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Hot deformation and processing maps of titanium matrix composite

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Abstract: The hot deformation characteristics of TiC particles reinforced titanium matrix composite were studied in the temperature range from 900 ℃ to 1 150 ℃ and in the strain rate range of 10^{-3}−10 s^{-1} by compression tests with Gleeble1500 simulator system. The flow behavior was described by the hyperbolic sine constitutive equation, and an average activation energy of 436.72 kJ/mol was calculated. The processing maps were calculated and analyzed according to the dynamic materials model. The maps show domains in some combinations of temperatures and strain rates and these domains are correlated with specific microstructural processes occurring during hot deformation by metallographic investigations and kinetic analysis. At the low strain rate domain occurs in the temperature range of 900−960 ℃ and strain rate range of 0.001−0.03 s^{-1} superplasticity and dynamic recrystallization were observed. At a high strain rate domain occurs in the temperature range of 980−1 120 ℃ and strain rate range of 0.1−10 s^{-1} the β phase undergoes dynamic recrystallization. Also, at a strain rate range of 0.1−10 s^{-1} and the temperature range of 900−930 ℃, the material exhibits flow localization.

Key words: titanium matrix composite; hot deformation; processing map

1 Introduction

Because of their high specific strength, high specific modulus, high elevated temperature property wear resistance and low fabricating cost, titanium matrix composite are used very popular for structural applications at high temperature. ZHANG et al[1] studied the strengthening mechanism of titanium matrix composite. MAO et al[2] described the characteristic of principle properties and microstructure of titanium matrix composite. But the report on hot deformation of titanium matrix composite based on processing maps is scarce. It is well known that the thermomechanical processing conditions can be optimized to control the microstructure mechanical property characteristics. However, considering the restrictive workability limit(or processing) of titanium matrix composite, an increasing understanding of the relationship between processing and microstructure is particularly critical for sustaining further improvements in performance and reliability.

The aim of the present investigation is to evaluate the mechanisms of hot deformation in these titanium-matrix composite over wide ranges of temperature and strain rate. Such a study would be beneficial not only for designing hot working processes but also for controlling microstructure in the composite during processing. For this purpose, three approaches have been adopted: analysis of the stress-strain behavior, determination of kinetic parameters, and development of processing maps. The correlation of microstructure with the processing parameters has been attempted.

2 Experimental

The experimental material was the TiC particles reinforced titanium matrix composite which was prepared by NIN(Northwest Institute of Nonferrous Metals)using pre-treatment melt process. The composite was double melted by vacuum arc remelting(VAR), cast into ingot 150 mm in diameter, and forged into rods with 20 mm in diameter, then hot rolled into rods with 13 mm in diameter.

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Hot compressive deformation behavior of TiC particles reinforced titanium matrix composite at elevated temperatures was studied on Gleeble 1500 thermal simulator using cylindrical specimens (8 mm in diameter and 12 mm in height). The specimens were directly electrified to heat and the temperature was controlled with a thermocouple spot welded on the specimen surface. In the present investigation, the compressive tests were performed at deformation temperatures ranging from 900 to 1 150 ℃ and at strain rates from 10^{-3} s^{-1} to 10 s^{-1}. The specimens were held for 5 min at the deformation temperature before the commencement of deformation to ensure homogeneous temperature fields. After completion of the required deformation, the specimens was quenched by water quickly to retain the deformed microstructures for microstructural investigation. The compressibility was 65%. In order to reduce frictions, two ends of specimen and the indenter of Gleeble 1500 thermal simulator were coated with graphite lubricant. The microstructure of TiC particles reinforced titanium matrix composite was observed and analyzed using Olympus optical microscope.

3 Results and discussion

3.1 Stress-strain behavior

The shapes of the flow curves exhibited by the material at different temperatures and strain rates of testing can be classified into three categories, and curves representative of these features are shown in Fig.1.

1) In the $\alpha+\beta$ temperature range, continuous flow softening after a peak stress was observed (Fig.1(a)) at strain rates higher than 0.01 s^{-1}, which is resulted from dynamic recovery and recrystallization.

