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IMPROVING THE PROCESSING OF FORGINGS MADE OF TITANIUM ALLOYS BY THE UNIFORM DISTRIBUTION OF DEFORMATION IN THE BLANKS DURING THE COMBINED FORGING PROCESSES

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ABSTRACT

In order to create the rational technology of forgings and determine the optimal values of the angles of broach and the unit compression, the stress-strain state (SSS) of the blank in flat and combined strikers was investigated. The quantitative data was gained by the methods of finite elements and MSC. Super Forge software; the main regularities of SSS distribution, the temperature in the simulation of forging in flat and combined strikers with the different angles of tilting and the amount of reduction was established. Experimental-industrial technology of forging two-phase titanium alloys has been developed and tested.

Key words: Forging, strikers, Stress-strain state, Numerical simulation, The intensity of the stresses and strains, Manipulation, Compression.

INTRODUCTION

Forging is the most important forge operation, which is used not only for the forming purposes, but also is used for improving the quality of the metal[1]. The rational thermo-mechanical deformation modes contribute to the improvement of the mechanical properties of metal forgings, i.e. improving their quality during forging blanks[2]. Temperature modes, methods of forging and used tool at the broach also have a significant impact on the performance of forging. Therefore, during the development of technology, the technological parameters should be chosen correctly and the effect of forgings to the quality of pulling should be evaluated.

In recent years the different ways of pulling shafts of [1-5] forging types, forging tools

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of various configurations (such as flat, composite, cut-out, and special relief strikers) are developed for implementation, which improves the quality of forgings.

The forging is widely used in flat, combined, and cut-out strikers and on RFM for reducing the cross section and increasing the length of the blank during forging by the "square-square", "circle-square-circle" or "circle-circle" schemes[2-5]. Results of the study of stress-strain state (SSS) of metal forging in flat and combined strikers show that the deformation is localized by forging cross, and the maximum deformation is concentrated in the central and average blank areas[4-9]. The significant contour forgings and strains could be appeared in the areas adjacent to the tool. They can form the disruption of the continuity of metal during the forging from few plastic alloys.

Analysis of the research results of well-known works showed[1,3-5] that the non-uniformity of deformation on blank section is viewed from the perspective of a single compression. It is known that the level and stability of the material properties of forgings depend on the value of accumulated strain[10], however the calculation of which are not given in the above mentioned works. Optimization criteria of tilting angles are given differently by different researchers. As a result, these values of tilting angle of the blank in combined strikers rather contradictory and they need a refinement.

The aim of the work is to develop the rational technology of titanium alloys forging by examining the SSS and calculating the accumulated deformation at broaching in flat and combined strikers.

EXPERIMENTAL

Materials and experimental procedure

The specialized standard MSC.Super Forge software was used for calculating the SSS[11]. Three-dimensional (3D) geometric model of the blank and of the striker was created in CAD by the Inventor software and it was imported into the CAE to the MSC. Super Forge software. The 3D volume element CTETRA (four-node tetrahedron) was used for creating a finite element model of the blank and striker.

The cylindrical sample with the size of ∅60 × 300 *mm* was used for calculations. The material stretches blank of titanium alloy VT9 with a temperature range of deformation of 900-1250°C and chisel steel were designated from a database of materials. The elastic plastic model of Johnson-Cook was chosen for modeling the plasticity of the blank material.

The contact between the striker and the blank is modeled by Coulomb friction; friction coefficient of 0.3 was adopted.

The industrial cast slab of VT9 alloy with the size of ∅ 750 × 1875 *mm* was used as an initial material.

The polished specimens were prepared for the metallographic examination by the traditional method on the grinding and polishing circles. A concentrated nitric acid solution in ethanol was used for etching the samples.

