Materials Characterization 120 (2016) 304–310

Contents lists available at ScienceDirect

Materials Characterization

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

Strengthening effect of *in situ* TiC particles in Ti matrix composite at temperature range for hot working

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A R T I C L E I N F O

Article history:
Received 20 April 2016
Received in revised form 25 August 2016
Accepted 9 September 2016
Available online 10 September 2016

Keywords:
Titanium matrix composite
Strengthening
Hot working
Flow stress
Threshold stress

A B S T R A C T

In this work, hot-working behavior of Ti matrix composite reinforced with TiC particles was investigated by means of hot compression tests and metallographic techniques. The strengthening effect of TiC particles on flow stress was measured. It was found that there is an about 100 K increase in βt of the 5 vol.% *in situ* TiC reinforced Ti-1100 composite compared to that of the monolithic Ti-1100 alloy. The incorporation of TiC particles increased the flow stress significantly. Sharp decreases in flow stress are observed at 10^{-1} s^{-1} or 10^{-2} s^{-1} strain rates and 1373 K or 1423 K during hot compression. An improved model was used to characterize the strengthening effect of ceramic reinforcement in term of threshold stress. The calculated values of deformation activation energy and threshold stress vary with test temperature from 1273 to 1423 K, and the threshold stress of the composite decreases from 70 MPa to 18 MPa. Besides the effect of temperature, the great variation of threshold stress may result from the transformation of αphase to βphase partly.

1. Introduction

Titanium matrix composites (TMCs), Ti reinforced with ceramic particles, have considerable potential application for improving mechanical properties and service temperature. TMCs can be extensively applied in areas such as aerospace, advanced weapon systems and the automotive industry, because of their high specific strength, good specific modulus and resistance to elevated temperatures [1,2]. TMCs can be prepared by the *in situ* technique, which overcomes the shortcomings of traditional techniques, such as the problems of contamination of reinforcements and wettability between ceramic particles and matrix encountered in the casting technique. Therefore the preparation and process of the *in situ* TMCs have been widely studied all over the world in recent years [3–5].

Studies on hot working, superplasticity and mechanical properties of TMCs have been carried out. Strengthening effect of TiC particles in TMCs was reported during the superplasticity deformation [6] and creep process [7,8]. A power-Arrhenius as Eq. (1) has been extensively applied to represent the relationship between the stress and strain rate of the composite [9]:

$$\dot{\varepsilon} = A_1 \cdot \sigma^n \cdot \exp\left(-\frac{Q}{RT}\right) \tag{1}$$

where $\dot{\varepsilon}$, A_1, σ, n, Q, R and T are strain rate, material constant, stress, stress exponent, deformation activation energy, gas constant and absolute temperature, respectively. Wang et al. [10] studied the superplastic deformation of (TiB + TiC)/Ti-1100 composites. Their results show that the calculated activation energies of this material are 641 kJ/mol at 1273 K but only 275 kJ/mol at 1293–1353 K using Eq. (1). It was also reported that significantly higher values of stress exponent and deformation activation energy compared with their matrix alloys resulted from the hindering effect on dislocations movement by ceramic particles [6–8,11–14].

Nardone and Strife introduced threshold stress in the Eq. (1) to study the relationship between flow stress and strain rate of metal matrix composite (MMCs) [15]. Activation energy and stress exponent of MMCs after modification by threshold stress are decreased to a similar value compared to those of their matrix alloys. In this model, the strengthening effects of reinforcements of MMCs can be calculated with the value of the threshold stress. The threshold stress method has been extensively studied for hot deformation or creep deformation of aluminum matrix composites [16–18], but corresponding works on TMCs are very few [19].

In this work, the strengthening effect of 5 vol.% TiC particles in TMCs was investigated in the temperature range for hot working, and it was discussed and evaluated in terms of flow stress and threshold stress.

2. Experimental Procedure

The material used in this experiment was monolithic Ti-1100 alloy and Ti-1100 alloy reinforced with TiC (5 vol.%) ceramic particle. The

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http://dx.doi.org/10.1016/j.matchar.2016.09.010
1044-5803/

matrix of the composite was Ti-1100, and the nominal composition was Ti–6Al–2.7Sn–4Zr–0.4Mo–0.45Si. The composite and monolithic matrix alloy were prepared in a vacuum arc remelting furnace (VAR) and TiC was formed utilizing the reaction between Ti and C element ($Ti + C \rightarrow TiC$). In order to ensure the chemical homogeneity of the composite, the ingots were melted three times. After casting, homogenization annealing was performed at 1423 K for 1.5 h and cooled by air. Hot working of Ti alloys is usually performed in a temperature range near the $(\alpha + \beta)/\beta$ transform temperature for near α Ti alloys or TMCs with near α alloy matrixes (*i.e.* β transus or βt), whether in the $(\alpha + \beta)$ phase field named the conventional hot working or in the β field named β hot working. It is necessary to measure the β transus temperature of the composite at first for the hot working study.

Hot compression specimens were cut from the ingots after breakdown. The hot compression specimens were a column 8 mm in diameter and 12 mm in length. Hot compression tests were conducted using a Gleeble-1500D thermo-simulation test machine. The specimens after compression were quenched into water. No crack was found on the specimens' surface by eyes after compression.

Samples for optical microscopy (OM) were cut from the specimens after compression. Then the samples were prepared using conventional techniques of grinding and mechanical polishing. The samples were etched in Kroll's reagent (composition: 1–3 ml HF, 2–6 ml HNO_3, 100 ml water). A LECO 2000 image analyzer was used to characterize the microstructures of the samples. Thin foils for transmission electron microscopy were prepared by twin-jet electro-polishing technique using an electrolyte composed of 10 pct $HClO_4$ and 90 pct CH_3COOH at temperature 283–303 K and a potential of 30–50 V. The foils were examined using a JEM-2010 electron microscope operating at 200 kV.

