Ultrafine-grained structure formation in Ti-6Al-4V alloy via warm swaging

2014 IOP Conf. Ser.: Mater. Sci. Eng. 63 012070

(http://iopscience.iop.org/1757-899X/63/1/012070)

Ultrafine-grained structure formation in Ti-6Al-4V alloy via warm swaging

M Klimova[1], M Boeva, S Zherebtsov and G Salishchev
Belgorod National Research University, Belgorod 308015, Russia

E-mail: klimova_mv@bsu.edu.ru

Abstract. The influence of warm swaging on the structure and properties of Ti-6Al-4V alloy was studied. Warm swaging of the alloy in the interval 680-500°C with the total strain of ε=2.66 was found to be resulted in the formation of a homogeneous globular microstructure with a grain size of 0.4μm in both longitudinal and transversal sections. Room temperature tensile strength and tensile elongation of the swaged alloy was 1315MPa and 10.5%, respectively. Ultrafine-grained Ti-6Al-4V alloy produced by swaging exhibited good workability at 600-700 °C.

1. Introduction

One of the promising approaches to improve mechanical properties of structural materials is the formation of an ultrafine-grained (UFG) structure with a grain size less than 1μm [1]. In comparison to coarse grained materials UFG materials exhibit enhanced static and cyclic strength, hardness and wear resistance [2]. Such combination of properties can reduce the dimensions and weight of parts while keeping their structural strength. This fact is especially important for titanium alloys. Providing low density, high specific strength and an excellent corrosion resistance [3], titanium alloys are used in a wide variety of aviation, aerospace, shipbuilding, automobile production.

To obtain the UFG structure in metallic materials severe plastic deformation at low temperatures (typically below 0.5 T_m) is usually used [1]. One of the main parameters of severe plastic deformation which can influence on the kinetics of ultrafine-grained structure formation is strain path. In comparison to unidirectional deformation, change in the load direction during large straining can considerably increase both the kinetics of microstructure refinement and the final structure homogeneity. One of the well-known ways to use this approach is multidirectional forging (MF); this method shows particularly good result in case of two-phase titanium alloys allowing formation of a homogeneous microstructure with grain size of 0.4μm [4]. However MF has an essential fault associated with a relatively high laboriousness of the method.

More efficient way to obtain the UFG structure in rod preforms is warm swaging [5]. Swaging consists in periodic compressions of a rod and reduction its diameter by split dies which simultaneously move along radial, rotational and axial directions relative to the axis of the rod. In this case the deformation has a quasi-hydrostatic compression scheme. This gives a possibility to deform materials with high accuracy to large strain without fracture.

The aim of the present work was to study the formation of UFG microstructure of Ti-6Al-4V titanium alloy in both longitudinal and transversal sections during swaging in the temperature range 680-500 °C with the total strain of ε = 2.67.

2. Materials and procedures

The program material was a two-phase Ti-6Al-4V alloy with a nominal composition (in wt%) of 6.3 Al, 4.1 V, 0.18 Fe, 0.03 Si, 0.02 Zr, 0.01 C, 0.018 O, 0.01 N, Ti bal. It was received in the form of a hot rolled 60mm diameter 500 mm length rod with a β-transus temperature (at which $\alpha+\beta\rightarrow\beta$) of 995 °C. The heat treatment of the rod before swaging included water quenching from 960 °C.

Then the diameter of the rod was sequentially reduced via swaging from 60mm to 35 ($\varepsilon = 1$), 21 ($\varepsilon = 1$) and 15mm ($\varepsilon = 2.67$) along the following schedule:

1) Ø60→ Ø35 at T=680 °C, ($\varepsilon = 1$);
2) Ø60→ Ø35 at T=680 °C and Ø35→21 at T=500 °C, ($\varepsilon = 2$);
3) Ø60→ Ø35 at T=680 °C and Ø35→15 at T=500 °C, ($\varepsilon = 2.67$),

where ε is a true strain determined as $\varepsilon = \ln(F/F_0)$, in which F_0 and F are the initial and final area of the rod, respectively. At each step the rod was sectioned in half for microstructure examination.

