Materials and Design 35 (2012) 80–86

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Enhanced the superplasticity in Ti–6.5Al–2Zr–1Mo–1V alloy by a two-step deformation method

Q.J. Sun [a,*], G.C. Wang [b], M.Q. Li [a]

[a] School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, China
[b] School of Aeronautical Manufacturing Engineering, Nanchang HangKong University, Nanchang 330063, China

ARTICLE INFO

Article history:
Received 30 July 2011
Accepted 10 September 2011
Available online 17 September 2011

Keywords:
A. Non-ferrous metals and alloys
F. Plastic behavior
G. Metallography

ABSTRACT

A two-step deformation method was adopted to investigate the superplasticity of Ti–6.5Al–2Zr–1Mo–1V alloy in this work, in which the specified pre-elongation was obtained by the constant velocity in the first step, and then the specimen was deformed to fracture by the maximum *m*-value method in the second step. The superplastic tensile tests were performed on a SANS CMT4104 electronic tensile testing machine at all temperatures ranging from 1123 to 1223 K and pre-elongations ranging from 100% to 200%, and the maximum elongation-to-failure values between 188% and 1456% were obtained. For comparison, the constant velocity and the maximum *m*-value methods were also applied separately at 1173 K in the study. The experimental results indicate that the superplasticity of Ti–6.5Al–2Zr–1Mo–1V alloy has been improved greatly by the two-step method compared with these single-step deformation methods. The ductility of the alloy was increased significantly at a pre-elongation of 150% and deformation temperature of 1173 K, at which the maximum elongation of 1456% was attained in the present work.

1. Introduction

Superplasticity refers to the phenomenon in which the large tensile elongations can be achieved in polycrystalline materials under certain conditions of strain rate, temperature and a suitable microstructure [1]. Due to its low flow stress and the high uniformity of plastic flow, superplastic forming has been developed to simplify the complicated assembly structures, allowing the manufacturing of complex shaped structural component, and it also offers remarkable savings of cost and weight over other conventional manufacturing processes [2]. A number of research efforts have been made to investigate the superplastic deformation process of various titanium alloys during the past several years, especially Ti–6Al–4V alloy. In some reports, theirs microstructures evolution [3,4], superplastic properties [5,6] and superplastic behaviors [7] during superplastic deformation have been investigated. In addition, the ways for enhancing the superplasticity of titanium alloys are also extensively investigated, including severe plastic deformation (SPD) [6,8], thermo-mechanical treatment [9,10], additions of small amounts of hydrogen [11–13] and so on, and the superplasticity was improved significantly by these means.

Ti–6.5Al–2Zr–1Mo–1V alloy, which is a kind of near α titanium alloys, has received much attention in manufacturing large structural components of aircraft due to its low density, moderate strength at room or high temperature, good welding performance and excellent high temperature durability [14]. However, it is difficult to form the complex geometry of large parts under the conventional deformation conditions because of its high resistance of deformation and narrow range of deformation temperature, which limit applications of the alloy in the aerospace industry. Moreover, there are limited studies done on the superplasticity of Ti–6.5Al–2Zr–1Mo–1V alloy in the related reports. Therefore, a better understanding of the superplasticity on the alloy is important for the successful introduction of this material for wider industrial applications. The purpose of the present work is to investigate the superplastic behaviors as well as the related mechanisms of the alloy. Due to belonging to near α titanium alloy, the plasticity of Ti–6.5Al–2Zr–1Mo–1V titanium alloy is relatively inferior to two-phase titanium alloys [15]. Therefore, a two-step deformation method was attempted in the study in order to improve the superplasticity of the alloy. The rationale of this method is that the whole superplastic deformation process has been finished by two deformation steps, and the first step was carried out by the constant velocity method, in which the specimen was elongated to a specified pre-elongation value, then the second step of the process was conducted by the maximum *m*-value method [5,16] until the sample was fractured.

2. Experimental procedures

Ti–6.5Al–2Zr–1Mo–1V alloy used in the work was supplied by Beijing Institute of Aeronautical Materials. The nominal chemical

---

[*] Corresponding author. Tel.: +86 791 3863027; fax: +86 791 3863028.
E-mail address: cruzesun@nchu.edu.cn (Q.J. Sun).

0261-3069/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.matdes.2011.09.025

Table 1
Chemical composition of Ti–6.5Al–2Zr–1Mo–1V alloy.

Element	Al	Mo	V	Zr	Si	Ti
Wt.%	5.5–7.0	0.5–2.0	0.8–2.5	1.5–2.5	0.15	Other

composition of as-received material is given in Table 1. The β-transus temperature is about 1255 K with the quantitative metallography technique. Because the grains size of as-received material is coarse, as shown in Fig. 1a, the thermo-mechanical processing was adopted to refine the grains in order to obtain a fine and equiaxed microstructure, in which the three-dimensional upsetting and cogging was applied to deform Ti–6.5Al–2Zr–1Mo–1V alloy uniformly in three directions, *X*, *Y*, *Z*, reiteratively, and the total amount of deformation was about 50%. The billets of the alloy were forged in $(\alpha + \beta)$ phase field and subsequently cooled to room temperature rapidly by water. The tensile specimens with a gauge length of 15 mm and a diameter of 5 mm [17] were prepared by a spark cutting machine, as shown in Fig. 2. The superplastic tensile tests were carried out in air on a SANS CMT4104 testing machine with a 10 kN load cell at three different temperatures, viz., 1123, 1173 and 1223 K. Before superplastic tensile tests, the gauge segments of all the specimens were coated with a thin special glass layer in order to prevent the specimens from early damage or failure due to oxidation during superplastic deformation at high temperatures in air [17]. In addition, the samples were homogenized for 15 min at the desired temperatures before deformation. After superplastic deformation, the fractured samples were cooled rapidly to room temperature by forced hydrocooling in order to preserve the deformed microstructures. Moreover, after the specified pre-elongations were obtained in the first step, some experiments were terminated to study the microstructure evolution.

