Simulation of Deformation Behavior and Microstructure Evolution during Hot Forging of TC11 Titanium Alloy

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Abstract. Finite element method is the most powerful tool for development and optimization of the metal forming processes. Analysis of titanium alloy critical parts should include the prediction of microstructure since their mechanical and technological properties essentially depend on the type and parameters of the microstructure. The technological process of parts production for aerospace applications is multi-operational and consists of deformation, heating and cooling stages. Therefore, it is necessary to simulate the microstructure evolution to obtain high quality parts. In presented paper FE simulation coupled with microstructure evolution during hot forging of TC11 titanium alloy has been performed by QForm FEM code. Constitutive relationships, friction conditions and microstructure evolution model have been established using the experiments. The kinetics of phase transformations has been described by the Johnson-Mehl-Avrami-Kolmogorov (JMAK) phenomenological model. The approach is illustrated by industrial case study that proved its practical applicability and economic advantages for technology development of titanium alloy critical parts.

Introduction

Titanium alloys, particularly dual-phase titanium alloys, have been widely used as advanced structural materials in aeronautic applications [1, 2]. TC11 alloy is an α+β heat resistance titanium alloy that is applicable for critical aerospace applications owing to its high strength to weight ratio, good corrosion resistance and a high service temperature up to 500 °C [3]. The alloy is widely used in aircraft engine compressor disks and blades and some airplane components. An understanding of the mechanisms of thermo-mechanical processing of this alloy will be highly beneficial to control its microstructure during manufacturing [4]. The objective of this study is to identify the flow behavior and friction conditions for wide range of temperature and strain rate and to characterize the microstructural evolution of TC11 having initially α+β equiaxed microstructure during hot forging of part «Lever».

Materials and Procedures

Materials. The billet used in the present work was a 55 mm diameter hot-rolled bar stock of TC11 titanium alloy (according to GB/T 2965-2007). Its measured composition (in wt%) was 5.9 aluminum, 3.27 molybdenum, 1.40 zirconium, 0.2 silicon, balance titanium. The β transus for this material is about 1008 °C. The study of TC11 alloy deformation behavior and microstructure evolution have been performed in as supplied state. The initial microstructure of TC11 is shown in Fig. 1. Microstructure is bimodal with globular volume fraction of 0.4 and primary α-phase average grain size of 7.4 μm.

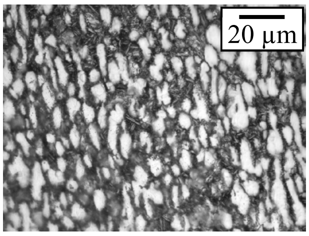

Figure 1. Initial microstructure of TC11 alloy

Uniaxial Hot Compression Tests. Tests have been performed at low strain rate (≤ 1 s^{-1}) by universal testing machine Zwick Z050 and at high strain rate (50 s^{-1}) by Gleeble 3800 simulator. Tests have been carried out in isothermal state in the air in accordance with ASTM E0209-00 [5]. An aqueous solution of hexagonal boron nitride has been used as a lubricant.

Hot Ring Compression Tests. The ring compression test is a proven test to determine friction factor m in Siebel (shear) friction law [6, 7]:

$$\tau = mk = m\frac{\sigma_s}{\sqrt{3}}, \quad (1)$$

where τ – friction shear stress, MPa;
m – friction factor;
k – plasticity constant, MPa;
σ_s – flow stress, MPa.

In order to obtain the magnitude of friction factor the change in inner diameter of the compressed ring must be compared with this obtained from finite element analysis, for example by FEM commercial code QForm.

Microstructure characterization. Microstructure has been characterized using optical microscopy images. The average grain size has been evaluated by the random secant method according to GOST (State Standard) 21073.3-75. The globular grains have been identified by a ratio between the longitudinal and transversal sizes of no larger than 3:1. The volume fraction of globular α-phase in the bimodal structure has been determined by computing the area occupied by globular grains using an overlain mesh with a cell size of 5 µm.

