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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 $MoSi_2$ heating source for achieving high temperature, and two piston rods added to complement the double-synchronous assembled system. During the experiments, the specimen can be supported by asbestos and semi-Alumina ceramic tube. To estimate the thermal conduction of the tested specimen during the cold contact time (CCT), the time during which the hot specimen is in contact with the cold bars before being compressed, the CCT was measured experimentally based on an on-off circuit, and the finite element method (FEM) was also employed to calculate the thermal conduction of the tested specimen. High speed camera was employed to record images of the specimen during testing through a window in the heating furnace. For better understanding of the influence of oxidation of specimens, the system was also equipped with an argon supply system to prevent the specimen from oxidation at the high temperatures. 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 2000 s^{-1}, and on SiC at temperatures ranging from 20 to 1600 °C at the strain rate of 250 s^{-1}.

1. Introduction

1.1. Historical background of the Hopkinson bar technique

Mechanical properties of materials under the combined effects of high temperatures and high strain rates have been an important and challenging issue for decades. 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 ($10^2 s^{-1}$ to $10^4 s^{-1}$). Through the use of momentum traps of differing lengths, Hopkinson studied the shape and evolution of stress pulses as they propagated down long metallic rods as a function of time. Based on this pioneering work, the experimental apparatus using elastic stress pulse propagation in long rods to study dynamic processes in materials was named as the Hopkinson pressure bar. Later work by Davies [2] and Kolsky [3] used two Hopkinson pressure bars in series, with the specimen being sandwiched between the two elastic bars, to measure the dynamic stress strain response of materials. This technique thereafter has been referred to as either the split Hopkinson pressure bar, Davies bar, or Kolsky bar. In the SHPB system, a short specimen is sandwiched between the two elastic loading bars. The impact of the striker bar (projectile) on the free end of the incident bar generates a stress pulse ($\varepsilon_i(t)$) which travels along the incident bar towards the interface of the incident bar and the specimen. When the stress pulse reaches the interface of the incident bar and the specimen, due to the mismatch of the wave impedance between the loading bars and the specimen, part of the incident pulse ($\varepsilon_r(t)$) is reflected back to the incident bar, while the other part ($\varepsilon_t(t)$) is transmitted to the transmission bar.

1.2. Dynamic tests at high temperatures using SHPB

Knowledge of the dynamic behavior of materials at various temperatures is crucial to their application. A lot of researchers have paid much attention to the dynamic mechanical behavior of materials at high temperatures using SHPB since 1960′s. To ensure the stress pulse to propagate between the specimen and the loading bars, close contact of the specimen with the loading bars is necessary. As for dynamic test at high temperatures, it is impractical to heat the whole system (specimen and loading bars) because the properties of the bar may change a lot at high temperatures. For example Latella and Humphries [4] found that the Young's modulus

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of 2.25Gr-1Mo high strength steel decreased from 212.4 GPa at room temperature to 169 GPa at 600 °C, and it would become even much lower at higher temperatures.

Others researchers proposed that it was practical to heat the specimen and a small portion of the pressure bar adjacent to the specimen [5–7]. However, a temperature gradient would be established in the two elastic bars since the far ends of the bars are still at room temperature. The temperature gradient in turn affects the elasticity of the bars, and results in the dispersion of the stress pulses. 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. Thereafter, Galvez et al. [6] found that the yield strength of Rene41 super-alloy used to make the input and transmission bars for their set-up decreased to 450 MPa at 900 °C, insufficient for testing very hard specimens even the temperature gradient can be corrected. For another method [7] employed short ceramic (aluminum oxide) bars, which had their impedance matched to the pressure bars in direct contact with the cold steel bars and heated specimen for testing up to 1500 °C. However, as the brittle ceramic bars are easily damaged, this method was not widely adopted for experiments at high temperatures.

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. After heating the specimen to the desired experimental temperature, the bars were moved towards the specimen so that the specimen is sandwiched just before the dynamic compression. However, this dynamic process should be finished within an extremely short time. Nemat-Nasser et al. [8] and Yulong Li et al. [9] 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, as shown in Fig. 1(a). 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. As the loading bars are almost unheated, the temperature gradient effect could be avoided and therefore more reasonable results could be obtained. Nemat-Nasser et al. [8] used this technique to measure the isothermal flow stress of Ta and Ta-W alloys at temperatures up to 1000°C. Apostol et al. [10] suggested that the cold contact time (CCT, the time during which the hot specimen stays in contact with the cold bars until being compressed [11]) should be less than to 50 ms. Li et al. [9] measured the dynamic mechanical properties of various materials at high temperatures, and designed new experiments to investigate the influence of CCT on the test results. Their experimental results indicated that the CCT does have a strong effect on the experimental results, and the data can faithfully reflect the material behavior if the CCT is shorter than 50 ms. Apostol et al. [10] developed an automated high temperature system in which the specimen was held by a holder and heated within a furnace located aside the SHPB, as shown in Fig. 1(b). After the desired experimental temperature was achieved, the slider moved the specimen from the heating furnace into the gap between the incident and transmitted bars automatically, as shown in Fig. 1(c). At the same time, the pneumatic cylinder which attached with the transmitted bar was activated and brought the bar to move towards the specimen. Since the heating furnace was setup away from the SHPB, the loading bars were not heated. Therefore, after the heated specimen was moved into the gap between the incident and transmitted bars, the distance between the specimen and loading bars can be controlled to be only several millimeters. By using this method, the dynamic properties of materials was measured at the temperatures up to 1000 °C. Similar method was also employed by Song B et al. [12] for dynamic experiments at high temperatures.

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. As metals or other materials easily react with oxygen at high temperatures, affecting the accuracy of the test after oxidation of the specimen, a high temperature heating furnace that could be filled with Argon to protect the specimen against oxidation at the high temperature was employed to heat the specimen. 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. The results show that the proposed method is a practical method for testing the dynamic properties of material at high temperatures.

2. Modifications to SHPB

In order to investigate the dynamic properties of materials at high temperatures, in the present work an improved split Hopkinson pressure bar with a high temperature heating furnace, a double-synchronous assembled system, and a high speed camera was developed, as shown in Fig. 2.

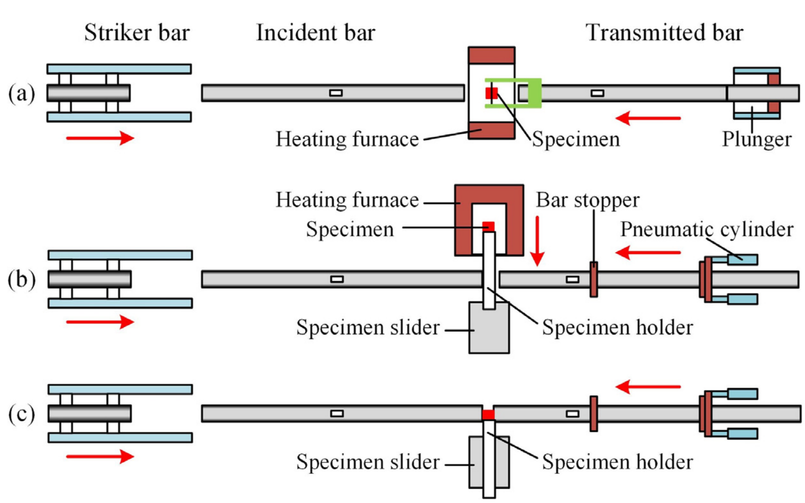

Fig. 1. Two typical of high temperature split Hopkinson bar.