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Microstructural Transformation of β-solution Treated and Forged Ti-6Al-4V Alloy during Superplastic Deformation

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Fine-grained and equiaxial microstructure of two-phase titanium alloys is usually developed in thermomechanical process with properly selected parameters of plastic deformation and heat treatment. In previous works it was established that β-solution treatment — initial heat treatment preceding plastic deformation in thermomechanical process — distinctly increased superplasticity of Ti-6Al-4V alloy. In current studies fine-grained microstructure was obtained in thermomechanical process consisting of β-solutioning followed by forging in α+β range. Next superplastic deformation tests were carried out at temperature T = 875°C and at strain rate in the range of 10^{-3}~10^{-2} s^{-1}. For investigation of microstructural transformation during superplastic deformation some of the tests were interrupted at the characteristic points of stress-strain curve: maximum stress and superplastic flow stress at strain of ~400%. Digital image analysis methods were employed for evaluation of changes of stereological parameters of Ti-6Al-4V alloy microstructure.

Keyword: *superplastic deformation, thermomechanical process, microstructure, Ti-6Al-4V alloy*

1. Introduction

Superplasticity of titanium alloys depends on relationship between grain growth control and plasticity. β phase grains are characterized by high diffusivity, therefore they grow extremely rapidly at the high superplastic deformation temperature which does not favor superplastic flow [1]. Particular volume fraction of α phase considerably limits β grains growth because in this case long way diffusion of alloying elements is necessary (e.g. vanadium in β phase). Existence of the second phase, besides stabilization of microstructure, influences the rate of grain boundary (α/α, β/β) and phase boundary (α/β) sliding [2-5]. Increase of volume fraction of β phase causes decrease of α/α grain boundaries area and consequently their contribution to deformation by grain boundary sliding (*GBS*). It is thought that improvement of superplasticity of α+β titanium alloys caused by the increase of volume of β phase should be considered in following aspects [3,6]:

1. α/β phase boundary sliding,
2. β/β *GBS,*
3. contribution of other deformation mechanisms.

It was also found that α/β phase boundary sliding proceeded easier than α/α and β/β *GBS*'s [7].

Taking into account the mechanism of superplastic deformation equiaxed microstructure favors proceeding of *GBS*. It was found that in fine grained polycrystalline materials with grains elongated crosswise deformation direction *GBS* is limited. The main reason is the difficulty of deformation accommodation in triple points. Transverse deformation is also related to cavities formation along grain boundaries and precludes superplastic deformation [2,8]. Nevertheless interesting results were obtained for Ti-6Al-4V alloy where α grains were separated by thin films of β phase. Superplastic elongation in this case was more than 2000%. Further investigations indicated that during superplastic deformation thin films of β phase coagulated in triple points into larger particles having irregular forms. In this case the effect of β phase thin film was compared with the role of grain boundaries in single phase materials. Slip and shearing in β phase thin film are caused by the movement and rotation of neighboring α grains. Mentioned processes enable accommodation of grain boundary and phase boundary sliding [3,6].

In previous works the effect of initial microstructure developed in thermomechanical process on superplasticity of Ti-6Al-4V alloy were analyzed. It was found that high superplasticity had been observed for microstructure different from equiaxed one. The best results were achieved for microstructure consisting with strongly elongated and deformed α grains (Fig. 1a, b) obtained after β-solution treatment and followed by deformation at α+β phase transformation range. Microscopic observations after superplastic tests revealed the essential changes of phase components morphology (Fig. 1 c) which had to occur during heating and the first stage of superplastic deformation [9-11].