Before swaging the rod was heated to the required temperature in a furnace and then it was deformed using cold dies in multiple passes with a reduction ~ 5mm per pass. After deformation the rod was cooled in air.

The evolution of the microstructure in the longitudinal and transversal sections was examined using a transmission electron microscope (TEM) TECNAI G2 F20 S-TWIN and a scanning electron microscope (SEM) Nova Nanosem 450 equipped with an orientation imaging microscopy (OIM) system.

Mechanical properties of the swaged alloy were evaluated via tensile test at room temperature using flat specimens with the gauge dimensions of 1.5×3×16 mm. Technological properties (modeling of superplastic forming) were evaluated by compression tests of cylindrical specimens ∅14×20mm in the interval 600-700 °C at a strain rate of about 10^{-3} s^{-1}. Flow stress was determined at 20% of strain.

3. Results and discussion

The microstructure of the alloy in the initial condition (water quenched from 960 °C) composed of primary globular α-grains with a mean size of 7µm and acicular α'-martensite within the former β-grains (figure 1a). During heating and soaking at deformation temperature α'-martensite decomposed with formation of α+β lamellar microstructure with a thickness of lamellae less than 0.2µm.

After swaging to $\varepsilon = 1$ at 680°C slightly elongated in the deformation direction particles of α-phase and very fine lamellar/globular α+β structure were observed in the longitudinal section (figure 1b). In the transversal section α-particles had an equiaxed shape of ~5µm in diameter (figure 1c). Increase in strain to $\varepsilon = 2$ at lower temperature 500°C resulted in the formation of a microstructure in which α-platelets were oriented along the metal-flow direction (figure 1d). Substructure was observed within elongated particles of α-phase (insert in figure 1d). Fine α+β lamellar microstructure was mainly transformed into globular one. Particles of α-phase in the transverse section were found to be folded and kinked in different directions forming a specific 'curly' type of microstructure that also is typical of extruded or drown conditions [6, 7]. The thickness of the elongated α-particles was found to be ~2µm (figure 1e). Warm swaging to the true strain of $\varepsilon = 2.67$ led to further microstructure refinement and to homogeneity improvement (insert in figure 1g). In the longitudinal section (figure 1f) SEM image shows a lamellar morphology of the microstructure. The thickness of lamellae decreased from 4 to ~ 2µm. In the transversal section curved α-particles became also shorter and thinner (about 1.5µm, figure 1g).

IOP Conf. Series: Materials Science and Engineering **63** (2014) 012070 doi:10.1088/1757-899X/63/1/012070

