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PHYSICAL METALLURGY. METALLURGY

Application of Finite Element Method for Simulation of Stress-Strain State in Manufacturing of Long Turbine Blades Made of High-Strength Titanium Alloys

V. P. Leonov[a], I. A. Schastlivaya[a], T. N. Igolkina[a], K. I. Kikinov[a], V. A. Kropotov[b], and A. N. Troshin[b]

[a]*Central Research Institute of Structural Materials PROMETEY, St. Petersburg, Russia*
[b]*VSMPO-AVISMA Corporation, Verkhniaya Salda, Russia*
e-mail: mail@crism.ru

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Abstract—The engineering simulation software Deform 3D is applied for development and adoption of 3D simulation of manufacturing of pressed semifinished 1600 mm blades. Three stages of pressing are considered, including heating, intermediate cooling in transporting, and cooling of billet as a consequence of heat exchange with the die. On the basis of simulation, the distribution of temperature fields and strain fields is obtained at various stages of pressing. The calculation reveals that, at all pressing stages, the temperature of billet does not exceed the temperature of polymorphic transformation. The simulation demonstrates that such billet can be pressed in accordance with standard specifications.

Keywords: titanium alloys, turbine blades, stress-strain state, 3D simulation

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INTRODUCTION

Steam turbine blades are among the most complicated items of power engineering with regard to design and manufacture. The integrated engineering process of pressing of semifinished turbine blades includes several stages: ingot melting, billet manufacturing, billet shaping, and stage-by-stage pressing.

In the current competitive environment, the designing of various technologies requires the application of up-to-date computing software oriented at reduction of the preproduction period, adjustment of technologies, and minimization of capital expenditures. Designing of engineering processes in up-to-date software makes it possible to reduce expenses which could arise during production, thus eliminating the possibility of occurrence of various defects related to engineering mistakes.

Analysis of R&D articles [1–4] demonstrates increased interest in mathematical simulation in the field of metal treatment under pressure by means of which it is possible to develop engineering processes of any complexity in the shortest possible time.

The development of 3D simulation of manufacturing technology of pressed semifinished large 1600 mm blades with the active part of 1400 mm was based on Deform3D software. Deform 3D meets the highest requirements in the field of simulation of processes of press forging. Simulation is applied for overall process flow, including controlled heating, forming, cutting, and cooling at each pressing stage. In addition to computation of temperature, stress, and strain fields, the software makes it possible to compute processes of resolidification and variation of grain size. On the basis of computational results, it is possible to forecast generation of defects, such as underfilling of die cavity, folds, shrinkage cavity, and cracks, and to adjust the production process [3–6]. Simulation of the production process promotes selection of an optimum solution and, as a consequence, superior filling of the die at the final process stage.

Three-dimensional simulation of manufacturing technology of pressed semifinished large 1600 mm blades with the active part of 1400 mm can be applied for computation of pressing process variables of another purpose. The computation project includes several variants of simulation and each variant has its process flow (preliminary and intermediate procedures of heating/cooling, forming, and cutting of flash). Using the developed procedure, it is possible to simultaneously analyze several variants of the engineering process in order to determine optimum variables. The process flow includes transition from 2D to 3D computations. After entry of initial data, the software performs automatic computation. This work in development of 3D simulation of manufacturing technology of pressed semifinished large 1600 mm blades with the active part of 1400 mm discusses the final process stage—pressing. Superior technology of hot pressing should provide preset parameters: complete die filling, optimum generation of structure of forged pieces, and no defects. The software also facilitates