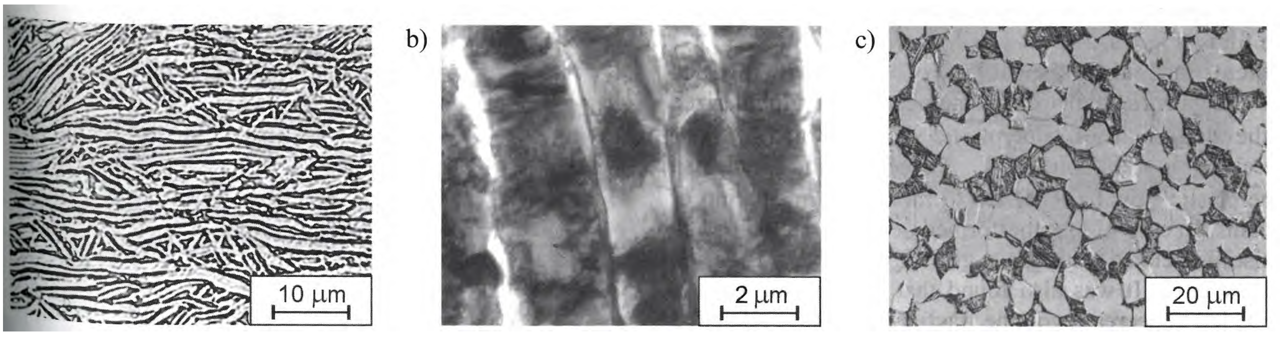

Figure 1. Microstructure of thermomechanically processed Ti-6Al-4V: a) before superplastic deformation (b - TEM) and c) after (temperature 850°C and strain rate of 10^{-3} s^{-1}) [10,11].

2. Research Methodology

The material tested was Ti-6Al-4V titanium alloy in the shape of rolled bars of 25 mm in diameter, made by Daido Steel Co. Ltd., Japan. On the basis of dilatometric test the start and the finish temperature of α+β→β phase transformation were determined T_s = 887°C and T_f= 985°C respectively. Cylindrical samples 80 mm in length were β-solutioned, heated up to 900°C (α+β→β range) and locally open die forged (forging reduction $\varepsilon \approx 60$ %).

Superplastic deformation (SPD) tests were carried out on Instron 8801 testing machine. Round samples (l_0 = 3 mm, ϕ = 4 mm) were deformed in vacuum chamber (0.005 Pa) at 875° C at the strain rate $1 \cdot 10^{-3}$ and $1 \cdot 10^{-2}$ s^{-1}. Tests were finished at specimen rupture (ε_f - III) or at the strain values corresponding to maximum (ε_{max} - I) and superplastic flow stress ($\varepsilon_{sf} \approx 400\%$ - II) (Fig. 2).

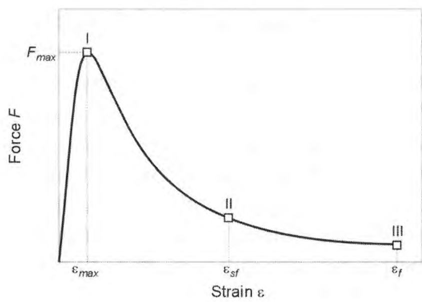

Figure 2. Assumed points of stress-strain curve for metallographic investigations.

Microstructure of tensile test samples were analyzed in two zones: gauge length (GL) and grip part — at distance of about 1 mm from gauge length (G). Metallographic specimens were etched using Kroll's reagent and analyzed on Nikon Epiphot 300 microscope equipped with image analysis system based on Aphelion 3.2 software. Following stereological parameters of α phase were determined: volume fraction (V_a), length (α_a) and width (b_a) of the minimum bounding rectangle of grain and grain elongation $f_\alpha = \alpha_\alpha / b_a$ [12)].

3. Results

Microstructure of Ti-6Al-4V alloy after β-solution treatment and subsequent deformation at α+β phase transformation range consisted with strongly elongated and deformed a grains (V_a = 81%, a_α = 28.2 μm, b_a = 3.3 μm, f_a = 8.5) separated by β transformed phase thin films (Fig. 1a, 1b).