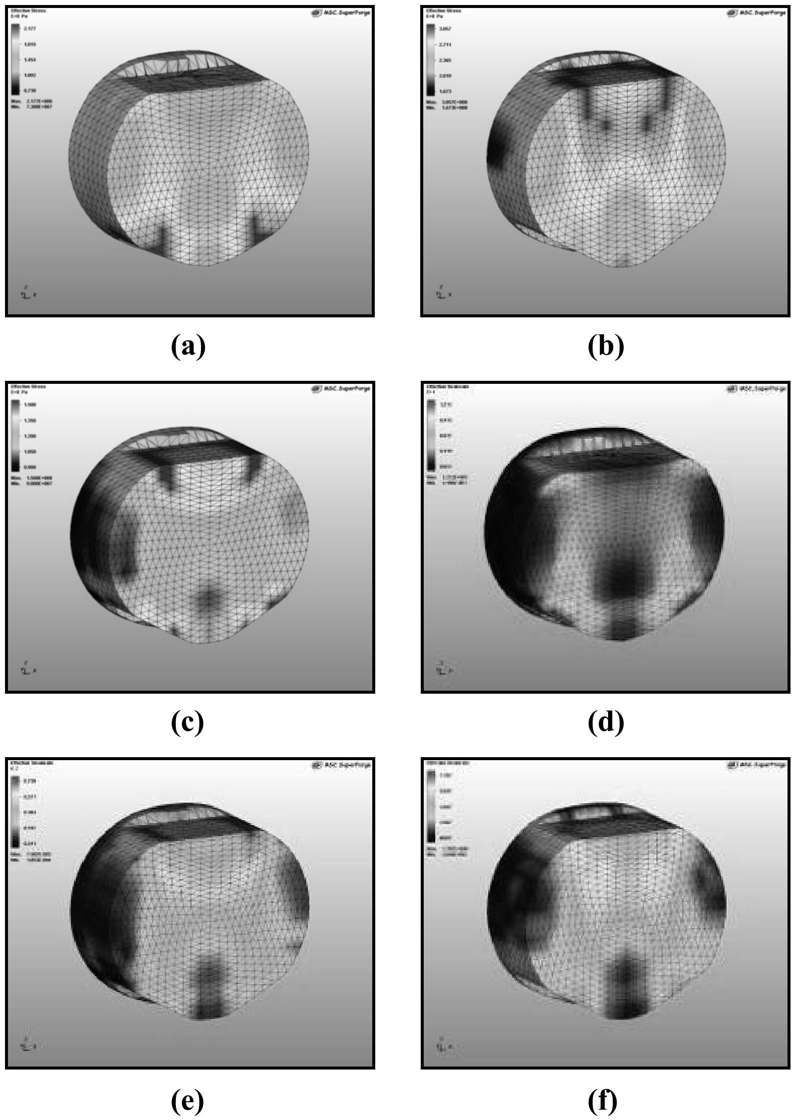
RESULTS AND DISCUSSION

Pictures of the SSS distribution along the cross section of the work piece during the broach bit in the combined strikers in the first compression and during deformation strain with the rotation angles of 30°, 60°, 90° and 120° degrees are shown in Figs. 1, 2 and 3.

Based on the results of numerical simulations the following was revealed:

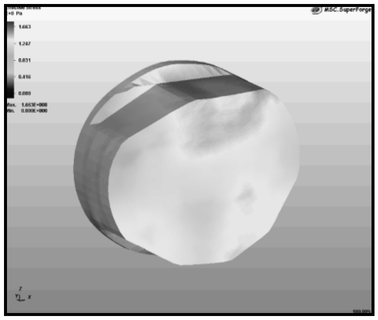
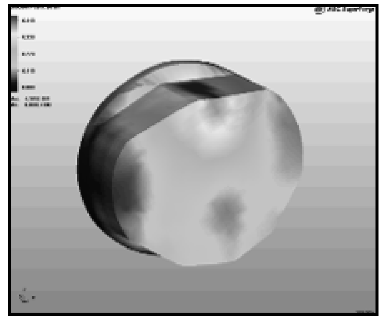
- During the first compression in the combined strikes the intensity of stress and strain have a great importance in the areas adjacent to the site of contact between tool and work piece; while the minimum values of the stresses and strains arise on the surface areas of the workpiece, which is free from the load;
- During broaching of the round billet in the combined strikes with the relative convey $S = l/D = 0.6$, 0.8 and 1.0 (where l - length of the deformation zone; D - diameter of the blank) the intensity of stress and strain concentrates at the first stage of the initial compression at the surface areas of the blank; with the increasing of the compression the intensity of the stress and strain localize along the forging cross;
- During broaching with the relative convey of $S = l/D = 0.6$, 0.8 and 1.0 the zones of stress and strain intensity localization is expanded with increasing of the compression;
- Broaching with the relative convey of $S = 1.0$ leads to the transfer of the zones of the stress and strain localization from contact area of workpiece with flat striker to the contact area of workpiece with contoured die;
- The stress and strain are concentrated under the flat die during broaching with the relative convey $S = 0.8$ and $S = 0.6$;

- During the drawing with 30^o, 60^o, 90^o, 120° tilting, regardless of the relative convey value the intensity of the stress and strain is concentrated in the contact areas of the metal with the tool; however the average by the value stress and strain are occur between contact areas of the tool and workpiece (Figs. 2 and 3).