Microstructure evolution model. The kinetics of recrystallization can be approximated fairly well by the Johnson-Mehl-Avrami-Kolmogorov equation (JMAK). In our model the fraction of the volume that has passed through dynamic recrystallization is calculated as follows:

$$X_d = 1 - \exp\left[-\beta_d \cdot \left(\frac{\varepsilon}{A_d \cdot d_0^{M_d} \cdot \dot{\varepsilon}^{L_d} \cdot \exp\left(\frac{Q_d}{RT}\right) + C_d}\right)^{k_d}\right], \quad (2)$$

where $A_d, M_d, L_d, Q_d, C_d, \beta_d, k_d$ are constants.

Finite element method (FEM) analysis. Simulations have been done by FEM commercial code QForm (www.qform3d.com). FEM analysis has been used to obtain true strain-stress curves by temperature correction for compensation of deformation heating by iterative procedure. Also, the friction factor has been determined by means of inverse analysis. Input data included the specific sample and dies geometry, kinematics of forming equipment, heating history used in the experiments, TC11 flow stress data corrected to exclude influence of deformation heating, thermophysical properties of TC11 alloy, the die material, and the value of the friction factor. All data except flow curves and friction conditions has been taken from QForm deformed materials database.

Results and Discussion

Flow Curves. To determine flow curves at elevated temperatures it is necessary to take into account the inhomogeneity of deformation, the thermal deformation effect and friction. The most effective method is an inverse analysis.

The inverse analysis technique for determining the flow stress curve has been developed by Cho and Altan [8] and in presented work we have used this technique for different temperature and strain rate conditions. The set of flow curves is given in tabular form. The objective function is the following expression:

$$\Phi = \frac{1}{K}\sum_{j=1}^{K}\frac{1}{N_j}\sum_{i=1}^{N}\left(\frac{F_{ij}-f_{ij}}{F_{ij}}\right)^2, \qquad (3)$$

where K – number of flow curves;
N – number of points approximating the flow stress curve;
F_{ij} – an experimentally determined force at a point, N;
$f_{ij}(p)$ – calculated force at point, N.

To minimize the objective function an iterative algorithm and an optimizer have been used. Specimens after deformation are shown in Fig. 2.

Figure 2. Deformed specimens of TC11 alloy

The flow stress curves for the temperatures from 850 °C to 1100 °C are presented in Fig. 3. As we see, only within the narrow range of temperature and strain rate the material softening can be observed. For the rest range of the temperature and strain rate TC11 alloy behaves as an ideal viscous-plastic material having constant flow stress.