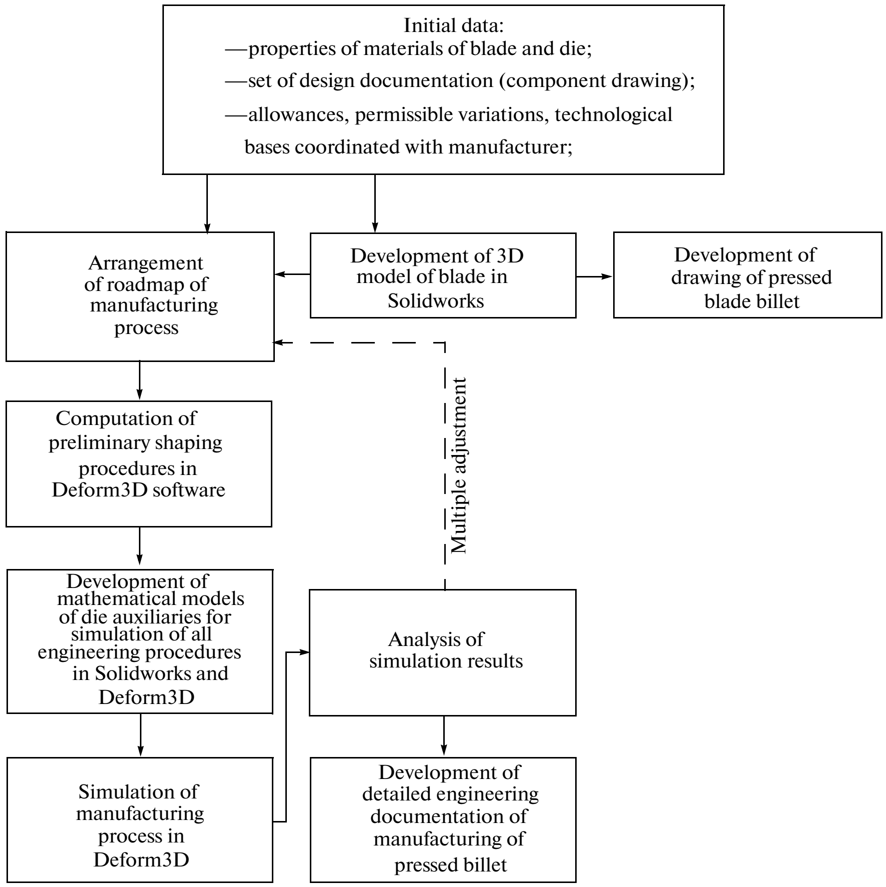

Fig. 1. Flow diagram of algorithm of development of manufacturing of 3D pressing of turbine blade billet.

forecasting of final structure of the material of pressed items.

INITIAL DATA FOR SIMULATION

The initial data for development of 2D and 3D models of pressed billet are as follows:

—characteristics of materials of blade and die (for instance, material density and strength properties);

—component drawings;

—allowances, permissible variations, technological bases coordinated with manufacturer.

The simulation of pressed billet was based on the blade drawings and models developed by manufacturer of turbine plant, OAO Power Machines.

The initial data for simulation of technological process are as follows:

1. Mathematical 3D model of pressed auxiliaries and die model.

2. The set of detailed documentation (operational flow charts, manufacturing methods, specifications, etc., available from the manufacturer).

3. Process variables of engineering equipment.

4. Characteristics of materials of billet and die, including physicochemical properties of material of blade and die, parameters of heat transfer in heating and cooling during manufacturing, coefficient of friction between billet and die, speed of motion of piston, and so on.

The model of pressed billet is used for simulation of the overall process flow of pressing procedures, development of mathematical models, and engineering documentation for pressing auxiliaries. In addition, simplified geometrical models (including only die bed contour) of auxiliaries are developed for simulation of the pressing process; dividing by a finite element grid is applied. Engineering parameters are assigned (equipment capacity, furnace heating temperature, preheating temperature of dies, and so on). If it is required to compute stresses in auxiliaries, tools are simulated with consideration for all peculiarities of the auxiliaries, including flash bridge, box, and die dimensions.

ALGORITHM OF COMPUTATIONAL PROCEDURE

In designing of the manufacturing process of pressed billets for long blades, engineering parameters should provide secure manufacturing of a semifinished product with the minimum possible amount of

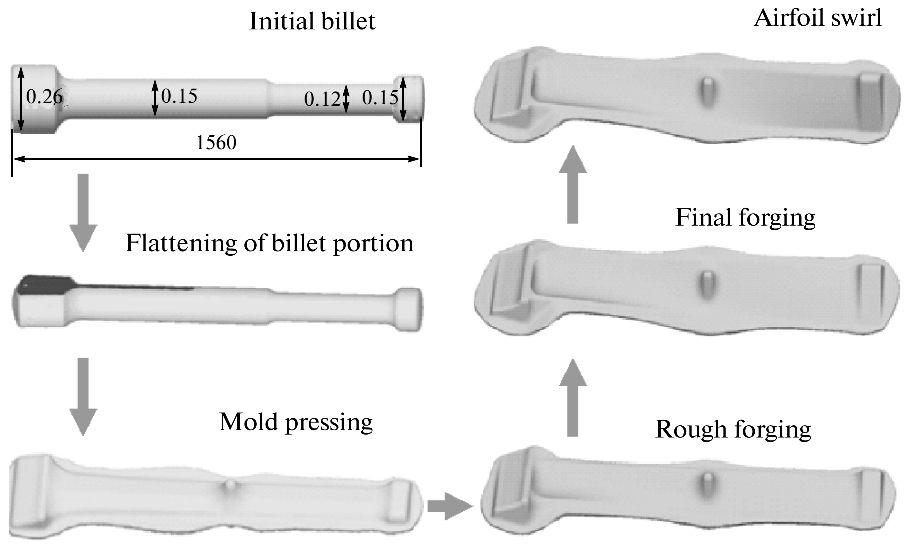

Fig. 2. Process flowchart of pressed billet manufacturing of shaped billet.