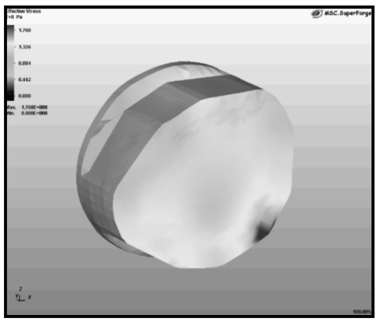
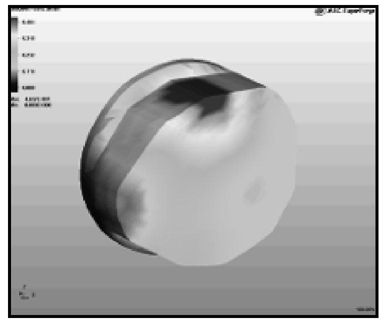


a,d – S = 1.0; b,e – S = 0.8; c,f – S = 0.6

Fig. 1: Distribution of the stress intensity (a, b, c) and strain (d, e, f) while forging in the combined strikers with a single compression of 80% of the full-time deformation, $t = 960^0$C

(a) 80% **(b) 80%**

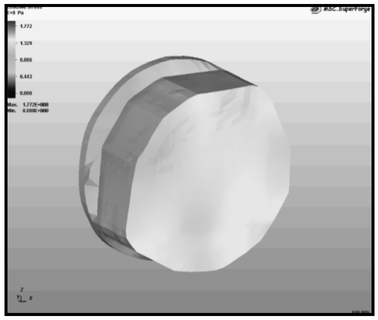



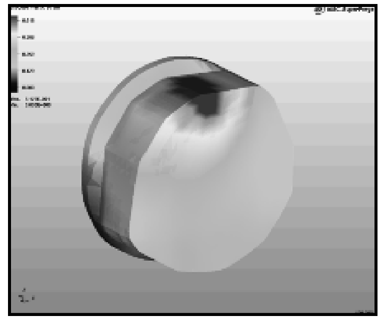
(c) 80% **(d) 80%**

Fig. 2: The distribution of the intensity of the stress and strains during forging in combined strikers with tilting angles of 30° (*a* and *b*) and 60° (*c* and *d*), *t* = 960^{0}C

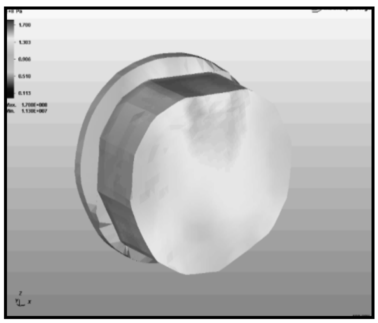
The stage of shear strain Λ (accumulated strain) for a number of technological modes of forging in combined strikers is calculated by summing up the intensity of deformation. Analysis of diagrams of Λ change along the cross section of the workpiece in the combined strikers shows that the reduction degree has a great importance in the areas adjacent to the work surface under the conditions that at most rational broach mode with relative convey 0.6 and tilting angle 30^0. Whereas under the same conditions at the central areas of the workpiece the degree of reduction has minimum value (Fig. 4) (where l_i and D_i - the distance before the measurement point along the length and to the diameter; l_0 and D_0 - length and diameter of the center of the deformation, respectively).

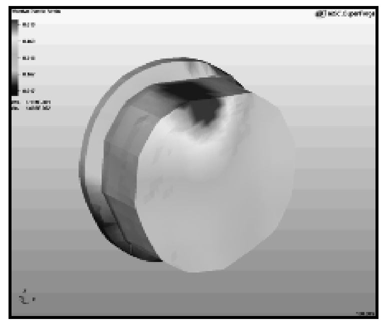
In the Figs. 5, 6, 7, a picture of the stress and strains intensity distribution along the cross section of the workpiece during the broaching in the flat die during the first compression and during the deformation with the tilting angles of 30°, 60°, 90°, 120°, 150°, 180° is presented.