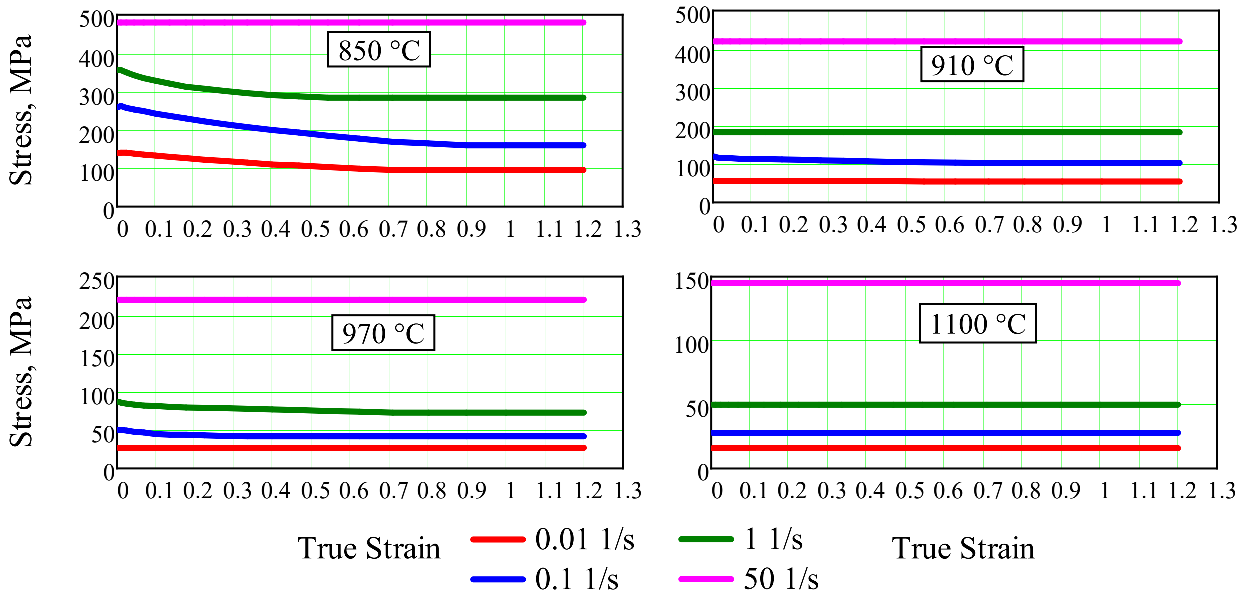

Figure 3. Flow curves of TC11 alloy

Friction Conditions. The friction factor has been studied in the temperature range from 850 °C to 970 °C. The samples after deformation are shown in Fig. 4.

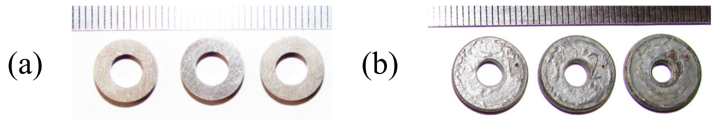

Figure 4. Initial (a) and deformed (b) ring specimens of TC11 alloy

Plot of the friction factor versus temperature is shown in the Fig. 5. As we can see the friction factor of TC11 alloy is highly dependent on temperature of deformation.

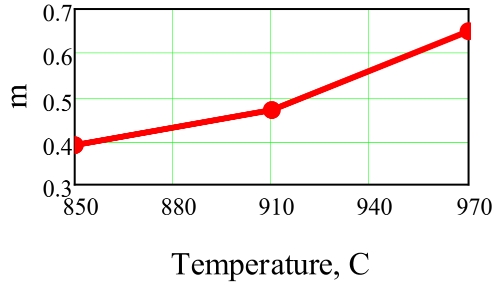

Figure 5. Temperature dependence of friction factor of TC11 alloy

Process characterization. Deformation behavior and microstructure evolution of TC11 Titanium alloy have been investigated during hot forging of part «Lever» (Fig. 6).

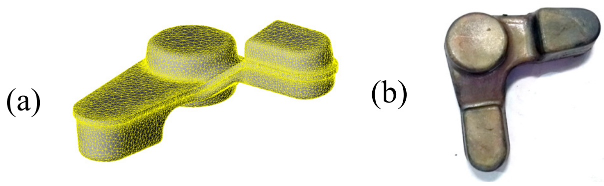

Figure 6. Finite element model (a) and the photo of forged part «Lever» (b)

The technological process includes the following stages: heating to forging temperature 970 °C, upsetting, preforming, flash trimming, reheating, final forging and second flash trimming (Fig. 7).

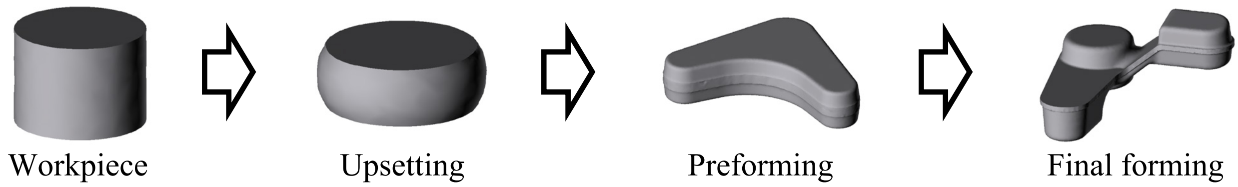

Figure 7. The sequence of forming process of the part «Lever»

Microstructure characterization and further FEM analysis have been carried out in certain crosscut sections that are shown in Fig. 8.

