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A modified Johnson–Cook model for titanium matrix composites reinforced with titanium carbide particles at elevated temperatures

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ABSTRACT

The dynamic properties of TiC particulate-reinforced titanium matrix composites (TiCp/Ti) prepared by pre-treatment melt process at elevated temperatures were characterized and tested by using split Hopkinson tensile bar (SHTB). The tensile properties of these materials were investigated to determine all the parameters of the Johnson–Cook constitutive mode. By considering the strain hardening and the coupled effects of temperature and strain rate, a modified Johnson–Cook constitutive model was proposed to predict the dynamic behavior of TiCp/Ti. The model predictions are in good agreement with the experimental results, which indicates that the modified model can be used to describe the flow stress for the studied composite at elevated temperatures.

1. Introduction

Metal matrix composites (MMCs) have received significant attention because of their potential improvements in mechanical properties such as modulus and strength [1]. As one class of metal matrix composites, titanium matrix composites (TMCs) are particularly attractive in the aerospace, automotive and gas-turbine industries because of their high specific moduli, high specific strength and good high-temperature properties [1–3]. Titanium matrix composites can be divided into fiber-reinforced titanium matrix composites and particulate-reinforced titanium matrix composites. During the past several decades, many research efforts have been directed toward continuous fiber-reinforced TMCs [4–5]. Due to the anisotropic behaviors and high cost for fabrication of these fiber-reinforced TMCs, more and more concerns are focused on ceramic particulate-reinforced titanium matrix composites (PTMCs) in recent years because of their isotropic characteristics and easy fabrication by using conventional technologies [6–12]. In order to obtain the best combination of properties at a low cost, the selection of the particle type, size and volume fraction is important for materials scientists and engineers. Several ceramic particles were proposed as titanium reinforcement: SiC, B_4C, TiAl. TiB_2, TiN, TiC and TiB. Extensive theoretical and experimental studies have been carried out on the fundamental relationships between the mechanical properties and the microstructure of PTMCs with different types of matrix and particles as the reinforcement [8,13]. It is found that carbide titanium (TiC) is excellent choices because of its compatibility with titanium matrix. With the addition of TiC particles, the resulting composite shows improved modulus, strength, and high-temperature stability through controlled creation of internal defects and boundaries that obstruct dislocation motion [1]. There are several processing technologies adopted in industrial production for producing carbide titanium reinforced titanium matrix composites (TiCp/Ti composites), such as cold and hot isostatic pressing (CHIP), solidification processing, exothermic processing, and so on [7]. However, the elongation of these composites produced by some of these methods is sort of low at room temperature, which significantly limits the application of TiCp/Ti composites as engineering materials. The motivation to improve the ductility of TiCp/Ti composites leads to the development of new processing technologies. Pre-treatment melt process (PTMP) is one of the technologies, which includes three stages: firstly, the titanium alloy and reinforcement are mixed intensively; secondly, the mixture was pre-sintered and pressed with titanium sponge to create consumable electrode; finally, arc melting was adopted to prepare titanium matrix composites. Although there are some great developments in the processing and manufacturing technology of TiCp/Ti composites [14–16], there is a lack of systematic understanding of the high-strain-rate and high-temperature response of

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these composites, which is essential for the design and application of TiCp/Ti composites subjected to high-temperature and high-strain-rate environment, especially in the aerospace industries.

It is well recognized that most materials exhibit different behavior at different strain rates and temperatures, so it is necessary to know the mechanical response of the materials involved in some structural components over a wide range of temperatures and the strain rates [17,18]. Generally, plastic deformation under quasi-static loading conditions can be treated as an isothermal process, while deformation at high strain rate can be considered as an adiabatic process. In the adiabatic process, since some of the heat produced by the plastic deformation cannot conduct and radiate in a very short time, elevated temperature arises naturally through the adiabatic heating. Obviously, the influences of strain rate, temperature, strain and adiabatic temperature rise on the plastic deformation of the metals are coupled during the high rate deformation. Therefore, understanding the coupling effect of strain rate, temperature and adiabatic temperature rise on the dynamic plastic behavior of materials at elevated temperatures is of fundamental importance for predicting their plastic deformation behavior.