2) In the β temperature range (Fig.1(b)), at strain rate of 10 s^{-1}, a rapid drop in the flow stress with strain or continuous oscillations/hardening were recorded. These observation results indicate the possibility of continuous recrystallization, localized or unstable plastic flow of material.

3) At strain rate of 0.001 s^{-1} and all temperature of testing, the stress-strain curves are flat and tend to reach steady state, which are indicative of steady state flow behavior.

3.2 Processing map

The theories about processing maps have been reported in many papers[3−5]. Briefly, the maps are developed using principles of the dynamic materials model, which considers the work piece undergoes hot deformation essentially as a dissipator of power. Power dissipation occurs at any instant of deformation by two complement any means: most of it through a temperature

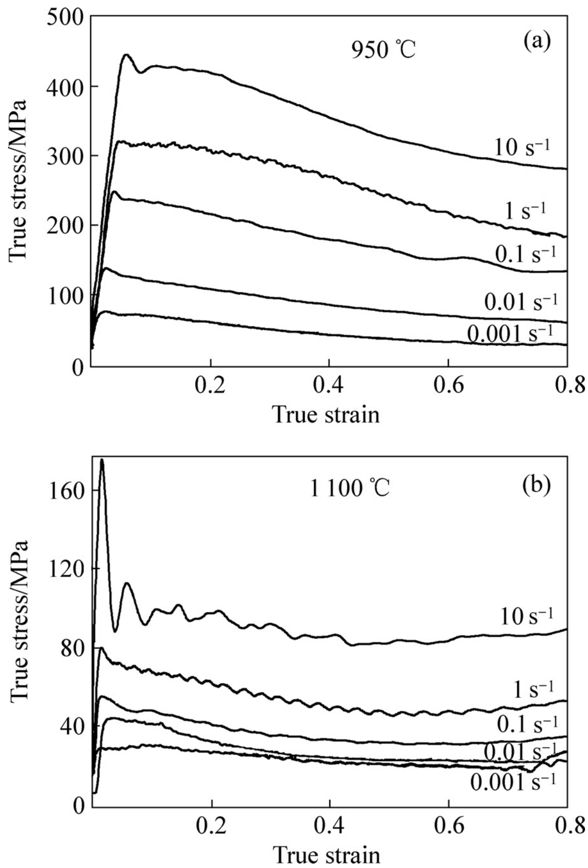

Fig.1 Flow curves of TiC particles reinforced titanium matrix composite at different strain rates in α-β phase field(950 ℃) (a) and β phase field(1 100 ℃) (b)

rise and a smaller part though a microstructural change. The efficiency of power dissipation η of a work piece can be obtained by comparing its power dissipation through a microstructural change with that occurring in an ideal linear dissipator, and is given by

$$\eta=2m/(m+1) \quad (1)$$

where m is the strain rate sensitivity of flow stress. The processing map exhibits domains in which the efficiency shows local maxima and where specific microstructure mechanisms operate. Furthermore, using the principle of maximum rate of entropy production[6], a condition for the microstructural instability may be obtained[7]:

$$\xi(\dot{\varepsilon})=\partial \ln\left[m/(m+1)\right]/\partial \ln \dot{\varepsilon}+m<0 \quad (2)$$

The variation of $\xi(\dot{\varepsilon})$ with temperature and strain rate constitutes an instability map in which regimes with negative values of the instability parameter represent microstructural instabilities. The instability map may be superimposed on the power dissipation map to obtain a processing map, which gives not only domains representing specific microstructural mechanisms but also regimes where microstructural instabilities occur.

The technique of processing maps has been applied with consistency to characterize the hot deformation behavior of a large number of materials and to solve processing problems[8]. The steps involved in generating the processing map from the data of flow stress as a function of temperature, strain rate, and strain are described elsewhere[8] and involve computer programs developed for this purpose.

The processing map obtained for TiC particles reinforced titanium matrix composite at a strain of 0.6 is shown in Fig.2, in which contour numbers represent percent power dissipation and shade area correspond to the instability regime, which reveals two domains where the efficiency of power dissipation reaches a local maximum, and a instability regime. It may be noted that the domain closes at temperatures beyond the β transus(about 1 020 ℃) and below the transus in accordance with the so-called β approach curve[9]. The characteristics of these domains are described below.

