Strengthening of Ti-6Al-4V Alloy Forgings

X. K. Meng, Z. G. Liu, Y. G. Zhou, J. M. Liu and Z. Q. Wu

National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210008, P. R. China

A strengthening process for a TC₄ (Ti-6Al-4V) titanium alloy is presented, consisting of "High Temperature Forging+High Temperature Solution Treatment+Conventional Annealing", and the mechanism of strengthening is discussed. Experimental results indicate that this new process can increase the room and high temperature strengths strikingly without reducing the ductility and thermal stability. Based on microstructural analyses, it is concluded that the most effective strengthening for the TC₄ alloy is the "boundary layer" strengthening rather than the more commonly considered dispersion and/or solution strengthening.

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I. Introduction

The conventional hot-working process for a TC₄ titanium alloy is to forge at 30~40°C below the transformation temperature and to anneal subsequently. Under this process the ductility and thermal stability of the alloy are usually quite good. Unfortunately the strength is relatively low and as a result the titanium forgings are often scrapped.

For the above reason, some technical standards for astronautical materials, such as those made in United States, now permit changes of heat treatment to strengthen this alloy. The authors' research⁽¹⁾⁽²⁾, in which the process of strengthening heat treatment for a TC₄ alloy is presented, has verified its feasibility. In recent years, a near- β forging process⁽³⁾ developed in the Chinese titanium industry has made dramatic success in raising hot strength and improving mechanical properties. It may be expected that by combining the near- β forging with the strengthening heat treatment, the strength of the alloy will be raised effectively while maintaining its ductility and thermal stability. With this consideration, the authors have developed the strengthening process "High Temperature Forging+High Temperature Solution Treatment+Conventional Annealing".

II. Experiment Procedure

The material used in this investigation is prepared from a 150 mm diameter rolled bar of a TC₄ titanium alloy, with a β transus (T_0) of 995°C and the chemical composition shown in Table 1.

The rolled bar is cut into samples 50 mm thick. After

covered with FR₅ lubricant, the samples are upset 50% by 3 T die-forging-hammer. The hot-working processes are as follows:

1. Conventional process

The as-rolled samples are forged at 40 and 30°C below T_0 respectively, and air-cooled. Then the as-forged samples are annealed at 800°C for 3 h and air-cooled.

2. Strengthening process

The as-rolled samples are forged at 10 and 5°C below T_0 respectively and cooled in water (High Temperature Forging). A two-step heat treatment is used to strengthen the as-forged samples. At first, they are processed with a solution heat treatment at 30°C below T_0 for 1 h and quenched in water (High Temperature Solution Treatment), then annealed at 800°C for 3 h and air-cooled (Conventional Annealing).

III. Results and Discussion

1. Microstructure and properties

Figure 1 shows the typical microphotographs of a TC₄ alloy after processing via the conventional process. Figure 1(a) was forged at 40°C below T_0 and then air cooled. The content of equiaxed α in Fig. 1(a) is 31%. It is increased to 45% after conventional annealing, as shown in Fig. 1(b). It can be seen that the microstructure after conventional processing produces an equiaxed α structure.

Differing from above, the microstructure after processing via the strengthening process is a bi-modal structure in which equiaxed α is accompanied by α -plate, as shown in Fig. 2, though the contrast of α -plates in Fig. 2(a) is not quite clear. The contents of equiaxed α in Fig. 2(a) and (b) are 12 and 23% respectively.

The mechanical properties under the above processes are tabulated in Table 2.

Table 1 Chemical composition of material (mass%).

Material	Ti	Al	V	Si	Fe	C	H	O	N
TC ₄	bal.	6.16	3.90	0.03	0.09	0.015	0.0046	0.112	0.019

Fig. 1 Microstructure of the TC₄ alloy processed via the conventional process. a-Forging at 40°C below T_0 followed by air cooling. b-a+Annealing at 800°C for 3 h followed by air cooling.

Fig. 2 Microstructure of TC₄ alloy processing via the strengthening process. a-Forging at 5°C below T_0 followed by water cooling. b-a+Processing with solution treatment at 30°C below T_0 for 1 h followed by water cooling and then annealing at 800°C for 3 h followed by air cooling.

Table 2 The mechanical properties of TC₄ alloy under the different hot-working methods.