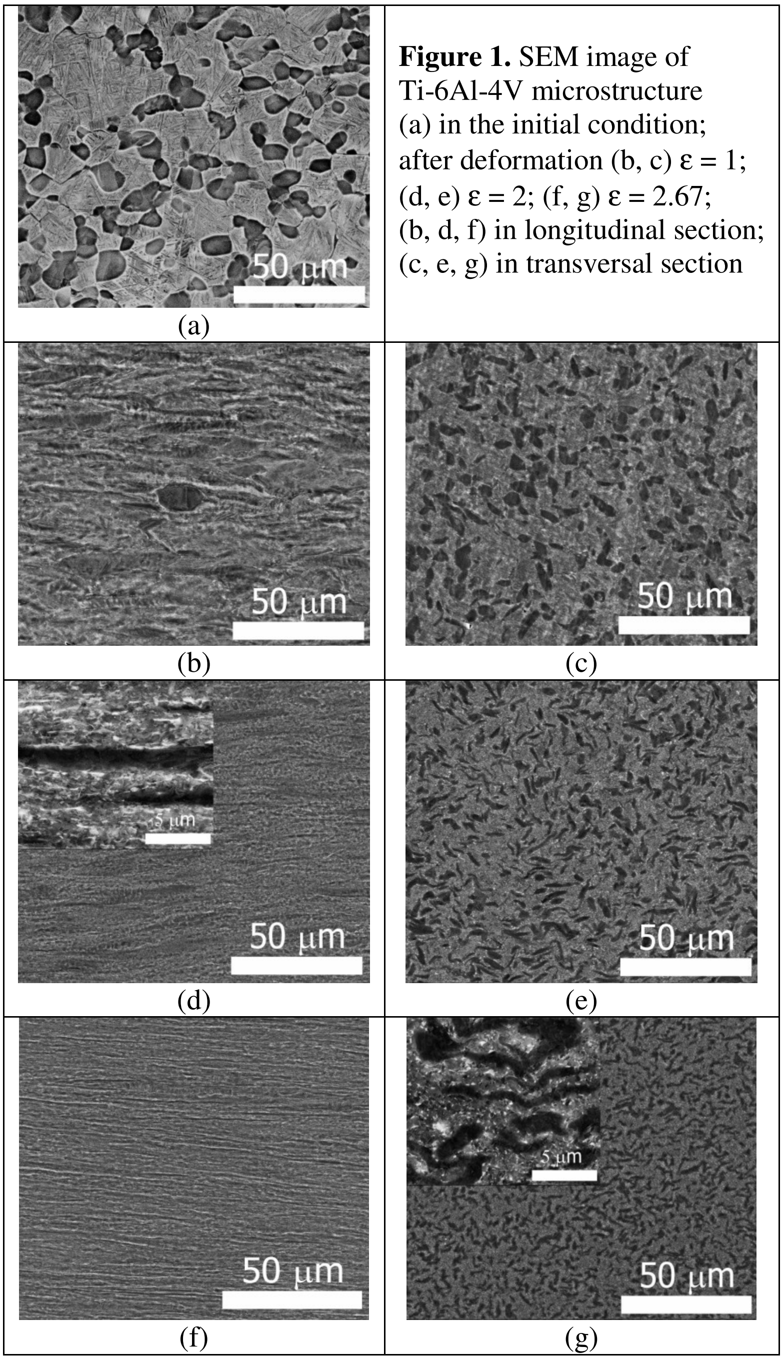


Figure 1. SEM image of Ti-6Al-4V microstructure (a) in the initial condition; after deformation (b, c) ε = 1; (d, e) ε = 2; (f, g) ε = 2.67; (b, d, f) in longitudinal section; (c, e, g) in transversal section

EBSD map in figure 2a taken from the longitudinal section of the specimen swaged to ε = 2 shows heterogeneous microstructure consisting of α-particles elongated along the deformation axis alternating with areas of fine globular α- and β-grains or subgrains of about 0.5μm in diameter. The thickness of the elongated α-particles was 2-4μm. Developed substructure was observed within both lamellae and fine grains; the fraction of low-angle boundaries was 77%. The volume fraction of the fine-grained structure was found to be 0.4. Swaging to the total strain of ε = 2.67 at 500 °C (figure 2c) resulted in the formation in the longitudinal section of a homogeneous globular UFG microstructure with the grain size of 0.4μm. After swaging a typical axial texture was formed in the α-phase of the

IOP Conf. Series: Materials Science and Engineering **63** (2014) 012070 doi:10.1088/1757-899X/63/1/012070

alloy when the basal $(0001)_{\alpha}$ plane normal direction is aligned with the transverse (radial) directions of the rod for both ε = 2 and 2.67 (Figure 2b and d).