(a) 80% **(b) 80%**





(c) 80% **(d) 80%**

Fig. 3: The distribution of the intensity of the stress and strains in forging in combined strikers with tilting angles of 90° (*a* and *b*) and 120° (*c* and *d*), $t = 960^0$C

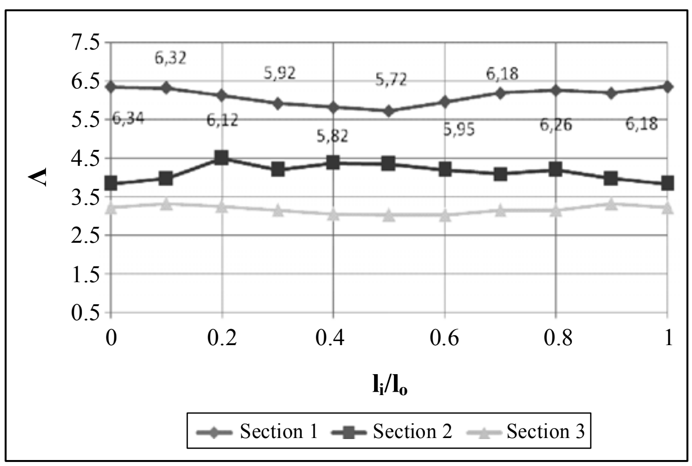
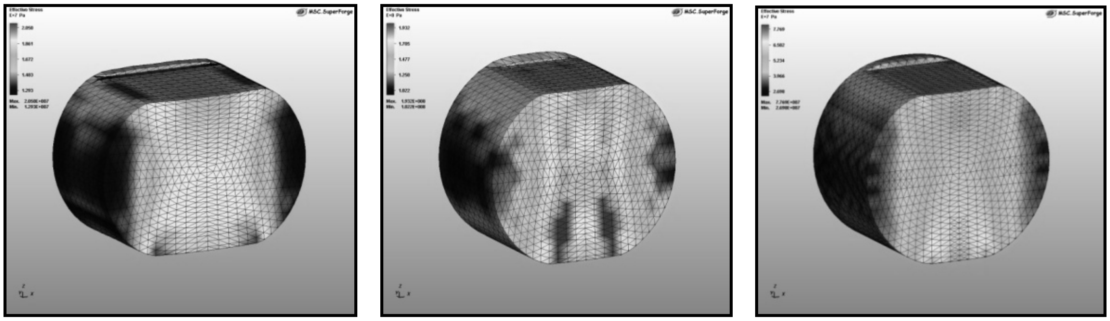
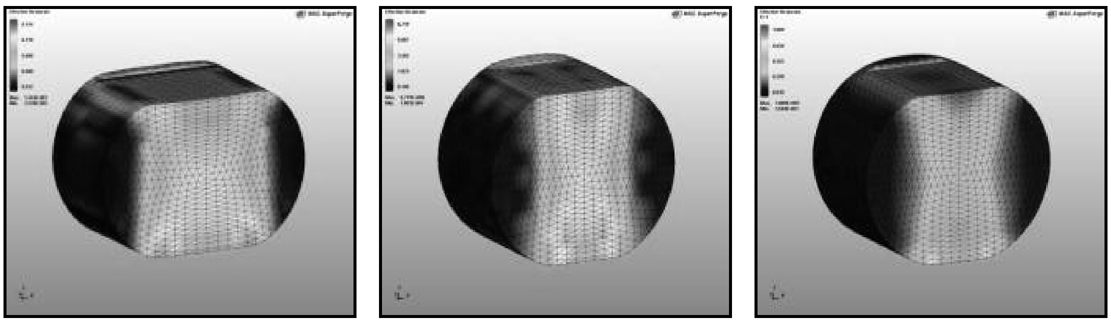


Fig. 4: Distribution of Λ along the longitudinal section of the workpiece during the broach in the combined strikers with the relative convey of 0.6 (section 1 - D_i/D_0 = 0.9; section 2 - D_i/D_0 = 0.75; section 3 - D_i/D_0 = 0.5)