Microstructural investigations of specimens revealed that elongated α grains were fragmented and globularized at the first stage of superplastic deformation (ε_{max} - I) especially in GL zone (Fig. 5b, 6b, 7 and Table 1). Superplastic flow (ε_{sf} - II) led to further fragmentation of a grains. In case of tests performed at strain rate of 10^{-3} s^{-1} is also associated with grain growth (Fig. 5c, 5d, 6c, 6d and Table 1). It was also found that superplastic tests at 875°C led to decrease volume fraction of α phase related to formation of β phase (Table 1 and Fig. 8). This relationship was observed on two analyzed specimen zones though in gauge length zone volume fraction of a phase was smaller than in grip zone.

Total elongations obtained in completed superplastic tests were 1230% at strain rate of 10^{-3} s^{-1} and 870% at 10^{-2} s^{-1}. Maximum load stresses σ_{pm} calculated with assumption of uniform cross-section reduction were 23 MPa and 63 MPa respectively. Load-strain curves obtained in superplastic tests are shown in Figure 3. Undeformed and superplastic deformed specimens are shown in Figure 4.

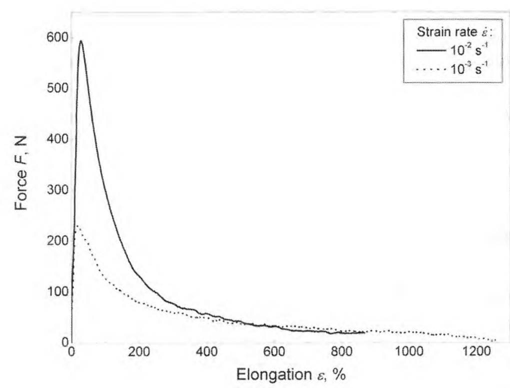

Figure 3. Load-strain curves of superplastic tensile deformed Ti-6Al-4V alloy at 875°C.

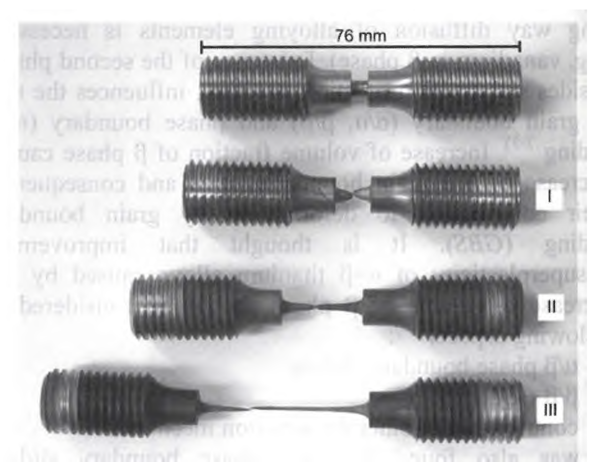

Figure 4. View of specimen before and after superplastic test at strain rate of 10^{-3} s^{-1}.

Table 1. Stereological parameters of microstructure of superplastic deformed Ti-6Al-4V alloy.

Microstructure	V_α %	a_α μm	b_α μm	f_α
Strain rate of 10^{-3} s^{-1}				
I/G	75.0	26.8	3.8	7.0
I/GL	73.1	10.1	3.1	3.3
II/G	74.0	18.0	6.5	2.8
II/GL	69.3	8.5	7.2	1.2
III/G	67.7	17.7	7.4	2.4
III/GL	58.8	9.9	8.8	1.1
Strain rate of 10^{-2} s^{-1}				
I/G	74.0	29,7	4.5	6,6
I/GL	74.1	13.4	2.9	4.6
II/G	71.7	21.2	4.6	4,6
II/GL	70.4	3.6	3.3	1.1
III/G	69.9	12.4	5.8	2.1
III/GL	68.4	9.4	8.4	1.1