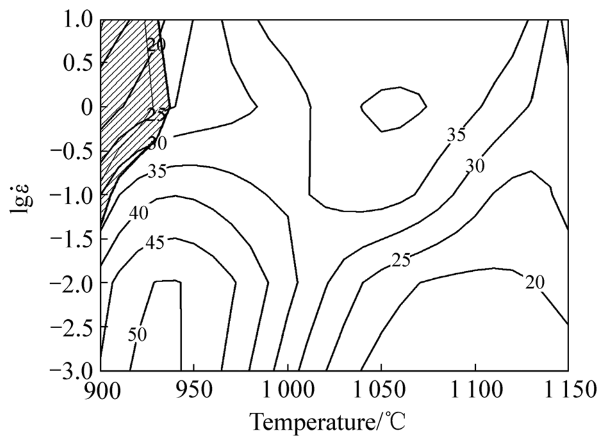

Fig.2 Processing map of TiC particles reinforced titanium matrix composite at a strain of 0.6(Contour numbers represent percent efficiency of power dissipation. Shaded region corresponds to flow instability)

The low strain rate domain occurs in the temperature range of 900−960 ℃ and strain rate range of 0.001−0.03 s^{-1}, and has a peak efficiency of about 50% at 925 ℃ and 0.001 s^{-1}. The high strain rate domain occurs in the temperature range of 980−1 120 ℃ and strain rate range of 0.1−10 s^{-1}, and has a peak efficiency of about 38% at 1 050 ℃ and 1 s^{-1}.

The instability regime occurs in the temperature range 900−930 ℃ and strain rate range of 0.1−10 s^{-1}.

The mechanisms occurring within the above domains are identified on the basis of microstructural features recorded on the deformed specimens, the shapes of stress-strain curves and kinetic analysis, as discussed in detail below. As compared, microstructures of starting material and specimens deformed in the low strain rate domain are shown in Figs.3(a)−(c).

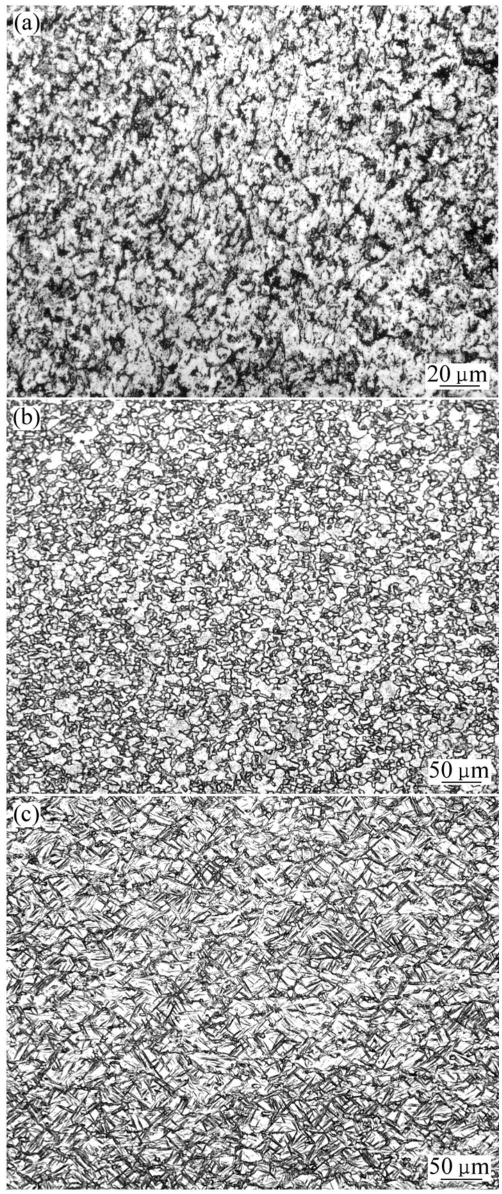

Fig.3 Microstructures of TiC particles reinforced titanium matrix composite: Original material(a), and specimens deformed at 950 ℃, 0.001 s^{-1}(b) and 950 ℃, 0.01 s^{-1}(c)