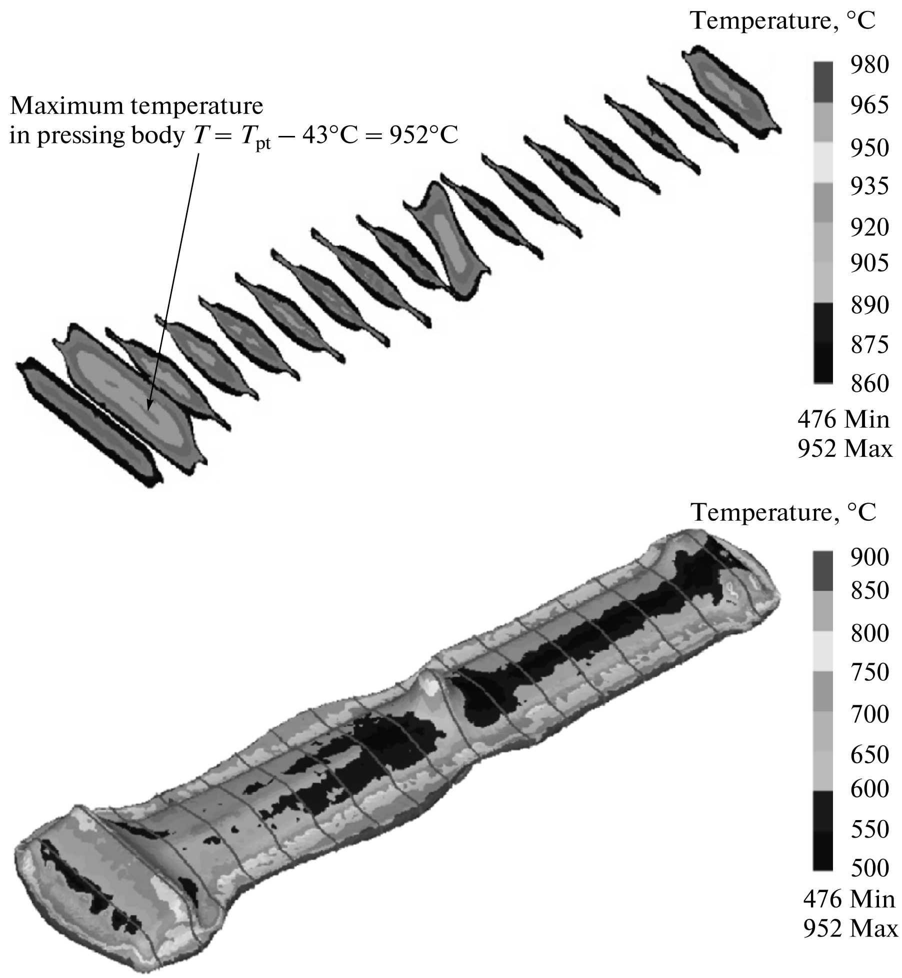

Fig. 3. Temperature field in cross section of blade billet

defects, as well as preset properties and parameters required for operation of long blades under conditions of high-speed flow of wet steam. The procedural algorithm developed for a prototype of annealed titanium alloy, Grade VT-6, with ultimate strength of 1100 MPa includes stage-by-stage development of a 3D model of

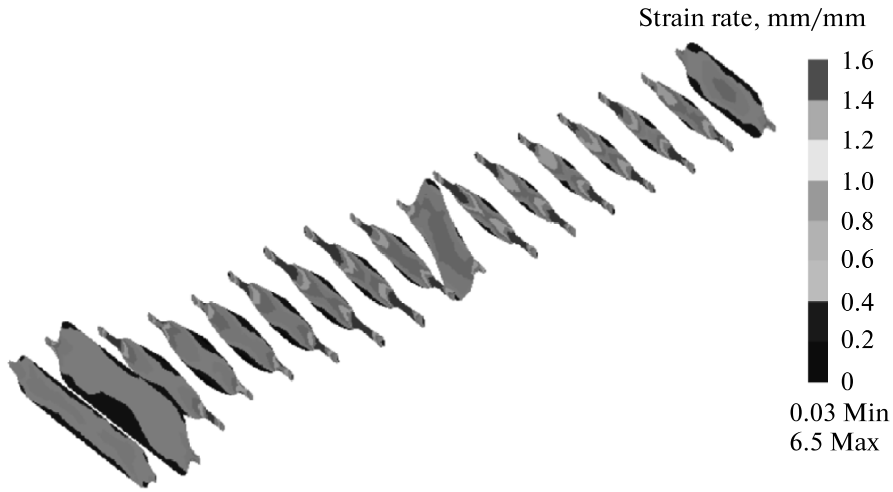

Fig. 4. Strain field in cross section of blade billet.

