Research Article

Prediction of Microstructure Evolution in Hot Backward Extrusion of Ti-6Al-4V Alloy

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Microstructure evolution of Ti-6Al-4V alloy during hot backward extrusion process was simulated with the combined approaches of finite element method (FEM) and microstructure prediction model. From experimental analysis, it can be found that the change of microstructure during hot forming process of titanium alloy has a close relation to α/β phase transformation and grain growth behaviour. A microstructure prediction model was established by considering the change of volume fractions and grain size of both phases varying with process variables and then implemented into the user-defined subroutine of FEM analysis. In order to demonstrate the reliability of the model, the volume fraction and grain size of primary α phase during the hot backward extrusion process of Ti-6Al-4V alloy were simulated. The simulation results were compared with the experimental ones.

1. Introduction

Computer simulation is an important and effective tool for the optimized forming processes and to reduce error which may be caused by trial and error method. Finite element (FE) analysis is widely used for the simulation of shape and microstructure changes in hot forming [1–3]. With the improvement in understanding of the relationship between microstructures and mechanical properties of structural components, the prediction of shape and microstructure changes has become a hot issue in the high-temperature forming.

The high-temperature forming processes for manufacturing titanium alloy products are normally conducted on the equiaxed structure in two-phase $(\alpha + \beta)$ field [4]. The microstructure change is mainly indicated as the change of volume fraction and grain size of α and β phases. It may be due to phase transformation and grain growth during the high temperature forming. In the past, most of microstructure simulations have focused on the prediction of the single-phase alloys using the recrystallization and grain growth models [5]. However, only a limited work [6, 7]

has been carried out on the simulation for microstructure evolution of Ti-6Al-4V alloy during hot forming processes. Therefore, the aim of this research is to establish the methodology for prediction of the microstructure evolution of Ti-6Al-4V components during high-temperature forming processes, and to develop a useful design tool for obtaining the optimum process condition in the high-temperature forming processes using finite element method (FEM) simulation.

2. Experimental Procedures

The material used in this work was a Ti-6Al-4V alloy billet annealed at 704°C for 2 h with a diameter of 100 mm. The chemical composition of the alloy is 6.32Al, 4.18V, 0.21Fe, 0.014C, 0.18O, 0.008N, 0.001Y, and balance Ti (in wt%). Initial microstructure of Ti-6Al-4V alloy was an equiaxed structure with the primary α grain size of about 16 μm as shown in Figure 1.

In order to investigate flow behavior and microstructure evolution of Ti-6Al-4V alloy in the α-β phase field,
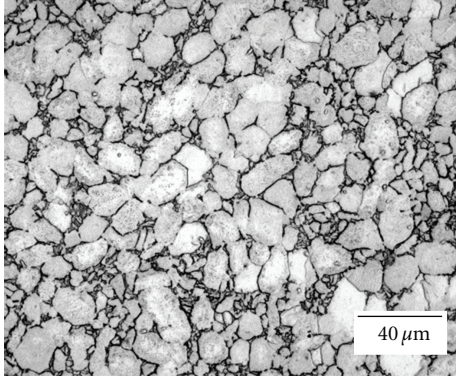
FIGURE 1: Typical microstructure of the annealed Ti-6Al-4V alloy billet.

FIGURE 2: Design of the punch, lower die, and preform used in hot backward extrusion.

compression and heat treatment tests were carried out. Compression tests were performed in the temperature ranges between 850°C and 1000°C with 25°C intervals using the strain rate ranging from 10^{-3} to $10\,\mathrm{s}^{-1}$. Heat treatment tests were carried out with the holding time of 30 min between 900 and 1015°C. To observe the actual microstructure at the test temperature, after the holding time of 30 min, the heat-treated samples were water-quenched. To analyze the microstructure evolution during cooling, the samples were heat-treated at the temperature of 900, 925, 950, and 975°C for 30 min. Following the heat treatment, the samples were cooled down using different cooling rates.