The original structure (Fig.3(a)) shows elongated α phases grains and a small amount of β phases. In Fig.3(b), the microstructure shows complete equiaxed grain, which is similar to the superplastic structure. As seen in Fig.2, the efficiency of power dissipation increases with the decrease of the strain rate in this domain, which is related with superplasticity. The stress-strain curve of 950 ℃ and 0.001 s^{-1} is also shown in Fig.1(a) and it is steady state flow behavior, suggesting that the deformation mechanism is not dynamic recrystallization. So the complete equiaxed grain may be resulted from grain boundary movement of superplasticity. The microstructure has significantly coarsening characteristic with the strain rate increases as seen in Fig.3(c), it is the typical dynamic recrystallization structure. With a view to identify the deformation mechanism from the kinetic aspect, activation analysis is conducted using the kinetic rate equation which relates the stead state flow stress(σ) to temperature (T) and strain rate ($\dot{\varepsilon}$)by follows [10],

$$\dot{\varepsilon} = A\sinh(\alpha\sigma)^n \exp[-Q/(RT)] \tag{3}$$

where A and α are constants independent of temperature and stress, Q is the activation energy, R is the ideal gas constant, T is deformation temperature, and n is stress exponent.

The variation of flow stress with strain rate at different temperatures is shown in Fig.4(a). Arrhenius plot showing the variation of flow stress with inverse of temperature on a semi-log scale is given in Fig.4(b), from which the deformation activation energy of 799 kJ/mol in the α-β phase field and 105 kJ/mol in the β phase field is estimated.

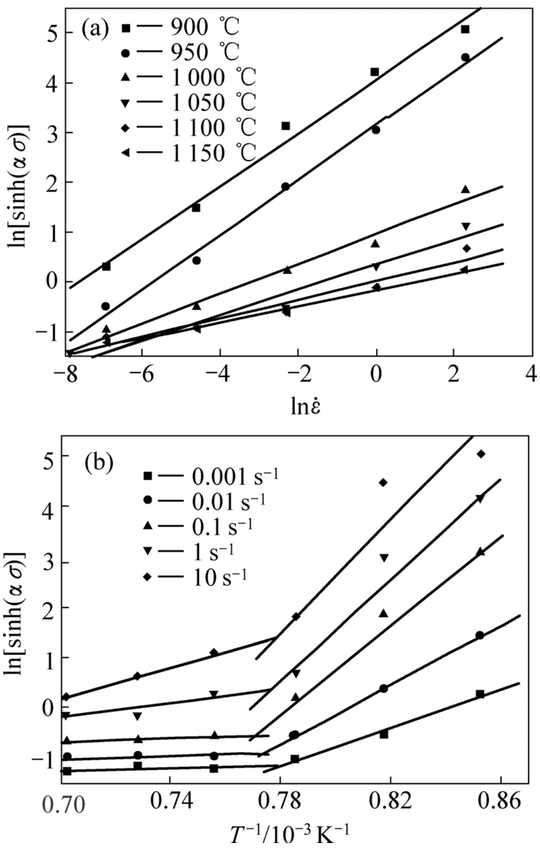

Fig.4 Plot of stress vs strain rate(a) and stress vs. inverse of temperature(b) of TiC particles reinforced titanium matrix composite

It may be noted that α-Ti, the activation energy for lattice diffusion is 150 kJ/mol[11]. The abnormally high Q value in the α-β phase field is most probably due to dynamic recrystallization in the TiC particles reinforced titanium matrix composite and the effect of TiC particles on dislocation movement.

The microstructure of specimens deformed at 1 050 ℃ and strain rate of 1 and 10 s^{-1} in the high strain rate domain are shown in Figs.5(a) and (b). A closer examination of the microstructure reveals that the grain is equiaxed and the grain boundary are curved. These evidences indicate that the material undergoes dynamic recrystallization, and the recrystallization grain size is refined with increasing strain rate, as shown in Fig.5(b) .The presently estimated activation energy in β field (105 kJ/mol) is close to that reported[8] for self-diffusion energy in pure β Ti(153 kJ/mol) suggesting that the dynamic recrystallization process in β phase is controlled by diffusion.