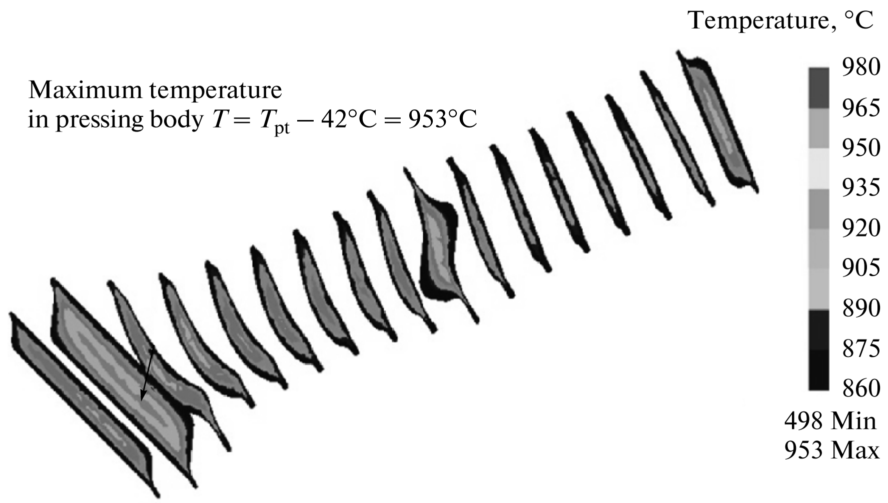

Fig. 5. Temperature field at the stage of rough forging.

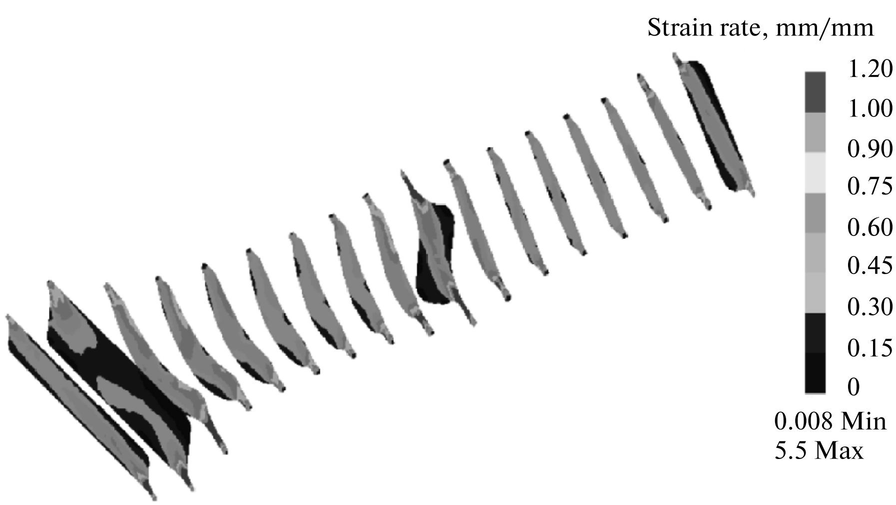

Fig. 6. Strain fields at the stage of rough forging.

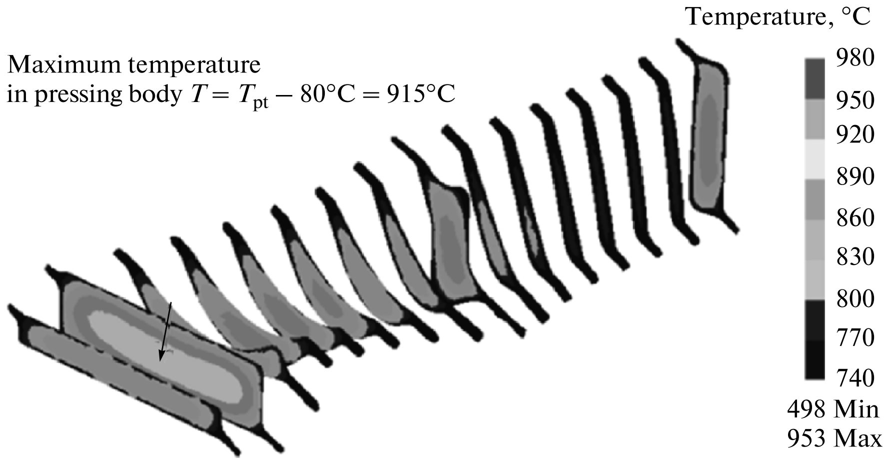

Fig. 7. Temperature fields at the stage of airfoil swirl.