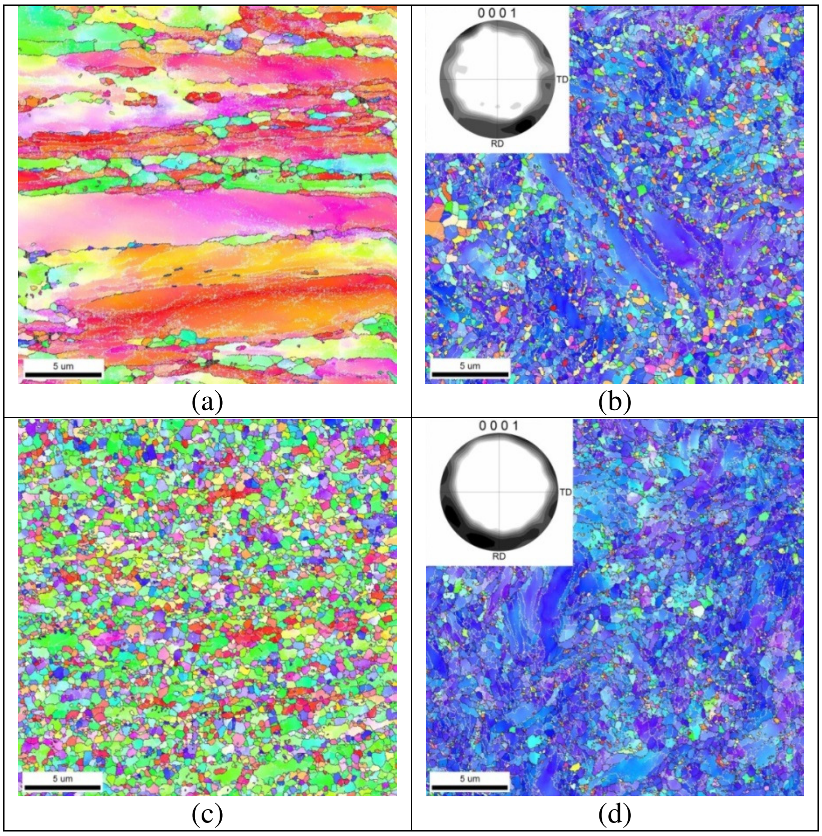
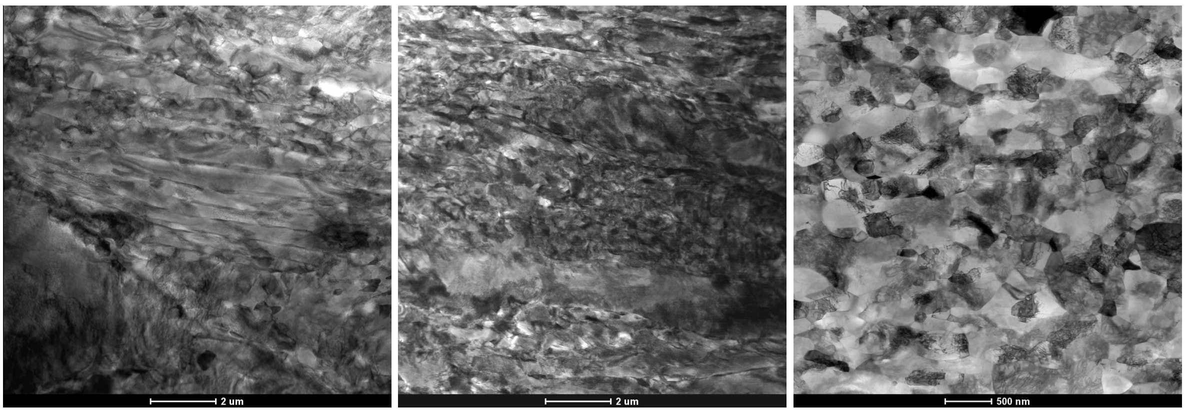


Figure 2. EBSD maps of microstructure after deformation in longitudinal section: (a, b) ε = 2; (c, d) ε = 2.67; (a, c) in longitudinal section; (b, d) in transversal section.



(a) (b) (c)

Figure 3. Microstructure of Ti-6Al-4V alloy in longitudinal section: (a) ε = 1; (b) ε = 2; (c) ε = 2.67.