3. Results and Discussions

3.1. Morphology and the Temperature Range for Hot Working

Morphology of the composite is presented in Fig. 1. Shape of TiC reinforcement prepared with *in situ* technology used in this work is particle, and TiC particles are distributed uniformly in the matrix with a diameter about 5 um to 20 um.

Metallographic techniques were used to measure the β transus temperature of the composite, and the results are presented in Fig. 2. The critical temperature at which primary α phase disappearing in the microstructure after quenching from increased temperature is identified as the β transus temperature of the composite in this method. Based on Fig. 2, the β transus temperature of the present composite can be identified as 1398 K. There is an about 100 K increase in βt compared to Ti-1100.

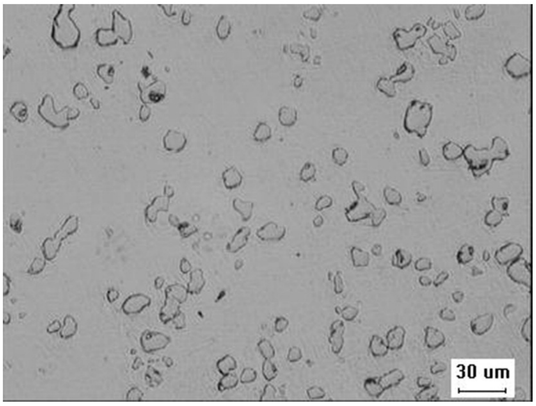

Fig. 1. Optical micrographs of the *in situ* TiC reinforced composite (unetched).

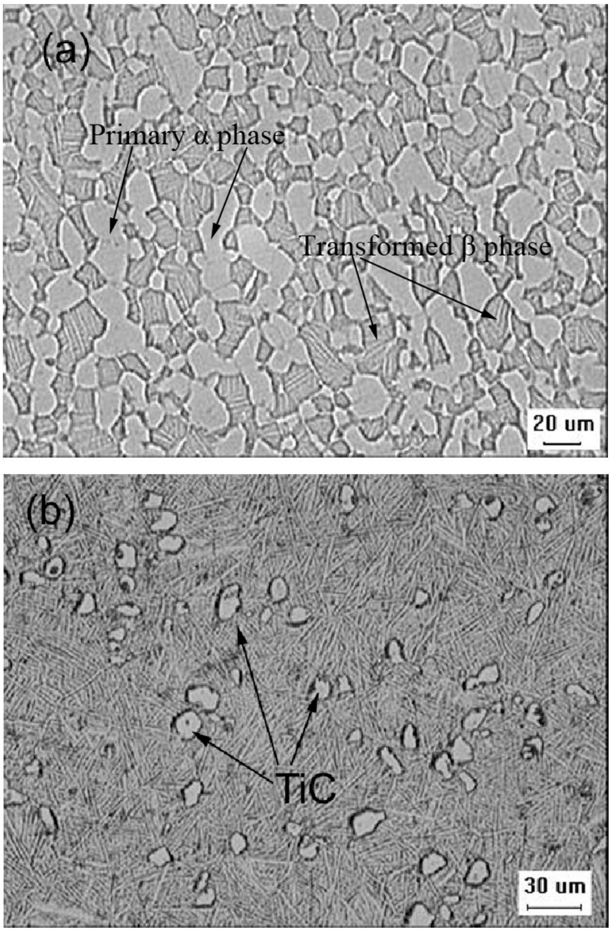

Fig. 2. Optical micrographs of the *in situ* TiC reinforced after quenched from (a) 1393 K, primary alpha phase and transformed beta phase, (b) 1403 K, transformed beta phase totally.

Ti-Al-C ternary phase diagram is used to interpret the obtained results. C element added in present work is one of α phase stabilizers for Ti alloys, and C element will increase the β transus temperature of the matrix alloy. The present matrix alloys also contain other α stabilizers, such as: Al, Sn, Zr, and O, the effect of these elements can be represented with Al equivalent content. According to Rosenberg [20], the equivalent of Al content can be expressed as $[Al]eq = [Al] + [sn] / 3 + [Zr] / 6 + 10[O]$. The O concentration of specimens in experiment was measured, and it ranged from 0.04% to 0.08%. [Al]eq of the present composite falls in the range 8.0–8.7. Thus the Ti-8Al-C phase system can be used to discuss the β transus temperature of the composite under study. A vertical section of the Ti-8Al-C phase diagram is presented in Fig. 3 [21], and the measured β transus temperature and corresponding composition of the composite is shown in Fig. 3, as marked with a sign of A. According to this vertical section, carbon solutes in the matrix and increases the β transus temperature rapidly when the carbon concentration in matrix alloy is below 0.28 wt.%. The β transus temperature of the composite measured in this work is slightly lower than that predicted with the Ti-8Al-C ternary phase diagram, which can be attributed to Mo and Si elements which are β stabilizers in the matrix.

The effect of the incorporation of TiC particles on the volume fraction of α phase in Ti-1100 alloy or in the 5 vol.% TiC/Ti-1100 composite at various temperatures for hot working was also measured accordingly, and the results are presented in Fig. 4. From Fig. 4, it can be seen that the solid solute carbon element in the matrix of the composite significantly increase the volume fraction of α phase in the composite compared with the monolithic Ti-1100 matrix.