In order to verify the reliability of the established microstructure prediction model, Ti-6Al-4V alloy tube was manufactured by hot backward extrusion process using a 150 ton hydraulic press. Backward extrusion process for evaluating the reliability of the model was selected to predict microstructure variation during actual hot working considering friction, interface heat transfer, and process variables. The design of the dies (punch and lower die) and preform is represented in Figure 2. Oil-based graphite lubricant was spread into the punch and lower dies to reduce die friction. The preform of Ti-6Al-4V alloy was glass-coated and heated to an extrusion temperature of 970°C. The punch and die temperatures were selected at 500°C and 600°C, respectively. After the backward extrusion, the Ti-6Al-4V tube was water-quenched.

3. Results and Discussion

Figure 3 shows the change of microstructures with increasing the heating temperature obtained from isothermal heat treatment tests of Ti-6Al-4V alloy. It can be found that the volume fraction and grain size of α phase decrease with increasing the heating temperature, and especially the grain size of α phase markedly decreases from more than 950°C. The β phase grains remain constant up to 950°C and dramatically grow at 975°C. This is in agreement with the observations by Semiatin et al. [8].

Figure 4 shows the change of microstructure with increasing hold time obtained from isothermal heat treatment tests of Ti-6Al-4V alloy. It is noted that the α grain
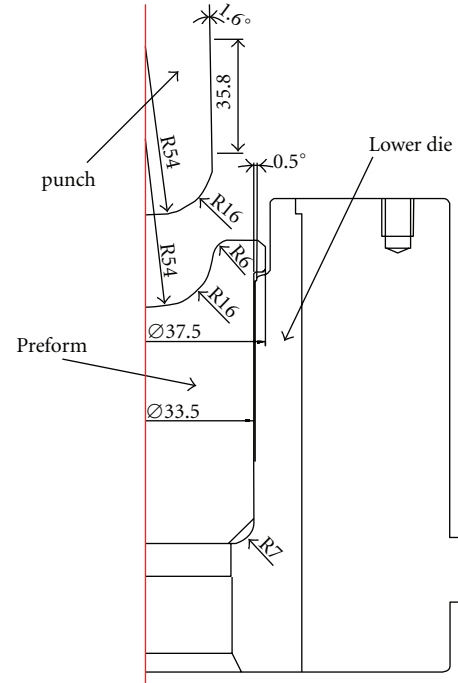
size does not change significantly with holding time whereas β grain size increases considerably. This is due to the high diffusivity in β phase.

In general, mechanical properties of Ti-6Al-4V alloy products forged at α-β region were directly affected by the volume fraction and grain size of equiaxed primary α phase. The microstructure prediction model reflecting microstructure evolution during heating and high temperature deformation is established in this work. To predict the volume fraction and grain size of primary α phase, the geometrical model for grain size change of α phase developed in previous work [2, 9, 10] was used. Assuming that the total numbers of α grains and β grain size are constant, the grain size of α phase (d) can be calculated by following equation:

$$d = d_0 \left(\frac{f_\alpha}{f_{\alpha 0}} \right)^{1/3} \quad (\mu \mathrm{m}), \tag{1}$$

where d_0 and $f_{\alpha 0}$ are the initial grain size and volume fraction of primary α phase, respectively, and f_α is the present volume fraction of primary α phase. Meanwhile, the volume fractions of each phase during heating and soaking can be expressed as a function of initial volume fractions of each phase and temperature

$$f_\alpha = f_{\alpha,RT} + \left(1 - \exp\left(-k \cdot \langle T_\beta - T \rangle \right) \right)$$
$$f_\beta = 1 - f_\alpha, \tag{2}$$