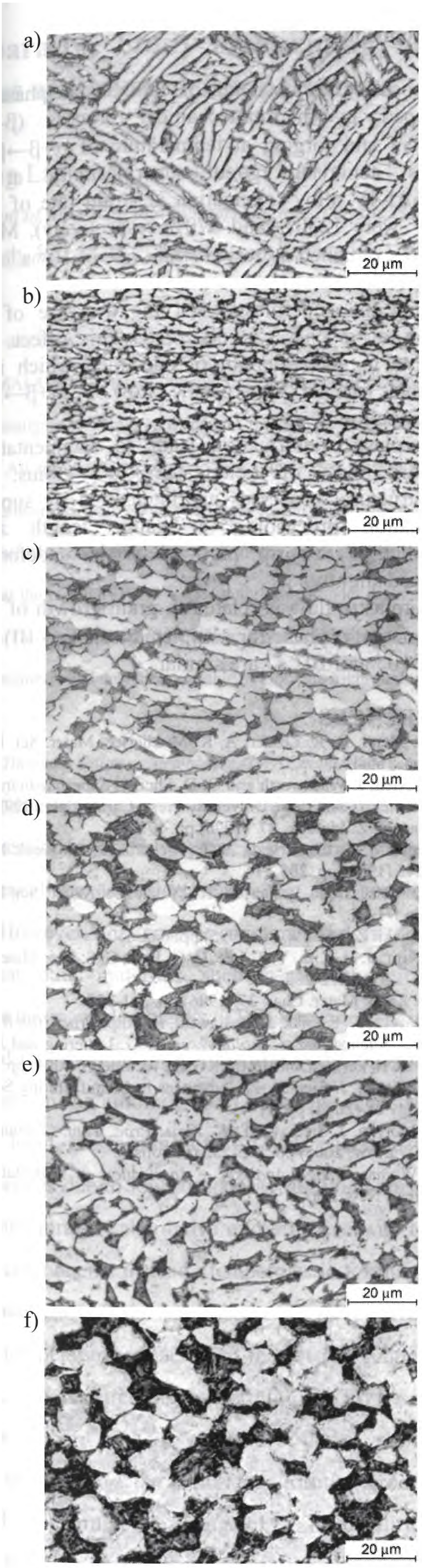

Figure 5. Microstructure of superplastic deformed Ti-6Al-4V alloy at strain rate of 10^{-3} s^{-1} (I - ε_{max}, II - ε_{sf}, III - ε_f, G — grip, GL — gauge length): a) I/G, b) I/GL, c) II/G, d) II/GL, e) III/G, f) III/GL.

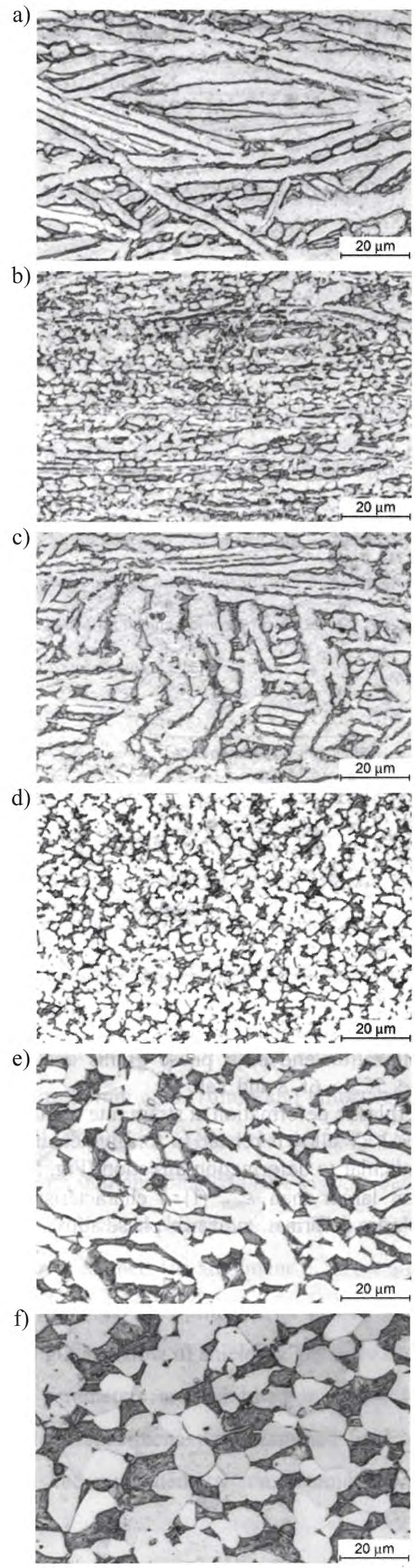

Figure 6. Microstructure of superplastic deformed Ti-6Al-4V alloy at strain rate of 10^{-2} s^{-1} (I - ε_{max}, II - ε_{sf}, III - ε_f, G — grip, GL — gauge length): a) I/G, b) I/GL, c) II/G, d) II/GL, e) III/G, f) III/GL.