Hot-working methods	Forging Temperature (°C)	Mechanical properties at room temperature				Mechanical properties at high temperature (400°C)			Thermal stability (400°C–100 h)			
		UTS σ_b (MPa)	YS $\sigma_{0.2}$ (MPa)	Elon. δ_5 (%)	ROA ψ (%)	UTS σ_b (MPa)	Elon. δ (%)	ROA ψ (%)	UTS σ_b (MPa)	YS $\sigma_{0.2}$ (MPa)	Elon. δ_5 (%)	ROA ψ (%)
Conventional process	T_0-40	875	852	15.0	46.7	600	14.8	62.8	887	872	15.2	44.0
	T_0-30	881	874	14.8	45.5	602	14.2	61.0	893	887	14.8	43.5
Strengthening process	T_0-10	965	940	12.0	42.0	680	12.2	60.5	980	954	11.6	36.8
	T_0-5	978	941	12.2	43.0	689	12.7	57.0	984	955	12.0	40.0

2. Forging on microstructure

During the heating process of the forging, the $\alpha \rightarrow \beta$ transformation occurs, so the α phase is transformed into the β phase gradually. The higher the heating temperature becomes, the less equiaxed primary α is retained. Moreover, at a higher temperature, acicular Widmanstätten α in retained β is partially broken into pieces. If the forging is followed by air cooling, the pieces will be trapped by α precipitated from retained β and hence be equiaxed (Fig. 1(a)). On the contrary, when water cooling is subjected to the forging, transformed β will be

transformed into metastable martensite. Therefore, α cannot be precipitated from transformed β and the pieces cannot be equiaxed. On this condition, a bi-modal structure occurs, in which equiaxed primary α and α -piece (Fig. 2(a)) which would grow into α -plate (Fig. 2(b)) during the solution treatment and the annealing process are contained. The large amount of the β phase and the ultra-refinement of the equiaxed primary α (and α -piece), obtained by high temperature forging with quenching in water subsequently, can improve the strength of the two-phase alloy, according to the conclusion made recently by Kawabe and Muneki⁽⁴⁾.

3. Boundary strengthening

It is generally accepted that the mechanism of strengthening for an equiaxed structure obtained with a TC₄ alloy by the conventional process is mainly based on solution and/or dispersion strengthening. Nevertheless, from the strengthening process presented by the authors, it seems that the striking strengthening should be attributed to a "boundary layer" strengthening resulting from a bi-modal structure between equiaxed α and α -plate.

Transformed β , which is defined here as a boundary layer between equiaxed α phases or between equiaxed α and α -plate, consists of acicular Widmanstätten α and retained β . As for the conventional process, a little Widmanstätten α which is not broken and equiaxed grows into long-acicular α and no subgrain β occurs at the boundary.

Figure 3 shows a boundary layer between equiaxed α and an α -plate in the strengthening process sample. Figure 3(a) is in a forged and water cooled state, in which Widmanstätten α is randomly distributed at the boundary and a large amount of subgrain β is formed. Due to

Fig. 3 TEM microphotographs of a boundary layer between equiaxed α and α -plate under the strengthening process. a-Forging at 5°C below T_0 and water cooling. b-a+Solution treating at 30°C below T_0 for 1 h and water cooling+Annealing at 800°C for 3 h and air cooling.

the subsequent processing, with solution heat treatment at higher temperature followed by water cooling, the morphology of subgrain β is almost constant, even after conventional annealing, as shown in Fig. 3(b). It can also be observed that Widmanstätten α in Fig. 3(b) is distributed at the boundary more randomly than that of in Fig. 3(a), and the secondary α precipitates from the boundary layer in the form of particles.

As for strengthening process, forging at a higher temperature near T_0 followed by rapid cooling and solution treatment processing is the main reason why subgrain β could be formed at the boundary layer, and its morphology and structure could be controlled even during conventional annealing process. Therefore, a striking effect of boundary strengthening is obtained. In the meantime, the ductility is not reduced due to the fact that a little equiaxed primary α is reserved. In the first process of heat treatment, i.e., high temperature solution treatment, dislocations in a pile-up slip or climb again and hence the differential energy of distortion between subgrains is reduced. Thus, the tendency for subgrain growth is suppressed. The second process of heat treatment is conventional annealing during which the equiaxed primary α , acicular Widmanstätten α and subgrain β may grow or nodulize. As a result, bi-modal structure, in which transformed β (a boundary layer) segregates α -plate from equiaxed α , is formed completely (Fig. 2(b)) and the effect of boundary strengthening becomes more effective. Furthermore, equiaxed α grains in this structure make the plastic deformation cooperate harmoniously⁽⁵⁾. Hence crack or void initiation or propagation is delayed, even suppressed, and a satisfactory ductility as well as thermal stability is obtained simultaneously.

IV. Summary and Conclusions

This paper shows that the most effective mechanism of strengthening for TC₄ alloy is "boundary layer" strengthening rather than solution and/or dispersion strengthening.

In comparison with the conventional process, the strengthening process raises room-temperature strength up to 978 MPa, high-temperature strength (400°C) up to 689 MPa, while the ductility and thermal stability are not reduced appreciably.

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