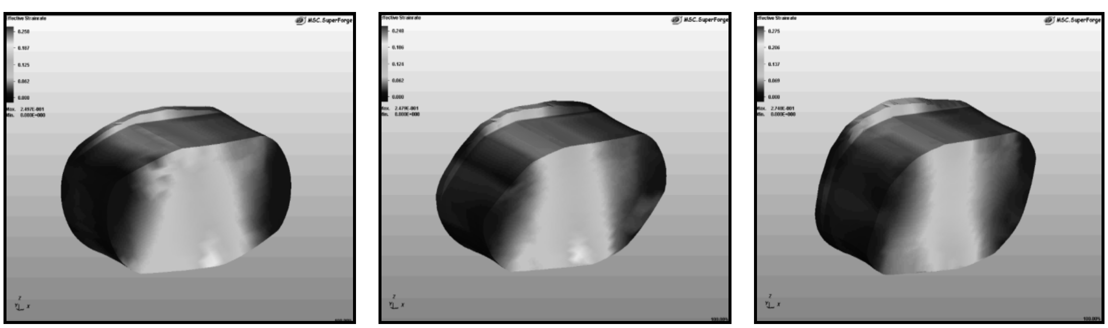
(a) **(b)** **(c)**



(d) **(e)** **(f)**

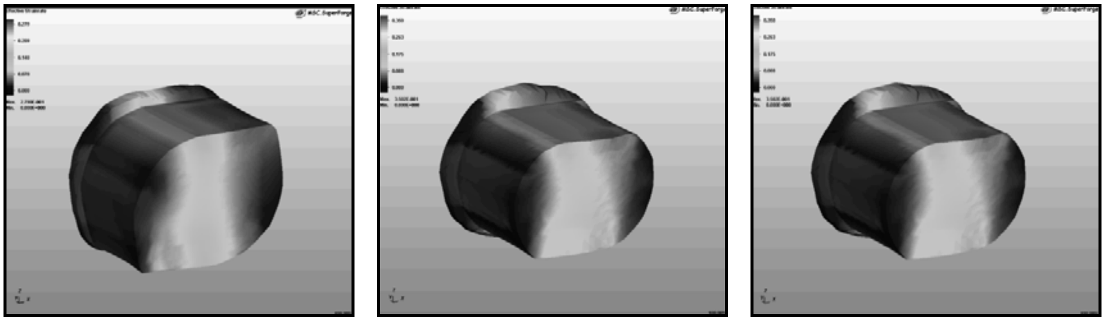
a,d – S = 1.0; b,e – S = 0.8; c,f – S = 0.6

Fig. 5: The distribution of stress intensity (*a, b, c*) and deformation (*d, e, f*) in the blank with the pulling in a flat die with a single compression of 80% of the full-time deformation, *t* = 1250°C



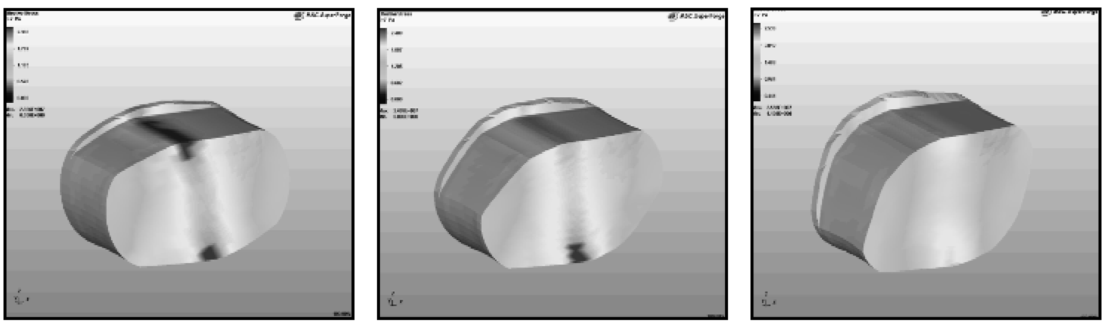
(a) **(b)** **(c)**

Cont…

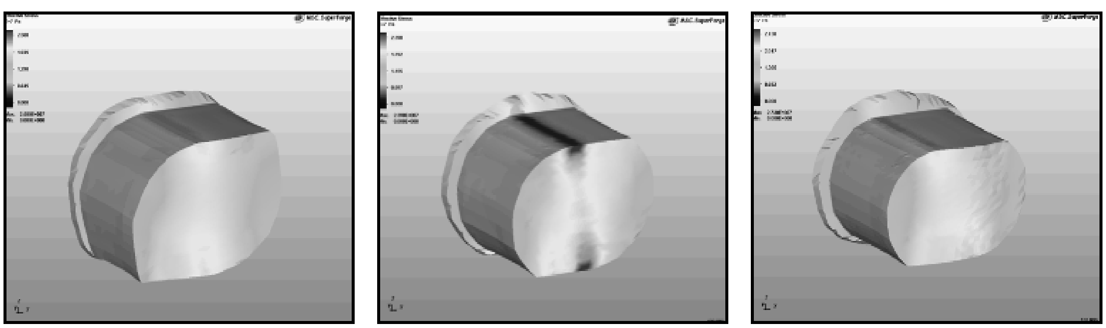


(d) **(e)** **(f)**

Fig. 6: The distribution of the deformation intensity in the blank during the broach in the flat die with a single compression of 80% and a tilting of 30° (*a*) and 60° (*b*), 90° (*c*) and 120° (*d*), 150° (*e*) and 180° (*f*)