To satisfy the two-step method and the maximum *m*-value method, the control software second development was carried out based on the general control software of the machine. The initial and deformed microstructures were observed under an optical microscope to correlate the mechanical properties. The linear intercept procedure was employed for measuring the grain size to study the optical micrograph. The specimens were sectioned from the gauge as well as regions and polished by silica paste. The Kroll's agent (2% HF + 4% HNO_3 + 94% H_2O) was used to etch the specimens for 3–5 s.

3. Results

3.1. Microstructure evolution after thermo-mechanical processing

It is well-known that control of the microstructure in titanium alloys is essential in achieving improved superplastic properties [10]. A fine and equiaxed microstructure is desirable for superplasticity of Ti–6.5Al–2Zr–1Mo–1V alloy, so the alloy has been treated by the thermo-mechanical processing technique. The original microstructure of the as-received alloy is shown in Fig. 1a. From Fig. 1a, it can be seen that in the initial state, the alloy had a microstructure typical for the hot-rolled materials and consisted of near equiaxed primary α-grains, having approximately a 25 μm in diameter on a continuous β-matrix. The volume of fraction of α phase was about 95%. The optical micrograph of as-processed alloy is indicated in Fig. 1b. From Fig. 1b, it can be seen that after the alloy was deformed severely, the coarsened microstructure has been refined significantly, which consists of the refined α-grains and the secondary α-grains precipitated from the β-matrix, and the average grain size is about 10 μm. During the thermo-mechanical processing, the distortion energy for grain refinement has been increased greatly by large deformation and water-quench, which be in favor of grain refinement and spheroidization by dynamic recrystallization.

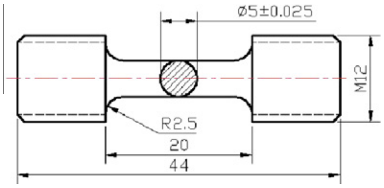

Fig. 2. The tensile specimen of Ti–6.5Al–2Zr–1Mo–1V alloy.

3.2. Effect of the temperature on the superplasticity

Deformation temperature is one of important conditions for the superplasticity. The superplastic tensile tests were conducted at the elevated temperatures from 1123 to 1223 K in the work. The dependence of elongation on temperature for Ti–6.5Al–2Zr–1Mo–1V alloy is shown in Fig. 3. From Fig. 3, it can be seen that Ti–6.5Al–2Zr–1Mo–1V alloy exhibits the better superplasticity at various temperatures by the two-step method. Moreover, at the same pre-elongation, the total elongation increases with increasing of the temperature from 1123 to 1173 K, but at temperatures higher than 1173 K, the elongation gradually decreases with increasing of the temperature. At 1173 K, the ductility of the alloy is in the optimal state, and a maximum elongation of 1456% was obtained when a pre-elongation of 150% was specified in the first step.

Fig. 4 shows the stress–strain curves of Ti–6.5Al–2Zr–1Mo–1V alloy for deformation at three different temperatures. Due to the application of two-step method, the stress–strain curves exhibit two states, which consist of the smooth segments and the undulatory segments, as shown in Fig. 4. The smooth curves were obtained by the constant velocity, whereas the undulatory curves were attained by the maximum *m*-value method. According to the rationale of maximum *m*-value method [5,16], the optimum

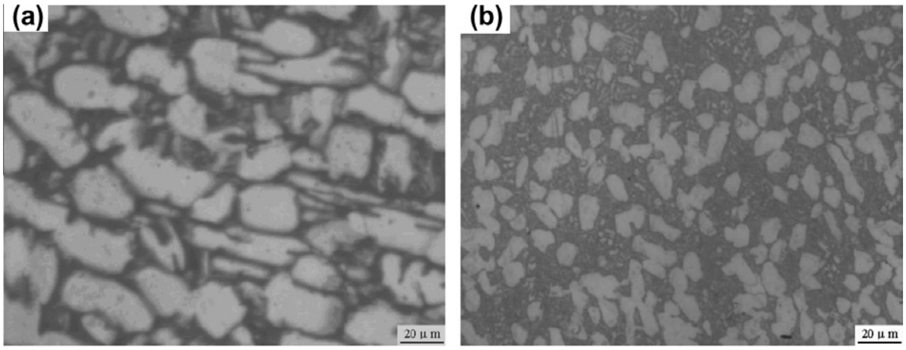

Fig. 1. Micrograph of Ti–6.5Al–2Zr–1Mo–1V alloy: (a) original microstructure (b) treated microstructure.