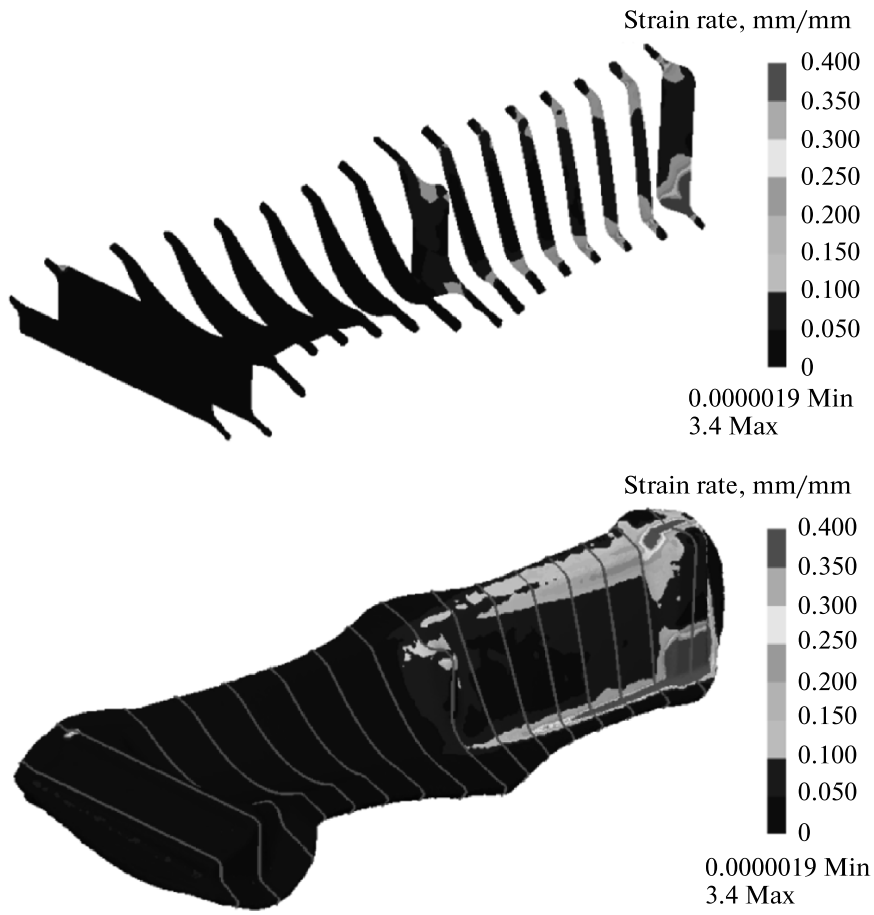

Fig. 8. Strain fields at the stage of airfoil swirl.

pressed billet in the $(\alpha + \beta)$ region for a large 1600 mm blade with the active part of 1400 mm. The algorithm flowchart is illustrated in Fig. 1.

In development of the design of pressed billet, the following steps are performed:

—A geometrical model of pressed billet is developed.

—A technical drawing of forging is made for coordination with manufacturing plant.

—Models for all procedures of the production process are developed, including the model of initial billet.

