding to 2-4 score by whole cross-section of the preform.

TABLE 1

Cogging modes in the flat dies

| Temperature, °C | Preform diameter before cogging, mm | Preform diameter after cogging, mm | Relative feed | Reduction, % | Tilting, degree |
|---|---|---|---|---|---|
| 1250 | 750 | 520 | 0.8-1.0 | 10-30 | 30-60 |
| 1100 | 520 | 420 | 0.8-1.0 | 10-30 | 30-60 |
| 960 | 420 | 350 | 0.4-0.6 | 10-15 | 30-60 |
| 1100 | 350 | 250 | 0.6-0.8 | 10-20 | 30-60 |
| 1100 | 250 | 200 | 0.6-0.8 | 10-20 | 30-60 |

TABLE 2

Comparable mechanical properties of forgings made by experimental technology and the existing regime

| № forging mode | The direction of samples cutting | Ts, tensile strength, MPa | EL, elongation % | AR, per. reduction area, % | KCV, impact strength, kJ/m$^2$ |
|---|---|---|---|---|---|
| Experimental technology | Axial | 1060 | 9.0 | 24.9 | 3200 |
| | Radial | 1050 | 8.8 | 25.1 | 3300 |
| | Tangential | 1040 | 8.6 | 21.7 | 3500 |
| Existing technology | Axial | 1050 | 9.0 | 25.0 | 3000 |
| | Radial | 1050 | 9.0 | 25.0 | 3400 |
| | Tangential | 1030 | 8.8 | 22.0 | 3400 |

Mechanical properties of forgings forged using experimental technology, corresponds to mechanical properties of the forgings produced by comprehensive forging (Table 2).

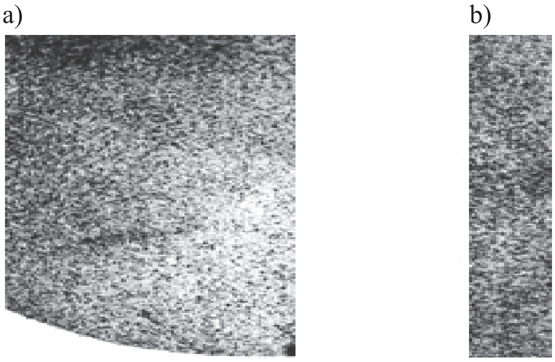

Fig. 9. Macrostructure of Ti6Al2Cr3Mo alloy in cross (a) and longitudinal (b) sections after cogging in flat dies at temperatures of 1250, 1100, 960, 1100 and 1100°C

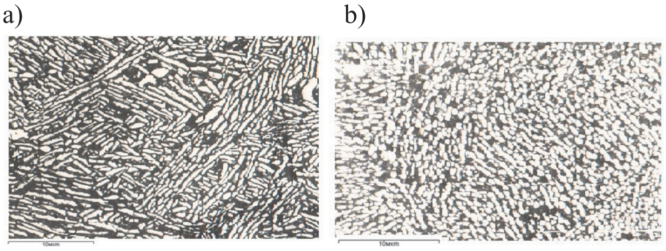

Fig. 10. Microstructure of forgings from Ti6Al2Cr3Mo alloy after cogging in flat dies at temperatures of 1250, 1100, 960, 1100 and 1100°C; *a*) in cross section of forging; *b*) in longitudinal section of forging

## 4. Conclusion

1. During forging of round preforms in flat dies with tilting 30°, 60°, 90°, 120°, 150° and 180° due to turning zones with the maximum intensity of stress and strain over the section of preform being intensively developed macro-shear strain causing profound changes in the structure of the metal due to trans-grain sliding.
2. In the first reduction localization of strain occurs in the central and adjacent to the tool areas of preform, but in the subsequent tilting and reduction the intensity of strain uniformly like the strip turn by the cross section and thereby promotes developing by the deformation zone the macro-shear strain which leads to increase the degree of deformation shear in central and adjacent to the tool areas of preform.
3. Localization of strain intensity in the initial reduction in surface and adjacent to the tool zones of preform, and the subsequent tilting and reduction an uniform concentration of them in the form of strip over the cross section of preform and thereby development in deformation zone of macro-shear strain leads to an increase the degree of deformation of shear in surface and adjacent to the instrument preform areas.
4. The uniform distribution $\Lambda$ over the cross section of preform can be achieved by cogging with relative feed of 1.0 in the first stage, the second stage of 0.8 and 0.6 in the third stage of cogging.
5. The result of the uniform distribution of the degree of shear strain is to increase the level and uniformity of the mechanical properties of the metal, as well as reducing the anisotropy of their properties.
6. The results of the calculation of the degree of shear strain and experiment forging allow to conclude that during forging in flat dies grinding of metal structure of preform can be achieved by varying the relative feed at an angle of tilting 30°, 60°, 90°, 120°, 150° and 180°.

Thus, by phased cogging of circular preform in flat dies with tilting angle 30°, 60°, 90°, 120°, 150° and 180° and the relative feed of 1.0 (the first stage), 0.8 (second stage) and 0.6 (the third stage) the forging with fine-grained structure and high mechanical properties can be prepared.

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