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A research on the creep properties of titanium matrix composites rolled with different deformation degrees

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ABSTRACT

(TiB + La_2O_3)/Ti composites were *in situ* synthesized and deformed with different deformation degrees. The influence of TiB whisker orientation and grain refinement on the creep properties of titanium matrix composites (TMCs) are discussed. The creep test reveals that the steady state creep rate of TMCs first decreases and then increases with the increase of deformation degree, which can be attributed to competing effects: TiB whisker rotating to the rolling direction, α plate grain boundary hindering and pinning dislocations can all decrease the creep rate, however, dislocation movement on the α plate grain boundary and dislocation emitting from the α plate grain boundary can both increase the creep rate.

1. Introduction

It is often stated that the creep properties of particle or whisker reinforced metal matrix composites (MMCs) are mostly influenced by two elements: firstly, the parameters of the reinforcement including the volume fraction, aspect ratio and shape; and secondly, the matrix microstructure. The former element plays the main role for MMCs, and a threshold stress σ_{th} [1–4] is generally employed to explain the higher activation energy and higher stress exponent in the MMCs, which represents the interactions between dislocation and the reinforcement. Besides the threshold stress effect, reinforcements can also bear the strength that transfers from the matrix and a stress transfer coefficient β can be introduced to express this effect [5–7]. By considering both of the threshold stress effect and stress transfer effect, the constitutive equation for steady state creep of the MMCs can be written as [6]:

$$\dot{\varepsilon}_c = A\frac{G}{RT}(1-\beta)^n\left(\frac{\sigma-\sigma_{th}}{G}\right)^n \exp\left(-\frac{Q}{RT}\right) \tag{1}$$

where $\dot{\varepsilon}_c$ is the steady state creep rate of the MMCs, A is a constant, G is the shear modulus, R is the gas constant, T is the Kelvin temperature, β is the stress transfer coefficient, σ is the applied stress, σ_{th} is the threshold stress and Q is the activation energy.

In the above referred publications [1–7], the effects of reinforcement on the creep properties of the MMCs have been carefully examined, however, the matrix of MMCs, which also influences the creep properties a lot, receives little attention. Prior studies [8,9] indicate that with the decrease of the grain size, the high temperature creep rate of alloys increases, and the relationship between the steady state creep rate $\dot{\varepsilon}_c$ and grain size can be generally described as:

$$\dot{\varepsilon}_c \propto \left(\frac{b}{d}\right)^p \tag{2}$$

where b is the burgers vector, d is the grain size, and p is the grain size effect exponent. For titanium matrix composites or titanium alloys with a fully lamellar structure, few studies have revealed the influence of grain refinement on the creep properties of titanium matrix composites. It is also necessary to notice that in the prior published papers [6,10–14], the short fiber reinforcements are often assumed to be perfectly parallel to the tensile direction, and the influence of reinforcement orientation on the mechanical properties is neglected. However, this is not true in practice. So in this paper, the creep properties of the *in situ* synthesized titanium matrix composites (TMCs) with different deformations are examined, and we try to figure out the influences of TiB whisker orientation and grain refinement effects on the creep properties.

2. Experimental details

In this study, TMCs were *in situ* synthesized by consumable vacuum arc-remelting. The raw material for synthesizing the TMCs were LaB_6 powder, grade I sponge titanium and alloying elements,

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such as TiSn (65% Sn), AlNb (50% Nb), AlMo (50% Mo), Al, Zr, and Si. Stoichiometric amounts of sponge titanium, alloying elements, and LaB_6 were blended and melted in a consumable vacuum arc-remelting furnace, as Fig. 1 shows. The chemical composition of the matrix was similar to IMI 834. The following chemical reaction took place in the melt: $2LaB_6 + 12Ti + 3[O] = 12TiB + La_2O_3$ [15,16]. The volume fractions of TiB whiskers and La_2O_3 particles were designed as1.82% and 0.58% respectively. The $\alpha + \beta \rightarrow \beta$ transus temperature was 1313 K. The received specimens were rolled with deformation degrees of 60%, 80%, 90% and 95% at 1283 K, and then air cooled. The rolled specimens were annealed at 1318 K for 0.5 h and then air cooled. After that, the specimens were aged at 923 K for 1 h and air cooled. OM was used to study the matrix microstructure and reinforcement of the TMCs. The specimens for creep test were machined from the heat treated plates with the specimen axis paralleling to the rolling direction. The gauge sections of the creep specimens were 25 mm × 6 mm × 2 mm. The creep tests were carried out on CSS-3905 testing machine at 923 K at stresses of 150 MPa and 300 MPa. For TMCs with different deformation degrees, one specimen was used to perform the creep test. For each specimen, two sets of creep strain–time data were obtained after the test and the average value was used to draw the creep curve. TEM was used to study the matrix microstructure of TMCs after creep test.