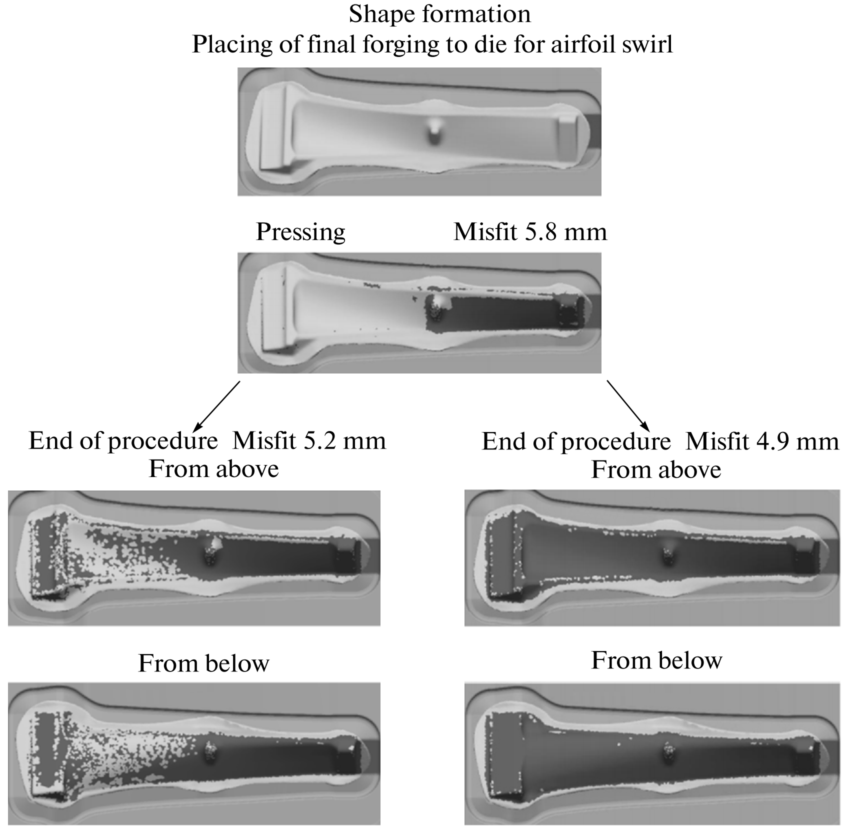

Fig. 9. Loading variants at the stage of airfoil swirl: 30.000 tf (right) and 18.000 tf (left).

—On the basis of analysis of the geometrical model of forging, preliminary pressing procedures are computed.

PROCESS FLOWCHART

Within the complete cycle of activities on optimization of the engineering process with achievement of preset parameters (no overheating areas in billets or defects, formation of facets), several process flowcharts of pressing were considered. The selected process flowchart (Fig. 2) includes the following procedures: flattening of shaped billet in the region of the highest thicknesses for more uniform filling of die mold, mold pressing, cutting of mold flash after mold pressing, rough forging, final forging, and airfoil swirl. Other process flowcharts are not considered in this article.

In manufacturing of pressed billets for blades of smaller dimensions (length of active part of 1200 mm), the first two pressing stages are combined. However, owing to extremely high dimensions of the formed billet and because of the necessity to prevent overheating of the cross section of the pressed billet, the number of stages had to be increased.

In simulation, variations of the temperature field were considered: heating in furnace, cooling in air during transport to press, heat exchange with pressing equipment. The heating temperature in the furnace was 900°C.

Simulation of shape formation was carried out for the condition of maximum die misfit of 5.5 mm.

SIMULATION RESULTS

The simulation produced temperature, stress, and strain fields and revealed points of possible generation of defects in pressed billet.

The highest strain rate is achieved at the stages of mold pressing and rough forging. In simulation of mold pressing defects (forging folds on surface, folds inside the blade), unacceptable strains or variations in preset blade thickness in cross sections were not detected; that is, mold pressing could be performed.

The results of mathematical simulation of shape variation of deformed body (billet) and deforming body (pressing auxiliary) are illustrated in Figs. 3–10. Figures 3 and 4 illustrate the fields of temperature and strains at the stage of simulation of mold pressing using high-strength titanium alloy with the temperature of phase $\alpha \rightarrow \beta$ transformation $T_{pt} = 1000$°C. The arrows indicate points in the cross sections where the temperature is the closest to T_{pt}.