Microstructure evolution during deformation was further elucidated by transmission electron microscopy (figure 3). Microstructure of the alloy after ε = 1 at 680 °C (figure 3a) consisting of fine-grained mix of (α+β)-phases, elongated α-particles with high dislocation density and thin α-lamellae divided by β-layers. After strain ε = 2 α-lamellar and (α+β)-globular structure with the size of (sub)grains of 0.5µm was observed (figure 3b). Some particles of α-phase contained low- and highangle boundaries. Increase in strain resulted in further microstructure refinement and increase in the homogeneity (figure 3c). Moreover, in contrast to SEM image (figure 1f), TEM investigation revealed not only considerable microstructure refinement. At higher magnification the microstructure consisted of equiaxed grains/subgrains with a mean size of about 0.4μm. Almost dislocation free grains observed in the microstructure after swaging to $\varepsilon = 2.67$ might suggest development of discontinuous dynamic recrystallization in phases. Processes of recrystallization in elongated α-particles and spheroidization in lamellar $(\alpha+\beta)$ areas resulted in formation of a homogeneous microstructure without noticeable elongation. Those processes were most likely intensified due to changing in deformation path, which is proper to swaging. For example very similar microstructure was obtained via multiaxial forging (MAF) [4, 8]. However heritable preferred orientation of boundaries along the metal flow direction revealed itself as a lamellar microstructure at low magnifications.

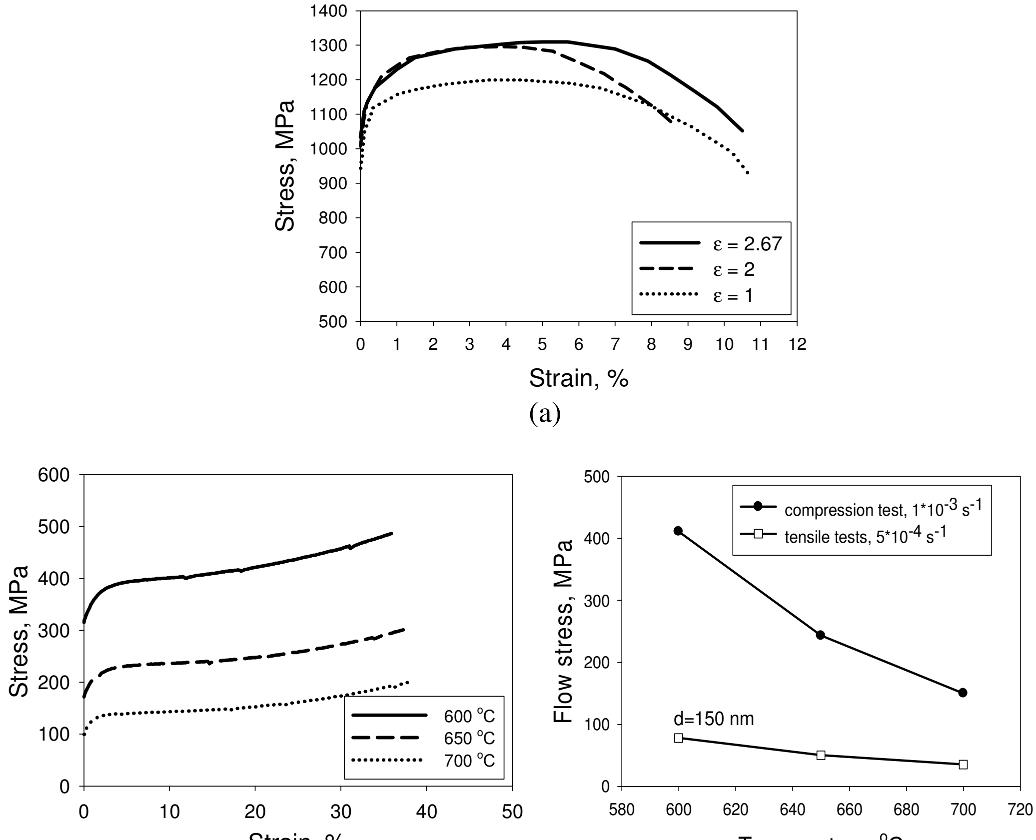


Figure 4. Engineering stress–strain curves of swaged alloy (a) tensile tests at room temperature; (b) and (c) compression test at elevated temperature