where f_{β_0} and f_β are initial volume fraction and present volume fraction of β phase, respectively. $f_{\alpha,RT}$ is the volume fraction of primary α phase at room temperature. The magnitude of $\langle T_\beta - T \rangle$ is zero when $T_\beta - T \leq 0$, and it is
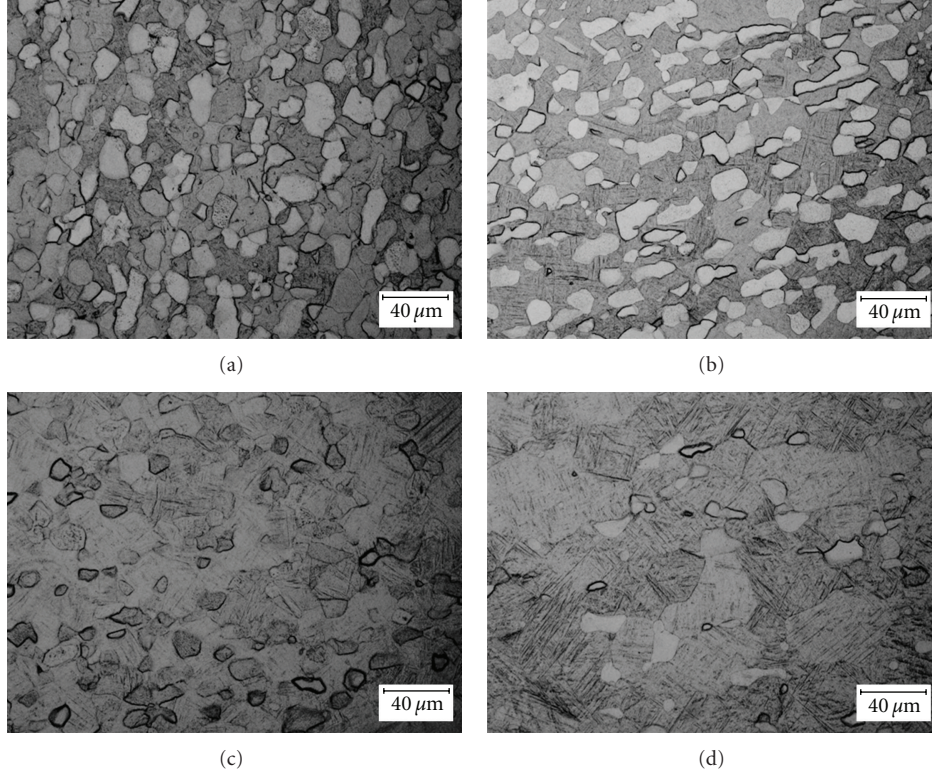
Figure 3: Microstructures of Ti-6Al-4V alloy samples water quenched after a 30 min heat treatment at (a) 900°C, (b) 925°C, (c) 950°C, and (d) 975°C.
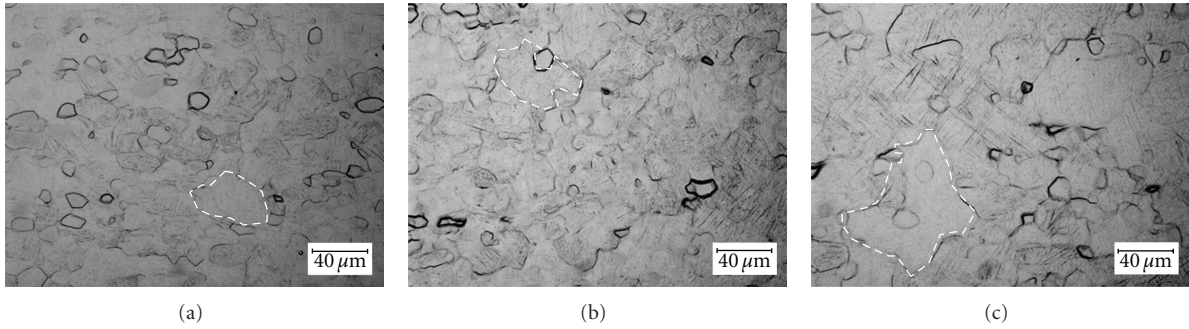

Figure 4: Microstructures of Ti-6Al-4V alloy samples water quenched after isothermal heat treatment at 950°C for (a) 10 min, (b) 1 h, and (c) 10 h. White dotted lines indicate β grains.

$T_\beta - T$ in other case. Through the isothermal heat treatment tests, the parameters $f_{\alpha,RT}$ and k in Ti-6Al-4V alloy with an equiaxed structure were determined by 0.942 and 8.17×10^{-3}, respectively.