3. Results and discussion

3.1. Microstructure and creep properties

Fig. 2 shows the microstructures of the TMCs deformed with different deformation degrees. It can be easily distinguished that with the increase of deformation degrees, microstructure refinement happens and α colony size/α plate thickness decreases. The microstructure refinement can be attributed to the rolling and heat treatment process, which has been discussed in detail in our prior publication [15]. TiB whiskers, as Fig. 2 shows, rotate to the rolling direction with the increase of deformation degree. It can be found that for the 60% deformed TMCs, the axial of most TiB whiskers is not consistent with the rolling direction, however, when deformation degree increases to 95%, almost all the TiB whiskers are parallel to the rolling direction perfectly. Besides TiB whiskers, La_2O_3 particles also exist in TMCs, however, La_2O_3 particles are roughly circular in shape and nano-scaled in size [17,18], which show no preferred orientation when the TMCs are rolled with different deformation degrees [15]. So in the present research, the influence of La_2O_3 particles on the creep properties does not change with the increase of deformation degree therefore are not discussed.

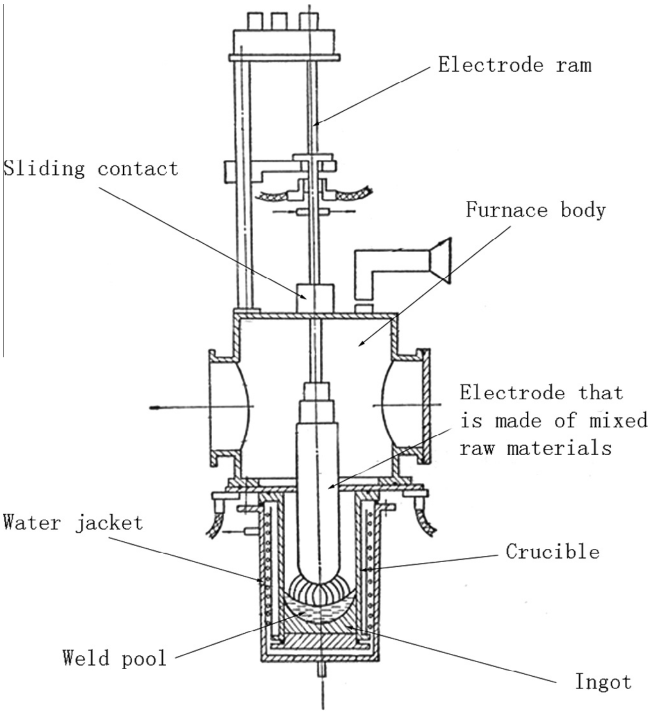

Fig. 1. Schematic diagram of consumable vacuum arc-melting.

The creep curves of the TMCs are shown in Fig. 3(a) and (c). The TMCs show typical creep curves of Class-M solution alloy: primary creep where creep rate decreases with the time, steady state creep with constant creep rate and accelerating creep (or tertiary creep) before creep rupture. At 150 MPa, the steady state creep lasted very long and the creep tests were terminated when the steady state creep rate was obtained. At 300 MPa, the steady state creep lasted relatively short and the accelerating creep took the most proportion of the creep time. Fig. 3(b) and (d) shows logarithmic steady state creep rates for the TMCs with different deformation degrees. It can be found that regardless of the stress, the steady state creep rate of TMCs firstly decreases and then increases with the increase of the deformation degree, which indicates that the creep resistance of TMCs firstly improves then degrades with the increase of deformation degrees. The matrix alloy, whose composition is the same as the matrix of the TMCs, also shows typical creep curve of Class-M solution alloy [6]. The steady state creep rate of the matrix alloy at 150 MPa and 923 K is $7.03038 \times 10^{-8}\ S^{-}$ $\{\log(7.03038 \times 10^{-8}) = -7.1530\}$, which is much higher than that of titanium matrix composites. This indicates that the TMCs own better creep resistance properties, which can be attributed to the threshold stress relating to the reinforcements and the stress transfer effect of whiskers [6,19,20].

The microstructure analysis reveals that with the increase of deformation degrees, TiB whiskers rotate to the rolling direction and the matrix microstructure refinement happens. Then next, we try to explain the influence of reinforcement rotation and matrix microstructure refinement on the creep behavior of TMCs.

3.2. Stress transfer effects of TiB whiskers

Previous studies [21,22] indicate that the stress transfer coefficient of reinforcement, β, can be expressed as:

$$\beta = \frac{\sigma_f v_f}{\sigma_0} = \frac{\sigma_f v_f}{\sigma_f v_f + \sigma_m(1 - v_f)} \tag{3}$$

where σ_f is the average stress transferred from the matrix to the whiskers, v_f is the volume fraction of the whiskers, σ_0 is the stress of the MMCs and σ_m is the stress of the matrix. It is necessary to notice that in the above equation that the longitudinal direction of the whisker is considered to be perfectly parallel to the tensile direction, however, in the present research, the orientation of TiB whisker depends on the deformation degree, and with the increase of deformation degree, more and more TiB whiskers rotate to the rolling direction, as Fig. 2 shows. In our prior publication [15], a whisker orientation parameter, C_0, was introduced to express the influence of the orientation of TiB whiskers on the strength of misaligned whisker reinforced titanium matrix composites. In the present study, C_0 can also be employed to show the influence of the orientation of TiB whiskers on the stress transfer effect and β can be rewritten as:

$$\beta = \frac{\sigma_f v_f}{\sigma_0} = \frac{\sigma_f v_f C_0}{\sigma_f v_f C_0 + \sigma_m(1 - v_f)} \tag{4}$$