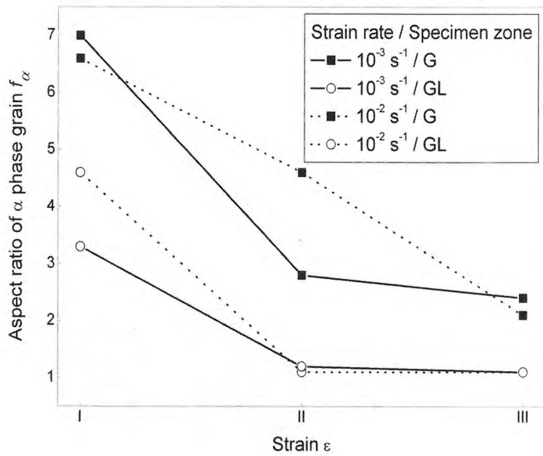

Figure 7. Dependence of aspect ratio of α phase grain on strain value.

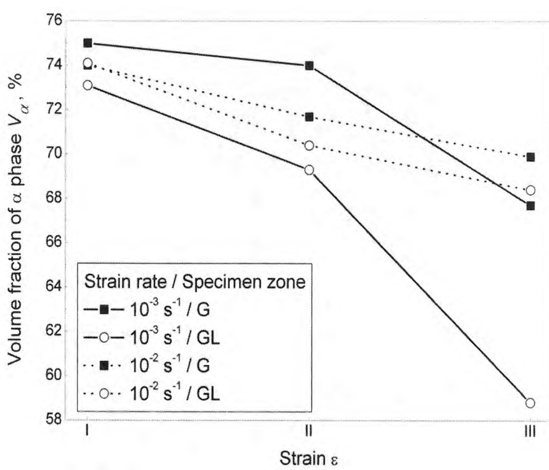

Figure 8. Dependence of volume fraction of α phase on strain value.

Completed superplastic tests (ε_f - III) caused spheroidization and of α phase grains and their growth (Fig. 5e, 5f, 6e, 6f, 8 and Tab. 1).

Superplastic deformation at strain rate of 10^{-3} and 10^{-2} s^{-1} of Ti-6Al-4V alloy is related to forming chains of α grains perpendicular to deformation direction (Fig. 5d, 5f, 6d, 6f) at strain larger than ε_{max} (I) — characteristic feature of superplastic deformation of two-phase alloys [8].

4. Conclusions

Microstructure consisting of elongated a phase grains, developed in thermomechanical process (β-solution treatment and forging at temperature of α+β→β range) enables achieving good superplasticity at 875°C of Ti-6Al-4V alloy (elongation at strain rate of 10^{-3} and 10^{-2} s^{-1} were 1230% and 870% respectively). Maximum stress σ_{pm} obtained in test at strain rate of 10^{-2} s^{-1} is higher than at 10^{-3} s^{-1}.

During the superplastic test the decrease of volume fraction of α phase is observed. This effect is more intensive in gauge length of specimen which indicates favorable role of superplastic flow in α+β→β phase transformation.

Superplastic deformation leads to fragmentation and globularization of elongated α grains. Those microstructural processes are intensified by superplastic deformation proceeding in gauge length zone in contradiction to grip part which is undeformed or deformed slightly.

Superplastic flow is related to grain growth of α phase. Grain size of α phase for completed tests (ε_f - III) at strain rate of 10^{-3} and 10^{-2} s^{-1} are similar.

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