In α-β Ti alloys, phase transformation ($\beta \rightarrow \alpha$) also occurs during cooling and forming. In order to express the volume fraction change of α phase during cooling and forming, the Avrami-type equation was applied

$$f_{\alpha,c} = f_{\alpha,h} + (f_{\alpha,RT} - f_{\alpha,h}) \cdot (1 - \exp(-f(T) \cdot t^n))$$
$$f(T) = A \cdot \left(\frac{T_{\text{heat}} - T}{T_{\text{heat}} - T_e}\right)^{n'}, \tag{3}$$

where $f_{\alpha,h}$ are the volume fraction of α phase after heating and soaking. T_{heat} is heating or soaking temperature. T_e

represents the finishing temperature of phase transformation and this value is assumed to be 298 K. The values of n, n', and A were 1, 6.67, and 0.0023, respectively.

A commercial FEM code, DEFORM 2D, was used to simulate the effect of process variables in hot backward extrusion process of Ti-6Al-4V alloy on the distribution of the internal state variables such as strain, strain rate, and temperature. The flow stress data obtained from compression tests were corrected for temperature increment calculated by the following equation:

$$\Delta T = \frac{0.9 \int_0^\varepsilon p\sigma d\varepsilon}{\rho C}, \tag{4}$$
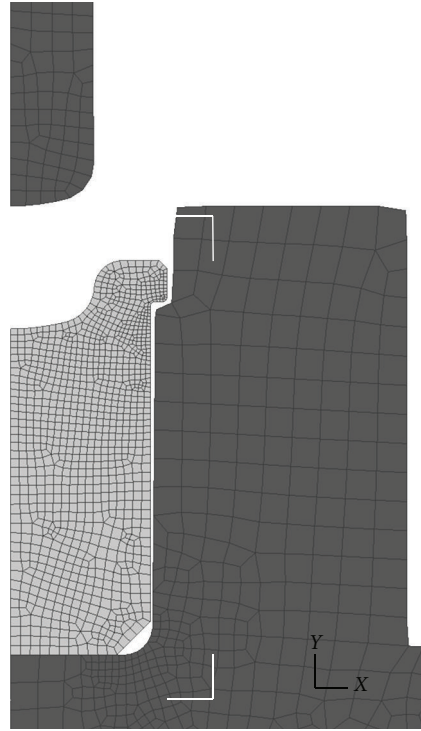
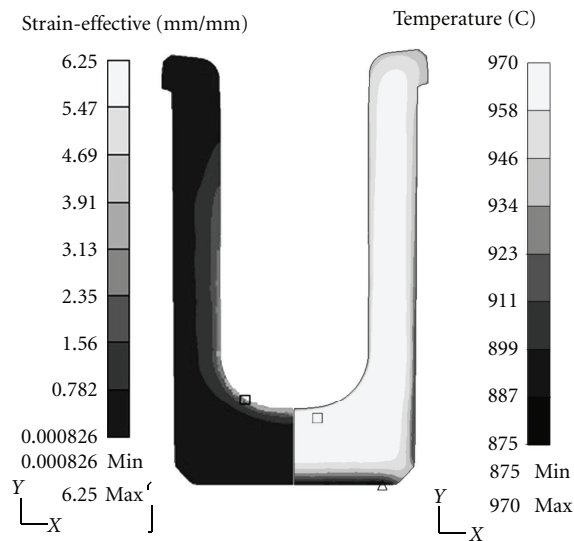FIGURE 5: FEM modeling for hot backward extrusion process of Ti-6Al-4V alloy.

FIGURE 6: Temperature and effective strain contours for hot backward extrusion simulation of Ti-6Al-4V alloy.

where ε_p is plastic strain, ρ is density of material, and C is specific heat. Corrected flow stress data were directly used to simulate material behavior of Ti-6Al-4V alloy during hot backward extrusion.

