An experimental method for determination of dynamic mechanical behavior of materials at high temperatures

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Abstract

An experimental method for measuring dynamic behavior of materials at high temperatures (up to 1600°C) was proposed in this work. The experimental system includes a classical split Hopkinson pressure bar, a MoSi₂ heating source for achieving high temperature, and two piston rods added to complement the double-synchronous assembled system. High speed camera was employed to record images of the specimen during testing through a window in the heating furnace. To verify the ability of the proposed method to operate at high temperatures, experiments were conducted on an TC4 alloy at test temperatures ranging from 20 to 1400°C at the strain rate of 2000s⁻¹, and on SiC at temperatures ranging from 20 to 1600°C at the strain rate of 250s⁻¹.

Keywords: High temperature, High strain rate, SHPB, High speed camera

1. Introduction

Mechanical properties of materials under the combined effects of high temperatures and high strain rates have been an important and challenging issue for

decades[1-4]. The split Hopkinson pressure bar (SHPB) apparatus named after Bertram Hopkinson [1], who used the induced-wave propagation in a long elastic metallic bar to measure the pressures under dynamic loading in 1914, has been widely used for the determination of the dynamic mechanical properties of materials at high strain rates (10^2s^{-1} to 10^4s^{-1}).

Knowledge of the dynamic behavior of materials at various temperatures is crucial to their application. Some researchers proposed that it was practical to heat the specimen and a small portion of the pressure bar adjacent to the specimen. However, a temperature gradient would be established in the two elastic bars since the far ends of the bars are still at room temperature. Chiddister and Malvern [5] might have been the first to discuss the pulse propagation in the bars with thermal conduction. They proposed that the temperature gradients must be measured and the effects of the thermal conduction must be numerically corrected, for particularly when the temperature is 600°C or higher in steel bars.

Many researchers opted to heat the specimen individually while both the incident and the transmitted bars were kept out of the heating furnace and separated from the specimen during heating. Nemat-Nasser et al. [6] and Yulong Li et al. [7] proposed a high temperature dynamic testing method leased on the SHPB in which the incident and the transmitted bars were kept away from the heating zone of the furnace. After heating the specimen to the desired experimental temperature, the bars were brought into close contact with the specimen by a synchronous assembled system before the

stress pulse reached the interface of the incident bar and the specimen. Nemat-Nasser et al. [6] used this technique to measure the isothermal flow stress of Ta and Ta-W alloys at temperatures up to 1000°C. Apostol et al. [8] developed an automated high temperature system in which the specimen was held by a holder and heated within a furnace located aside the SHPB.

In the present work, combined with a high speed camera, a method equipped with a double-synchronous assembled system was developed to determine the dynamic properties of materials at temperatures up to 1600°C. With the aid of high speed camera, the dynamic process of the deformation at high temperatures can also be captured. Based on the method, we characterized the high strain rate behavior of TC4 and SiC at high temperatures.

2. Modifications to SHPB

2.1 Heating Furnace and specimen fixation

In this work, an electric furnace with a temperature controller was employed to heat the specimen. The length of heating furnace is 300 mm along the axial direction of the bar. The size of the internal heating zone of the furnace is 70mm×70mm×70mm. To achieve high temperatures, MoSi₂ was used as the heating source. To enable observation during experiment, the viewing port is equipped with a quartz glass. The maximum temperature of the heating system is up to 1650 °C when the viewing port is plugged up with insulation. As mentioned before, heating of the loading bars together with the specimen will easily influence the experimental results in a negative

way. In the present work, the specimen was supported by high temperature block, which was made of polycrystalline mullite fibers and can bear high temperature up to 1800°C, and a semi-alumina ceramic tube (see Fig. 1).

Fig. 1. Detailed configuration of the furnace and the specimen section.