(a) **(b)** **(c)**



(d) **(e)** **(f)**

Fig. 7: The intensity distribution of the stresses in the blank during the broaching in the flat dies with draft of 80% and with a tilting angle 30^0 (*a*), 60^0 (*b*), 90° (*c*) and 120° (*d*), 150° (*e*) and 180° (*f*)

Based on the simulation results the followings are revealed:

- At broaching of the round billet in a flat dies with the relative convey $S = l/D = 1.0$, 0.8 and 0.6 intensity of stress and strain at the initial stage of the first compression zone is localized in the work surface, and with the increase in compression strength and stress deformation is localized along the forging cross;
- The stress and strain is transferred to the center of the blank ($S = 1.0$) during the broaching in the flat dies with increasing compression, or the maximum value of the stress and strain is concentrated in the middle (S = 0.8) or at the work surface areas (S = 0.6) of the workpiece;
- Part of the volume of the geometric roll gap is obstructed in the deformation zone due to the action of contact friction forces during the first-pass broach with the relative convey of 1.0 and unit compression of 20-80% from the total time of deformation; whereas a small fraction of the volume of geometric deformation zone is localized in the zones of constrained deformation during broaching with the relative convey of 0.8, 0.6 and with draft of 20-80%;
- Localization of the strain in the forging cross and at the transition zones from the deformable to the non-deformable portion of the blank increases the heat release and the risk of metal fracture in these areas, and it also leads to the lack of deformation in the structure of the remaining volume of the blank and to the consertal structure of the cross section;
- Tilting of the blank at 30°, 60°, 90°, 120°, 150°, 180° and the strain with a reduction of 20, 40% of the total deformation time, regardless of the value of the relative convey, leads to localization of stress and strain on the surface of the blank; and the increase in compression till 60 and 80% allows to focus the stress and strain from the surface to the center, while the reversal part occurs with increasing compression with a maximum strain on the section of the blank;
- The macro displacements of the strain are developed intensively along the deformation zone during the forging of a round billet in the flat dies with the tilting angles of 30°, 60°, 90°, 120°, 150° and 180° due to the rotation of the areas with the highest stresses and strains along the cross-section of the workpiece; it might will cause profound changes in the structure of the metal because of the atomization of the metal original structure;

- Temperature raises during the forging in the flat dies in the stress localization zones, and temperature of the metal falls in the areas of contact of the tool with the blank metal;
- The result of grinding of the original metal structure is the raise of the level and uniformity of the mechanical properties of the metal, as well as reducing their anisotropy properties.

Analysis of the diagram changes of Λ along the billet cross section during the broach with tilting angles of 30°, 60°, 90°, 120°, 150° and 180° and the relative convey $S = l/D =$ 0.8 ... 1.0 shows that under the condition of rational mode of the deformation the degree of reduction has the highest value in the adjacent zones to the tool blank (Fig. 8), as well as in the central layers of the blank. In this case the work surfaces of the workpiece have the lowest values.

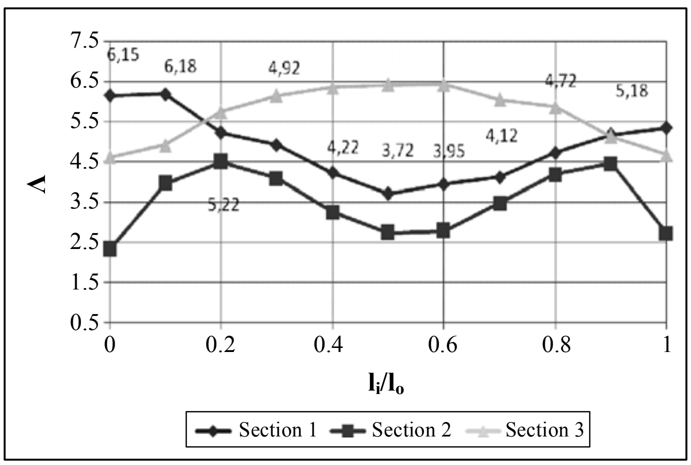


Fig. 8: Distribution of Λ along the longitudinal cross section of the blank during the broach in the flat dies with relative convey of 1.0 (section 1 - D_i/D_0 = 0.9; section 2 - D_i/D_0 = 0.75; section 3 - D_i/D_0 = 0.5)