Over the past decades, attempts have been devoted to determine the material's characteristics in the form of constitutive equations known as material models. Generally, two kinds of constitutive models are adopted to predict the dynamic mechanical properties of the materials at elevated temperatures [18–20]. One is empirical and semi-empirical based model and the other is phenomenological and physically based constitutive model. The key issue of all the constitutive models is to determine the related material constants and properties from precisely controlled experiments. Comparing with the phenomenological and physically based constitutive model, empirical and semi-empirical based model has less material constants identified by using limited experiments. Johnson–Cook (J–C) model with five parameters, one of the empirical based models, is widely used to predict the mechanical behavior of materials at high temperature and high strain rate by considering strain rate hardening and thermal softening simultaneously [21]. The models are essential requirements in numerical simulation of materials behavior especially at high strain rates and elevated temperatures. The models involve five material constants which are determined normally by experiment. The accuracy of the five undetermined parameters for J–C model is vital for the reliability of the numerical results. Usually, split Hopkinson bar (SHB) is adopted to identify the material constants with different loading modes, including tension, compression, and shear at elevated temperatures [22–23].

Generally, Split Hopkinson Bar (SHB) is used to investigate the dynamic behavior of materials at high strain rates [24]. In order to explore the high-temperature response of materials at high strain rates by using SHB, two kinds of methods are usually adopted to realize such a high-temperature experiment: contact method and non-contact method [25–28]. The contact method is to heat the specimen directly, which is connected to the input and output bars. There will exist a temperature gradient in the bars exerting some influence on the microstructure and mechanical characteristics of the bar material, such as modulus, impedance and wave velocity. Non-contact method is to heat the specimen directly and separately [29,30]. Only when a desired temperature is reached, the specimen is moved to contact with the bars just a few milliseconds before testing. Due to a short contact time, the temperature effect on the bar material is effectively minimized. Obviously, both methods have some limitations on SHTB tests. For tensile tests, the specimen must be glued or mechanically connected to the bars, which needs a long time to finish. In view of this case, a high intensity localized heating method was presented by Rosenberg by using induction heating for tests at temperatures up to 700 °C [31]. By using this method, the specimen can be heated locally to a desired temperature in a very short time. There is no enough time for temperature rise to develop within the bars, significantly reducing the temperature gradient in the bars.

Accordingly, this study employs a Split Hopkinson Tension Bar (SHTB) apparatus with a rapid contact heating system to investigate the mechanical properties of the TiCp/Ti composites under strain rates between 10^{-3} to 10^{3} and temperatures ranging from 20 to 650 °C. Based on the impact experiments, a J–C model for TiCp/Ti composites is proposed to predict the mechanical characteristics of the composites. In order to consider the strain hardening and the coupled effects of the temperature and strain rate, a modified J–C constitutive model was proposed to predict the dynamic behavior of TiCp/Ti.

2. Experimental

2.1. Materials

The material used in the present study was all titanium matrix composite reinforced with 10% TiCp (TiCp/Ti composites) manufactured by Pre-treatment melt process. The constituents of the titanium matrix alloy were Ti–6Al–2.5Sn–4Zr–0.5Mo–1Nb–0.45Si. The reinforced particle with an average diameter of about 5 μm dispersed homogeneously in the matrix [32]. The interfacial reaction layers between the particle and the matrix were stable and the reaction zone width was about 2 μm. The composites were firstly fabricated to the 20 mm diameter bars, and then the diameter of the composite was forged into 13 mm by rotary swaging at the temperature of 1000 °C. The heat treatment for the TiCp/Ti composite was carried out according to the following procedures: Heat preservation at 800 °C for 1 h, air cooling (AC). After the heat treatment, the bars were fabricated to the tensile specimen.

2.2. SHTB setup

Among all available testing methods for dynamic mechanical behavior of various materials, the split Hopkinson bar has been used widely to explore the mechanical properties of these materials [33]. It should be noted that a great deal of effort has been invested in understanding the mechanical characteristics of solid materials under quasi-static and dynamic loadings [6–9]. In contrast, the dynamic tensile behavior of these materials at elevated temperatures has received relatively little attention, especially for TiCp/Ti composites. This paper focuses on the characterization of the high-strain-rate and high-temperature response of TiCp/Ti composites by using SHTB at University of Science and Technology of China (USTC) (see Fig. 1). In order to obtain tensile waves for SHTB, a direct method proposed by Xia has been used to achieve this goal [34]. By using this method, direct impact on an impact block connected to the input bar is employed to generate tensile waves and a short metal bar is placed between the impact block and the input bar (see Fig. 1). Tensile wave will be created while the short metal bar is subjected to impact loadings and deformed to fracture. By using this method, the amplitude and duration can be easily controlled by adjusting the diameter and length of the short metal bar.

2.3. Specimen preparation

Specimens for dynamic tensile tests were machined from the TiCp/Ti composite via linear cutting. The specimen was dumbbell-shape with a thickness of 1.1 mm and the schematic of the specimen was shown in Fig. 2. The specimen was glued to the