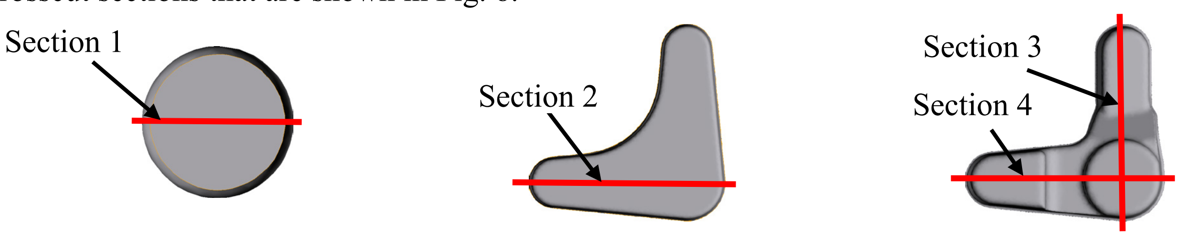

Figure 8. The scheme of crosscut sections in the part «Lever»

Typical microstructure after upsetting can be characterized as bimodal with volume fraction of recrystallized α-phase of 0.16 (Fig.9 a).

Macrograph and typical microstructure after preforming are shown in Fig. 9 b, c. Microstructure is almost homogeneous with volume fraction of recrystallized α-phase of 0.26.

Figure 9. Typical microstructure (a) after upsetting (Section 1), macrograph (b) and typical microstructure (c) after preforming (Section 2)

Macrograph and typical microstructures after final forming in Sections 3 and 4 are shown in Fig. 10 and 11 respectively. As we can see there is almost homogeneous microstructure in bosses with volume fraction of recrystallized α-phase of 0.40 and localized flow bands in adapters with volume fraction of recrystallized α-phase of 0.68.

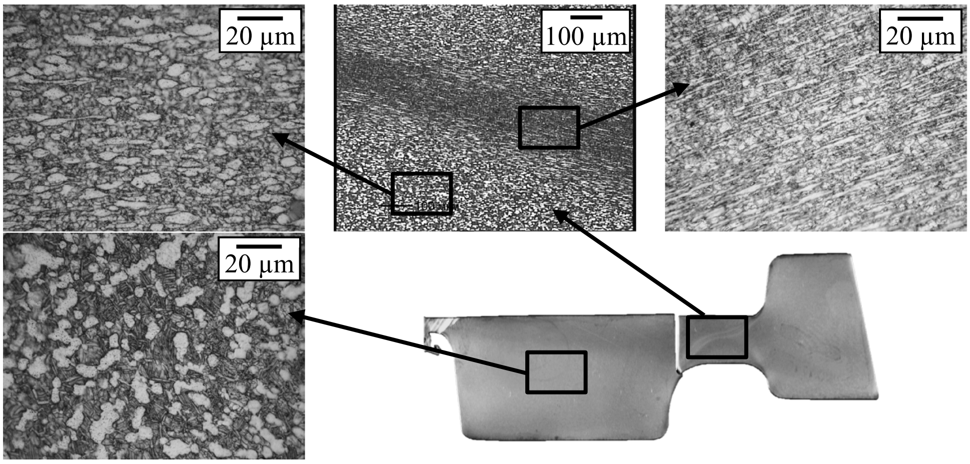

Figure 10. Macrograph and typical microstructure after final forming (Section 3)

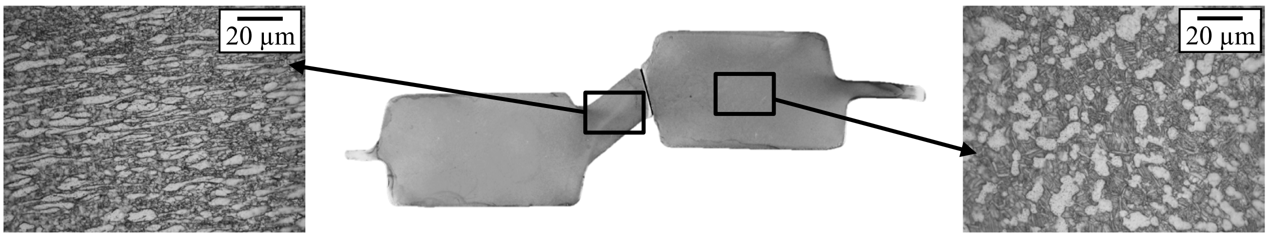

Figure 11. Macrograph and typical microstructure after final forming (Section 4)