In the paper efficiency of the metal ductility value (EMDV) during the broach in the combined and flat dies was calculated. Disruption conditions of steel and alloys during the broach in the tool of any configuration can be estimated by EMDV[3]:

$$\psi = \int_0^t \frac{H(\tau)d\tau}{\Lambda_p[k_{ж}(\tau)]} = \int_0^{\varepsilon} \frac{H(\varepsilon)d\varepsilon}{\Lambda_p[k_{ж}(\varepsilon)]},$$

where Λ_p – maximum ductility of metal, which depends on the stress state; H – the intensity of shear strain rate; $k_{жс} = \sigma/T$ – stiffness coefficient of the stress pattern; T – the intensity of the shear stress; σ – average stress.

Theoretical data, obtained by the abovementioned procedure, was used for determining the H, T, σ, and the regression equation were used for Λ_p calculations in deforming the titanium alloy VT9[3]:

$$\Lambda_p = \exp(-48{,}322 + 107{,}917\,(T_н/1000) - 6{,}488\,\sigma/T - 0{,}011\,(T_н/1000)\,(\xi/1000) + 5{,}976\,(T_н/1000)\,(\sigma/T) - 56{,}732\,(\sigma/T)^2$$

Here $T_н$ – heat temperature; ξ – speed of strain.

The results of EMDV calculation during the forging in the combined and flat dies showed that discontinuity of the blank material does not occur in forging with tilting angles 30° and with compression 20% of titanium alloy VT9.

Thus, in terms of volume metal flow the absence of discontinuities during forging in combined and flat dies is proved by calculations.

The results of calculation the degree of shear strain showed that a uniform distribution over the cross section of the deformable Λ along the blank can be achieved under the condition of broaching with tilting angles of 30^0 and relative convey of 1.0 in the flat dies at the first stage and with a tilting angle of 30^0 and the relative convey of 0.6 in the combined dies at the second stage.

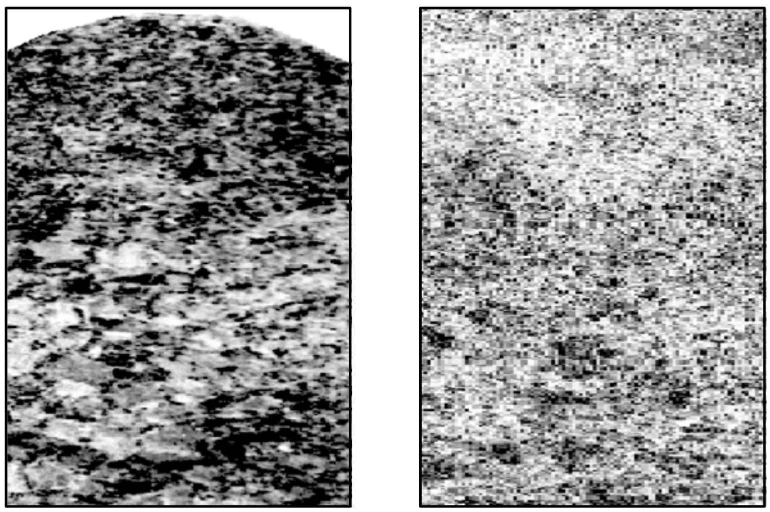
The results of study of SSS distribution during the broach in the combined and flat dies allow to develop a combined method of deformation of two-phase titanium alloys. The industrial alloy ingots of VT9 with the size of ∅960×1650 *mm* serve as the initial material.

Initially ingots were heated to 1250°C and stretched on a hydraulic press in the flat dies to the diameter of 500 *mm* with a tilting angle of 30^0 and a relative convey of 1.0. The resulting blank was cut into three parts. Intermediate blanks were heated to 960°C (40°C below the temperature of polymorphic transformation $T_{пп}$) and they were subjected to broach on a hydraulic press in the combined strikers to the diameter of 300 *mm* with 30° tilting angle and relative convey of 0.6. The resulting billet was cut into three pieces and stretched on a hydraulic press in the combined strikers to the diameter of 200 *mm* at a temperature of 1150° C (β -domain) with 30° tilting angle and relative convey of 1.0.

The transverse and longitudinal templates were cut after straining with every forging in order to study the macrostructure.

Forging in the flat dies at the temperature of the β – domain provides preferential deformation of the axial zone of the blank, resulting the actively passing of dynamic re-crystallization process. As a result, fine-grained structure is formed in this zone.