Generally, the friction between dies and workpiece is expressed by the friction law of constant factor. Also, interface heat transfer between dies and workpiece greatly affects the temperature change of the workpiece during hot forming process. Based on the results of previous work [11], the friction coefficient and interface heat transfer coefficient

were determined at 0.3 and 5.0 kW/m²°C, respectively. The element used in the simulation is brick elements, and automatic remeshing system was adopted during simulation. Figure 5 shows the 2D modeling for dies and initial preform shapes.

Figure 6 shows simulation results of strain and temperature distributions of hot backward extrusion process of Ti-6Al-4V alloy tube. The simulation results indicate that the highest strain region in the workpiece is found at inner wall, which is in contact with the punch during
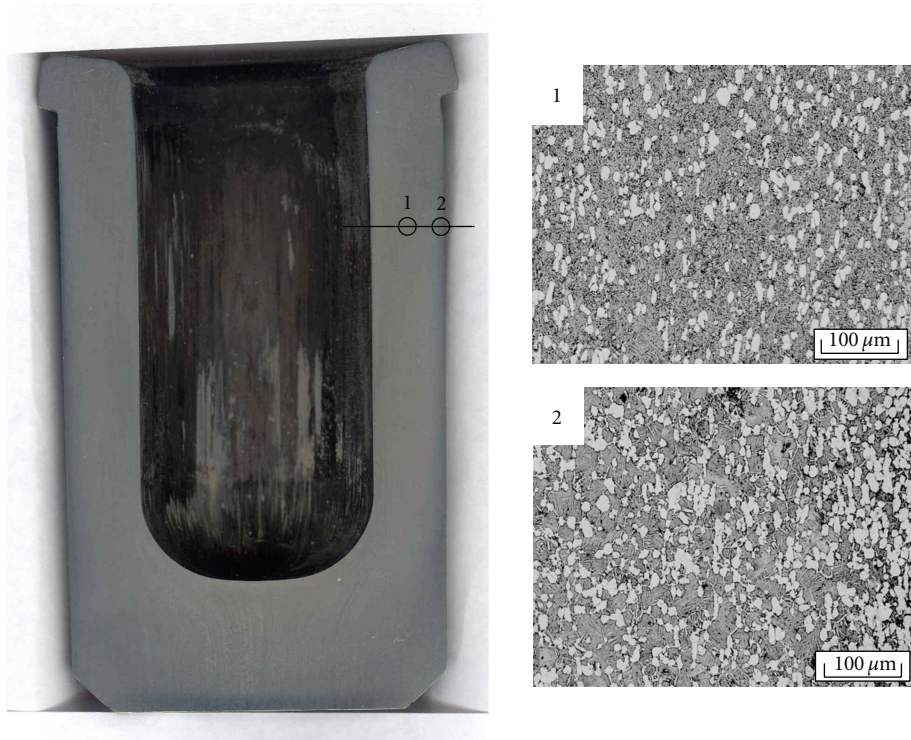
FIGURE 7: Microstructures observed at different locations for backward extruded Ti-6Al-4V alloy tube.
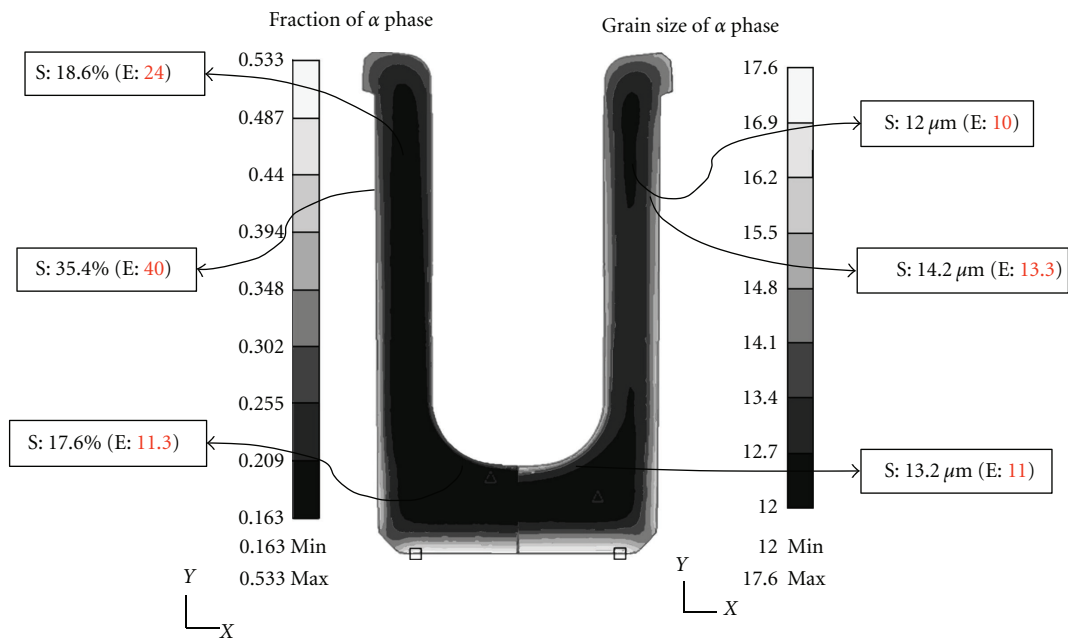