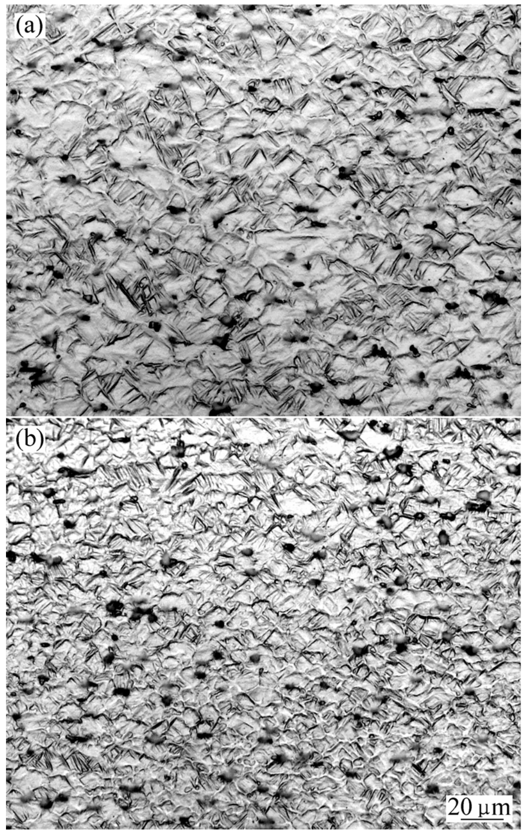

Fig.5 Microstructures of TiC particles reinforced titanium matrix composite specimens deformed at 1 050 ℃(a), 1 s^{-1} and 1 050 ℃, 10 s^{-1}(b)

The instability regime is shown as shade area in Fig.2. The prediction are validated with the microstructural observation made on the deformed specimens. Micrograph of the specimen deformed at 900 ℃ and 0.001 s^{-1} in this regime is shown in Fig.6, which exhibit flow localization band. The formation of localization band may be attributed to the adiabatic conditions created during deformation and the heat generated during deformation is not conducted away due to insufficient time, which reduces the flow stress locally and cause flow localization.

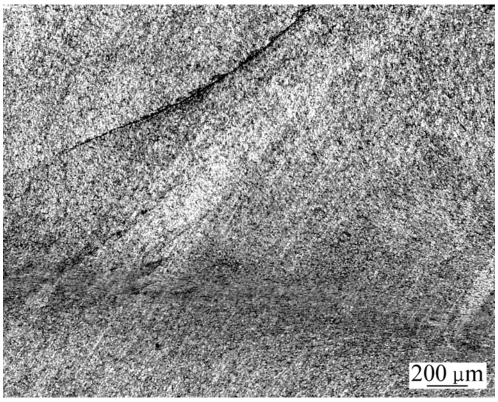

Fig.6 Microstructure of specimen deformed at 900 ℃ and 10 s^{-1} exhibiting flow localization band(Compression axis is vertical)

4 Conclusions

1) In the α+β temperature range, the curves exhibits continuous flow softening after a peak stress at strain rates higher than 0.01 s^{-1}, which results from dynamic recovery and recrystallization; In the β temperature range, at strain rate of 10 s^{-1}, the flow stress shows a rapid drop with strain or continuous oscillations/hardening, which result from flow localized.

2) The material exhibits superplasticity and dynamic recrystallization at the low strain rate domain occurs in the temperature range of 900−960 ℃ and strain rate range of 0.001−0.03 s^{-1}; The β phase undergoes dynamic recrystallization at the high strain rate domain occurs in the temperature range of 980−1 120 ℃ and strain rate range of 0.1−10 s^{-1}, and the dynamic recrystallization process in β phase is diffusion controlled.

3) The material exhibits flow localization band in the instability regime which occurs in the temperature range of 900−930 ℃ and strain rate range 0.1−10 s^{-1}.

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