Further deformation in the combined strikers in (a + b) – domains helps to shift the emphasis from the center of the deformation in the surface layers of the blank and to pass the dynamic re-crystallization in this area with the formation of fine-grained structure (Fig. 9).

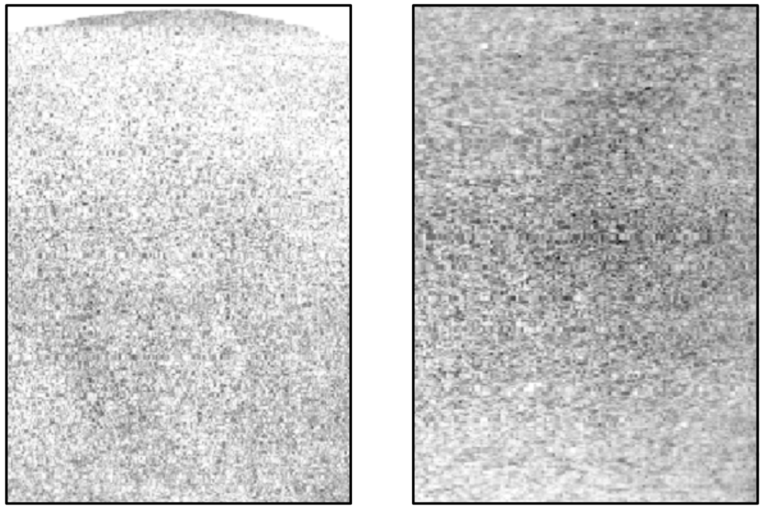


(a) **(b)**

Fig. 9: The macrostructure of forged piece made from the VT9 alloy in the transverse (*a*) and longitudinal (*b*) sections after pulling in the flat dies in the β – domain and in the combined strikers in (α + β) - domain

Forging at the initial stage in the flat dies in β – domain, and at next phases in the combined strikers in (α + β) - domain and in β – domain provides a fine-grained structure of the entire cross section of the forging (Figure 10).

Thus, obtaining macrostructure of forgings with the score of 3-4 in the whole cross-section without cracks, corresponding to the desired quality of the metal blank deformation was observed in the flat strikers at the first stage and in the combined strikers at the second and third stages.



(a) **(b)**

Fig. 10: The macrostructure of forged piece made from VT9 alloy in the transverse (*a*) and longitudinal (*b*) cross-sections after forging in the flat dies in β–domain and in the combined strikers in (α + β) - domains and β–domain

Mechanical properties of the forgings which are forged by experimental technologies were compared with the mechanical properties of the forgings which are forged by essential technology that provides multiple precipitate and exhaust at the temperature of β-, (α + β)- and β--domains (Table 1).

Table 1: Comparable mechanical properties of the forgings produced by experienced technology and existing technology

Number of forging mode	Direction of the sample cut	$\sigma_в$ (MPa)	δ (%)	ψ (%)	KCV (kJ/m^2)
1	Cross	1020	11.3	31.4	3000
	Longitudinal	1025	12.4	29.4	3000
2	Cross	1015	12.3	31.3	3000
	Longitudinal	1035	13.1	32.3	3000
Existing technology	Cross	1000	11.1	30.1	3000
	Longitudinal	1020	12.5	28.7	3000

As it can be seen from this table, the mechanical properties of the forgings, which are forged by experimental technologies appropriate to the mechanical properties of forgings produced by using the multiple precipitate. At the same time the heat is reduced and the productivity of forging process is increased, the complexity is decreased.

CONCLUSION

(i) The quantitative data is obtained by the method of finite element and MSC. Super Forge software; the basic patterns of SSS distribution, the temperature in the simulation of forging in the flat and combined strikers with different angles of tilting and the amount of reduction are established.

(ii) Equal distribution of the shear strain degree on cross-section of billet is achieved by forging in the flat dies with a relative convey of 1.0 at the first stage and in the combined dies with a relative convey of 0.6 and 1.0 at the second and third stages of the drawing.

(iii) The result of the equal distribution of the shear strain degree is to increase the level and uniformity of the mechanical properties of the metal, as well as reducing their anisotropy properties.

(iv) The results of the calculation of the shear strain degree and experienced forging allows to conclude that during the forging process in the flat and combined strikers, atomization of the structure of metal blank can be achieved by varying the relative flow at the tilting angles of 30°, 60°, 90°, 120°, 150° and 180°.

Thus, the forging piece with a fine-grained structure and high mechanical properties can be got by the phase-broaching of the round billet in the flat and combined strikers.

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