FIGURE 8: Contours of volume fraction and grain size of primary α phase for hot backward extrusion simulation of Ti-6Al-4V alloy. The symbols "S" and "E" in the bracket denote simulation and experimental results, respectively.

the forming process, and the temperature level at die contact area (or surface area) is lower than that at middle area due to heat transfer between dies and workpiece. Also, the lowest temperature region in the workpiece is found at the bottom, which is in constant contact with the lower

die throughout the forming process from the moment the preform is transferred to the die.

Figure 7 shows the Ti-6Al-4V alloy tube manufactured by hot backward extrusion process and the microstructures observed at the cross-section of the tube. It can be found

that extruded Ti-6Al-4V alloy tube is formed without the surface defects. Microstructures observed at most locations indicate a bimodal structure composed of equiaxed α and transformed beta phases. In the microstructural observation from surface to middle positions, it can be seen that the volume fraction of α phase at middle position is smaller than that of α phase at surface.

These microstructure changes during the extrusion process were closely related to the plastic strain and temperature varying at different positions. In this work, in order to predict the α grain size and the α/β phases volume fraction change, the decoupled approach between the microstructure model and FE analysis was applied. The model for predicting the volume fraction change and grain size of α phase was implemented into a post-user-defined subroutine of a commercial FE-code, DEFORM-2D.

Figure 8 shows the comparison between experimental data and simulation results. The experimental data measured from extruded tube were overlapped aside from simulation results. the values in the brackets especially indicate the experimental data. It was found that reasonable accuracy was obtained at most of region and the average deviation was below 15%. Only at a certain part of inner wall, 36% of error was noticed which is due to the contact of the inner wall with the punch occurring in the given microstructures. It is clearly demonstrated that simulation results of volume fraction and grain size of α phase at most locations for the extruded Ti-6Al-4V tube were relatively close to measured values. Consequently, it is suggested that the microstructure simulation module is very useful for hot forming process design of Ti-6Al-4V alloy.
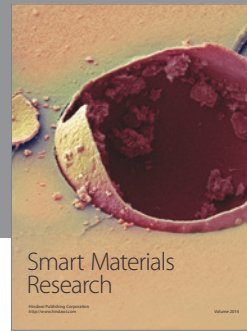
4. Conclusions

In this work, the microstructure evolution of Ti-6Al-4V tube during hot extrusion process was predicted by decoupled approach of FE analysis and microstructure prediction model. In order to evaluate the volume fraction and grain size of α phase during the hot backward extrusion process, the microstructure prediction model of Ti-6Al-4V alloy was suggested and implemented into the post-user sub-routine of FE code. The comparison of the microstructure simulation module with the actual microstructures of the backward extruded Ti-6Al-4V alloy tube has successfully validated the reliability of the present module in the prediction of the volume fraction and grain size of α phase.

Acknowledgments

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