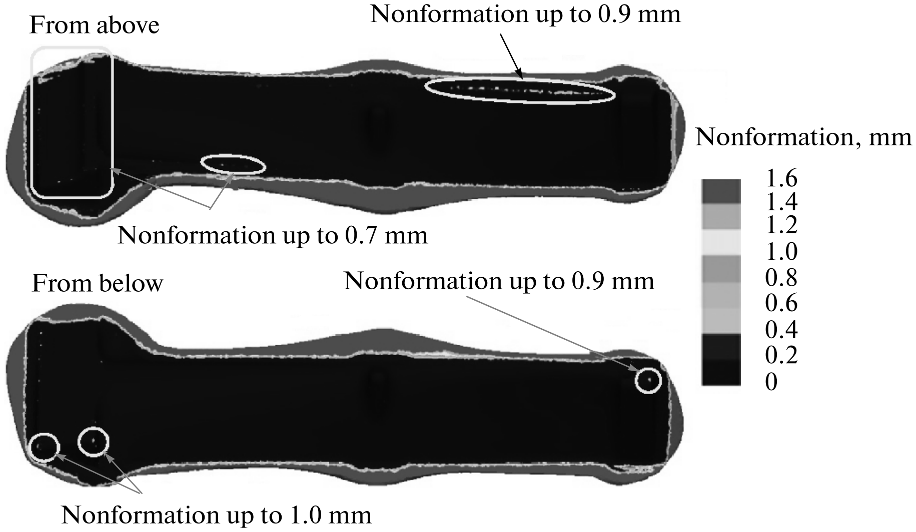

Fig. 10. Nonformation for loading of 30.000 tf.

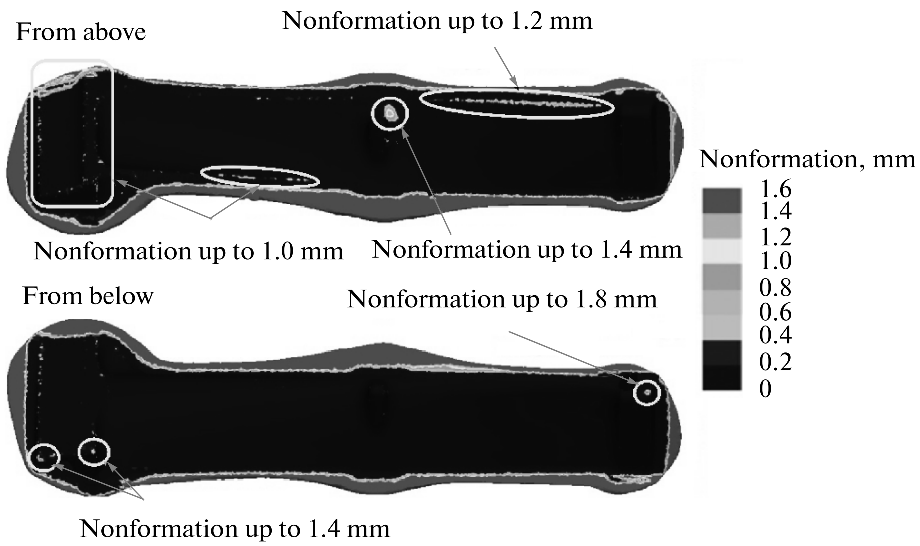

Fig. 11. Nonformation for loading of 18.000 tf.

At the first stage of molding shape formation, the average relative strain is 45%; here, the minimum strain rate is due to root and rim of billet.

Figure 5 shows that the temperature is distributed fairly uniformly in cross sections of the billet; the temperature decrease in cross sections near external boundaries is due to heat exchange with die tools. The existence of a minor local temperature increase in the tail cross section of the billet is due to its thickness, since the central part of this cross section is influenced by the contact with dies to a lower extent than thin cross sections of airfoil.

The temperature field and strain field at the stage of final forging are similar to those at the stage of rough forging. Figures 7 and 8 illustrate the temperature field and strain field at the stage of airfoil swirl.

At the final pressing stage, airfoil swirl, two variants of loading were considered: with press load of 30.000 and 18.000 tf (Fig. 9). Both variants provide sufficient formation of billet.

Figures 10 and 11 illustrate the regions of possible nonformation of facets of the pressed item for two loading variants of 30.000 and 18.000 tf, respectively. In both variants, the nonformation is not critical, since a billet can be pressed by two methods.

Owing to design peculiarities of pressed billet, that is, extremely swirled airfoil (about 90°), in pressing, the shear occurs in the transverse direction toward the blade axis, which tends to move the upper and lower halves of the die with respect to each other. Therefore, in order to decrease loading on the die equipment, the second variant of loading was selected.