The mechanical properties of the alloy after swaging are shown in figure 4a. Tensile tests show very high strength of the alloy (1200 MPa) already after deformation to $\varepsilon = 1$ at 680°C. For comparison this is a maximum value which can be attained in the alloy via strengthening heat treatment (water quenching and ageing). The tensile strength after $\varepsilon = 2$ or $\varepsilon = 2.67$ is 1315MPa in both cases. This is the same value as that obtained in Ti-6Al-4V alloy earlier by warm MAF [4, 8, 9]. Meanwhile some difference in the tensile elongation of specimens swaged to $\varepsilon = 2$ (δ=9%) or ε=2.67 (δ = 10.5%) is observed. This difference may be caused by increase texture intensity in the largely deformed rod (figure 2 b and d) [6]. It should be noted an ability of swaged alloy to strain hardening. .

It is not typical of USG structure produced by severe deformation in which flow instability and early necking is usually observed in the very beginning of strain [2].

Technological properties of the UFG alloy were evaluated by compression tests at elevated temperatures (figure 4b); the aim of this trial was (i) workability of the alloy at relatively low temperatures and (ii) to compare the behavior of the material under conditions which are known to be superplastic for the UFG alloy produced by MAF [10]. Stress-strain curves of the UFG alloy at temperatures 600-700 °C show a typical of superplastic flow steady-state-like stage after 5% strain suggesting very good workability of the material at these temperatures. Figure 4c shows flow stress (was determined at 20% of strain) of the UFG alloy as a function of temperature. However the value of flow stress of the alloy after swaging to total strain $\varepsilon = 2.67$ is considerably higher than that of UFG structure (150 nm), produced by warm MAF [10]. Nevertheless the flow stress of the alloy at 650 and 700°C (250 or 150MPa, respectively) is reasonably low to consider swaging as an effective way of producing UFG preforms with good workability.

4. Summary

Microstructure evolution in Ti-6Al-4V alloy during warm swaging in the interval 680-500 °C with the total strain of $\varepsilon = 2.67$ was study. A homogeneous globular microstructure with a grain size of 0.4μm in both longitudinal and transversal sections forms as a net effect of deformation. This microstructure yields the tensile strength of 1315MPa and the tensile elongation of 10.5%. Ultrafine-grained Ti-6Al-4V alloy produced by swaging exhibited good workability at temperatures 600-700 °C.

Acknowledgements

This work was supported by Russian Foundation for Basic Research (Grant no. 12-08-97544-p_center_a).

References

[1] Valiev R Z, Islamgaliev R K and Alexandrov I V 2000 *Prog. Mat. Sci*. **45** 103–189
[2] Meyers M A, Mishra A and Benson D J 2006 *Prog. Mater. Sci*. **51** 427–556
[3] Donachie M J 1988 *Titanium: A Technical Guide, second ed* (Ohio: ASM International).
[4] Zherebtsov S V, Salishchev G A, Galeyev R M, Valiakhmetov O R, Mironov S Yu and Semiatin S L 2004 *Scripta Materialia* **51** 1147–51
[5] Lim S -J, Choi H -J and Lee C -H 2009 *Journal of Materials Processing Technology*
[6] Zherebtsov S, Mazur A, Salishchev G and Lojkowski W 2008 *Mater. Sci Eng. A* **485** 39-45
[7] Zelin M 2002 *Acta Mater*. **50** 4431–4447
[8] Zherebtsov S, Kudryavtsev E, Kostjuchenko S, Malysheva S and Salishchev G 2012 *Materials Science and Engineering A* **536** 190–196
[9] Zherebtsov S, Kostjuchenko S, Kudryavtsev E, Malysheva S, Murzinova M and Salishchev G 2012 *Materials Science Forum* Vols. **706-709** 1859-63
[10] Salishchev G, Kudrjavtsev E, Zherebtsov S and Semiatin S 2013 *Materials Science Forum* **735** 253-258