2.2 Double-synchronous assembled system

To shorten the cold contact time and to avoid permanent deformation in the specimen with the assembly, two pistons were employed to bring both the incident and the transmitted bar into contact with specimen simultaneously, as shown in Fig. 2. The protective gas (Argon) could be imported into the furnace through the gas inlet in the furnace to prevent the specimen from oxidation, and the high speed camera was employed to obtain the image of the specimen during the dynamic testing.

Fig. 2. Schematic illustration of the high temperature split Hopkinson pressure bar with a double-synchronous assembled heating system and a high speed camera.

In the developed system, two pipes are connected to the sync air chamber through the circuit controller. During the experiment, as soon as the striker bar moves to impact the free end of the incident bar, the incident and transmitted bars are pushed towards the specimen by the push rod of the pistons simultaneously. As soon as the specimen is loaded, pressured air flowing into the sync air chamber via the backward pipes activates the push rods of the pistons backwards and brings the incident and the transmitted bars away from the heat furnace, avoiding heating of the loading bars. During the experiment, in case the incident stress pulse arrives before the contact between the loading bars and the specimen, it will reflect back into the incident bar without loading the specimen. On the other hand, if the incident stress pulse fails to reach the specimen shortly after the contact between the loading bars and the specimen, longer cold contact time and larger temperature difference between the specimen and the loading bars may lead to marked thermal dispersion and temperature drop within

the specimen. Therefore, a short CCT is very important. In the developed method, the CCT can be controlled within 10 ms through adjusting the pressure of the sync air chamber by using the double-synchronous assembled system developed in this work.

3. Dynamic experimental results

3.1 Dynamic mechanical testing of TC4 alloy and SiC at high temperatures

The stress–strain curves of TC4 at different temperatures are presented in Fig. 3. As shown in Fig. 3, the dynamic behavior of this material is highly temperature dependent, as the flow stresses decreases remarkably with the increase of the experimental temperature. For Example the peak flow stress drops from 1.6GPa at room temperature to 150MPa at 1400°C.

Fig. 3. Dynamic stress–strain curves of TC4 at different temperatures at the strain rate of 2000s⁻¹.

Fig. 4 presents the dynamic stress–strain curves of SiC at different temperatures at the strain rate of 250s⁻¹. It should be pointed out that the compressive strength of SiC

decreases monotonously with increasing temperature (420MPa at room temperature, 141MPa at 1600°C), indicating that the SHPB equipped with the double-synchronous assembled system presented in this work is capable of measuring the dynamic material properties at high temperatures (up to 1600°C). to the authors' knowledge, this is first time that such high temperature has been achieved during on SHPB experiment.

Fig. 4. Dynamic stress–strain curves of SiC at different temperatures at the strain rate of 250s⁻¹.

3.2 In situ observation of the dynamic deformation at high temperatures

To record the dynamic deformation process of the specimen, a high speed camera with a frame rate of 100,000Hz was employed. Fig. 5 shows the images recorded when the specimen was loaded at the strain rate of 2000s⁻¹ at the temperature of 1200°C. In the present work, based on the captured images, the Canny edge [9] detection method was also used to detect the bar/specimen interface and then to calculate the deformation of the specimen. Fig. 5 (b) shows the distance between the two loading

bars and the strain calculated by the Canny edge detection method. For comparison, the strain calculated by the classical SHPB theory is also plot in Fig. 5 (b). It can be seen that the strain determined by using the edge detection method agrees very well with that obtained based on the traditional Hopkinson bar theory.

Fig. 5. Experimental image: (a) Calculation area; (b) Results obtained by SHPB and by edge detection.

4. Summary and conclusions

A new experimental method for measuring the dynamic behavior of materials at high temperatures (up to 1600°C) was proposed. The experimental device includes a classical split Hopkinson pressure bar and a MoSi₂ heating source for achieving high temperatures and a double-synchronous assembled system. For in-situ observation of the deformation process at high temperatures, a high speed camera was also used. To verify the ability of the proposed method to operate at high temperatures, experiments

were successfully conducted on TC4 alloy and on SiC. The results show that the proposed method is a practical method for testing the dynamic properties of material at high temperatures.

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