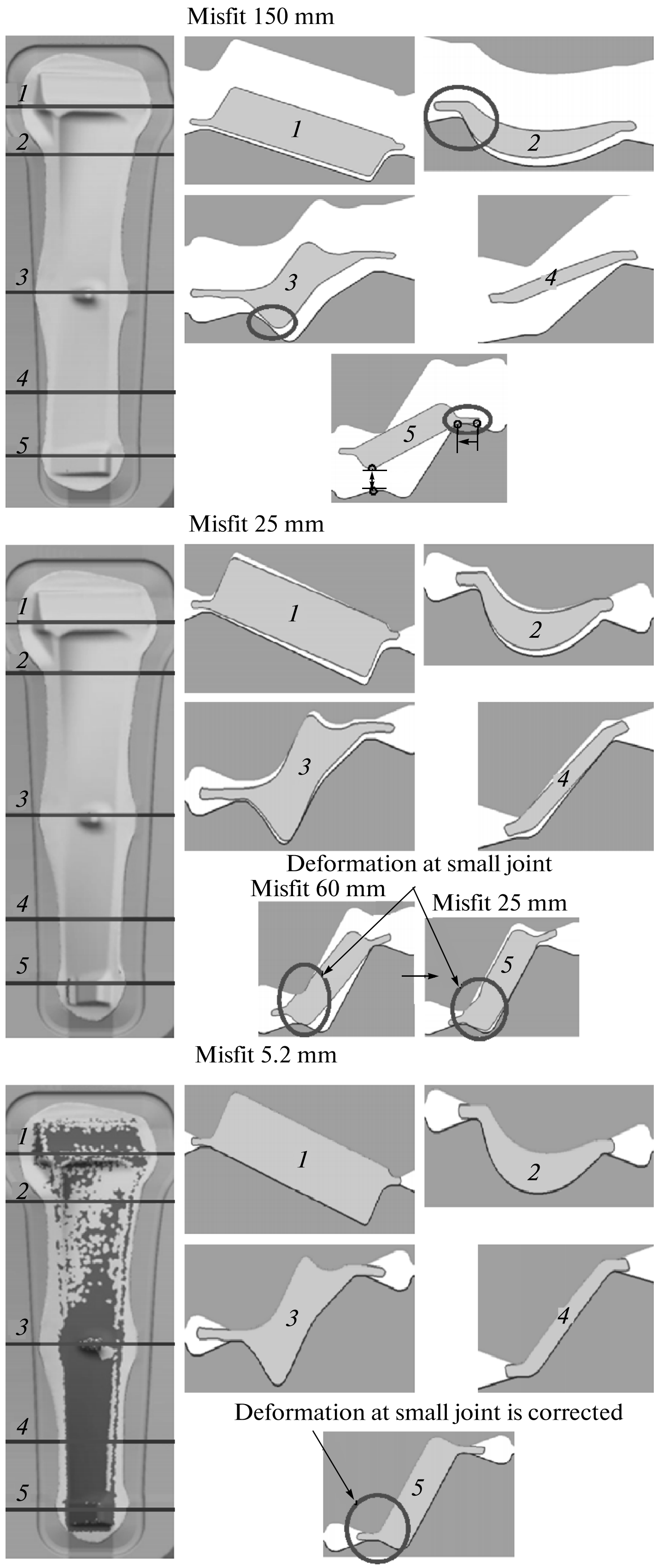

Fig. 12. Formation of cross sections at the stage of airfoil swirl.

Figure 12 shows the cross sections of pressed billet at the stage of airfoil swirl at various time points of lowering of the upper die. Simulation at the stage of airfoil swirl revealed possible deformation at a small joint (rim). At the end of the procedure, the deformation of small joint is eliminated, but in manufacturing owing to poor/heterogeneous lubrication of tools/billet, a small trace after deformation will possibly remain.

Therefore, in simulation of shape variation of final pressed billet, the data of stage-by-stage generation of temperature and strain fields in the cross sections of billet were obtained.

Analysis of strain and temperature fields of pressing stages performed by their mathematical simulation using Deform3D software made it possible to optimize the shape and configuration of pressing stages not during pilot manufacturing but before production of pressing auxiliaries, that is, at the stage of its designing.

The further scope of mathematical simulation of the manufacturing process will be optimization of strain rates (motion speed of press yoke) in order to eliminate generation of areas of intense deformation heating. On the basis of mathematical simulation of pressing stages, the die bed contours were adjusted for manufacturing of pilot specimens of pressed billets for long blades with the active part of 1400 mm.

CONCLUSIONS

1. Using Deform3D software, the procedure of 3D simulation has been developed for the final stage of manufacturing of pressed semifinished large 1600 mm blades with the active part of 1400 mm made of high-strength titanium alloy ($\sigma = 1100$ MPa).

2. On the basis of the computational results of temperature and strain fields in the cross section of pressed billet for each pressing stage, the process flowchart has been selected facilitating achievement of preset parameters.

3. On the basis of the computational results of metal flow during pressing, the configuration of die bed contours has been adjusted, which facilitates complete defect-free formation of facets of pressed billet.

4. Computer-aided simulation of pressing has facilitated forecasting of occurrence of defects in the production process.

5. In order to increase reliability and quality of pressing, decrease press loading, and reduce energy consumption, the optimum power parameters have been selected.

ACKNOWLEDGMENTS

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