FEM Simulation. Strain distributions obtained by means of simulation of the technological process in FEM commercial code QForm are shown in Fig. 12. Predicted distributions of recrystallized volume fraction of α-phase are shown in Fig. 13

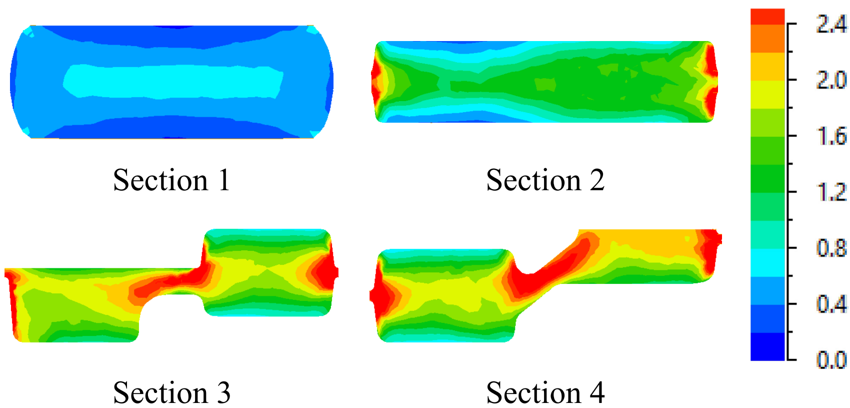

Figure 12. Strain distributions

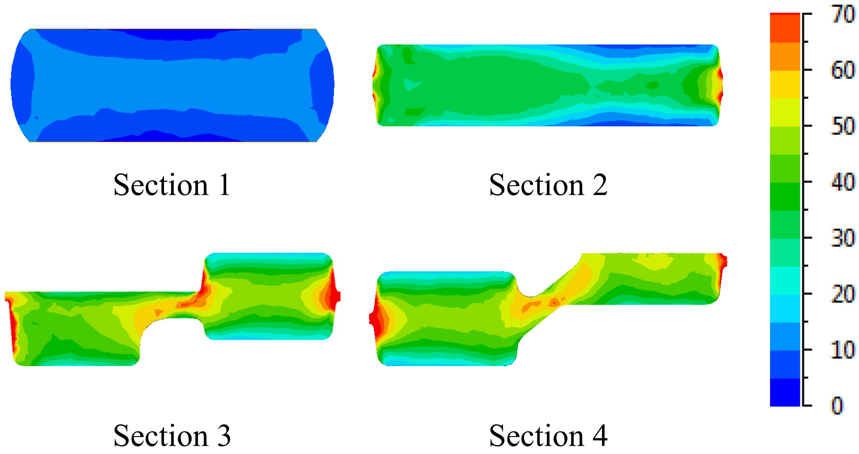

Figure 13. Recrystallized volume fraction of α-phase

As we can see the simulation predicts deformation localization in adapters. Predicted recrystallized α-phase volume fraction also well corresponds to experimental data.

Summary and Conclusions

1. Hot deformation behavior of TC11 alloy with an equiaxed α+β starting microstructure has been investigated by means of isothermal compression tests in the temperature range 850–1100 °C and strain rate range 0.01–50 s^{-1}.
2. Friction conditions in the temperature range 850–970 °C have been investigated by ring compression tests in the temperature range 850–970 °C.
3. Deformation behavior and microstructure evolution of TC11 titanium alloy during hot forging of part «Lever» have been analyzed.
4. The model of microstructural evolution based on JMAK approach has been implemented in FEM code QForm.
5. Predicted distributions of recrystallized volume fraction of α-phase are in a good agreement with the experimental data.

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