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A critical assessment of high-temperature dynamic mechanical testing of metals

Yulong Li [a], Yazhou Guo [a,b,*], Haitao Hu [a], Q. Wei [b]

[a] School of Aeronautics, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, PR China
[b] Department of Mechanical Engineering and Engineering Science, 362 Duke Hall, University of North Carolina at Charlotte, Charlotte, NC 28277, USA

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ABSTRACT

Determination of the mechanical properties of materials under the combined effects of high-temperatures and high strain-rates has been an important and challenging issue. A strategy has been proposed and evaluated recently towards this purpose in which a heating cell with accurate temperature control is synchronized with the split Hopkinson pressure bar (SHPB) system. This strategy allows pre-heating the specimen to desired temperatures before arrival of the stress wave and provides an experimental technique for the measurement of dynamic mechanical properties of materials at high-temperatures. Since its advent, this method has gained increasing interest in the community of dynamic mechanical testing owing to its ease of manipulation. However, a couple of critical problems should be addressed to validate the experimental results. Among the problems, a crucial one is associated with the temperature change in the heated specimen upon its contact with the relatively cold bars. In this paper, experiments were designed to determine the influence of cold-contact-time (CCT) on the temperature variation within the specimen. The experiments were conducted on Ti700 alloy at strain-rates of $\sim 10^4\ s^{-1}$ and at temperatures from 20 to 800 °C. The results show that the CCT does have a strong effect on the experimental results. Based on the experimental results and our analyses, we believe that the data can faithfully reflect the material behavior if CCT is shorter than 50 ms. While in most systems without the heating cell being synchronized with the SHPB system, the typical CCT is about 500 ms, and therefore the experimental data cannot be taken as representing the material behavior.

1. Introduction

1.1. Traditional SHPB system

The split Hopkinson pressure bar (SHPB) apparatus has been widely used for the determination of the dynamic mechanical properties of materials. Depending on the specific design of a SHPB system, it allows mechanical testing at strain-rates from $\sim 10^2\ s^{-1}$ to $\sim 10^4\ s^{-1}$ [1–6].

Fig. 1 shows a schematic of a conventional SHPB system. The primary components of this system are the two long elastic bars: the incident (input) bar and the transmission (output) bar. A short specimen is sandwiched between the two elastic bars. The impact of the striker (projectile) on the free end of the incident bar generates a stress pulse which travels along the incident bar. When the stress pulse reaches the bar/specimen interface, part of it ($\varepsilon_r(t)$) is reflected, and part of it ($\varepsilon_t(t)$) is transmitted to the transmission bar. Both signals can be recorded by strain gages and stored in a computer for subsequent analysis. Based on the theory of one-dimensional wave propagation [7], the stress, strain-rate and strain of the specimen can be calculated as follows:

$$\sigma(t) = \frac{AE\varepsilon_t(t)}{A_s}, \tag{1}$$

$$\dot{\varepsilon} = -\frac{2c\varepsilon_r(t)}{L_s}, \tag{2}$$

$$\varepsilon(t) = \int_0^t \dot{\varepsilon}(\tau)\mathrm{d}\tau, \tag{3}$$

where A, E, and c ($c = \sqrt{E/\rho}$, ρ is the mass density of the bar) are the cross-sectional area, Young's modulus and longitudinal wave speed of the bar, respectively. L_s and A_s are the length and cross-sectional area of the specimen, respectively. $\varepsilon_t(t)$ and $\varepsilon_r(t)$ are the

* Corresponding author. Department of Mechanical Engineering and Engineering Science, 362 Duke Hall, University of North Carolina at Charlotte, Charlotte, NC 28277, USA. Tel.: +1 704 687 8330; fax: +1 704 687 8345.
E-mail address: yguo12@uncc.edu (Y. Guo).

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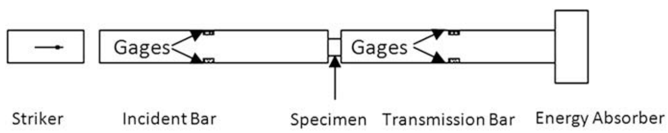

Fig. 1. Schematic of a conventional split Hopkinson pressure bar system, with only the key components displayed.

axial strains backed out from the transmitted and the reflected pulses, respectively. The energy absorber is used to absorb the residual energy after the loading process is completed.

1.2. High-temperature dynamic test using SHPB

In a number of important applications, knowledge of the materials' dynamic mechanical behavior at various temperatures is essential [8–15]. Such knowledge may be associated with the low-temperature dynamic behavior, or with dynamic properties at elevated temperatures. It has turned out that measuring dynamic mechanical properties of materials at low-temperatures using the SHPB technique is not as challenging as that involving heating the specimen to elevated temperatures. Difficulties in performing dynamic mechanical testing on heated specimens using the SHPB technique include the following. (a) Heating of the specimen to the desired temperature without causing drastic change of the specimen's microstructure and oxidation of the specimen, though for some problems the mechanical behavior of the microstructure representative of high-temperature applications may be desired. (b) Effect of specimen heating on the thermal condition of the elastic bars. This is important because temperature gradient may exist in the elastic bars which in turn changes the elastic constants, and thus the mechanical impedance of the bar material, leading to changes in stress wave propagation in the bars. For example, Latella and Humphries [16] found that the Young's modulus of 2.25Cr–1Mo high strength steel decreased from 212.4 GPa at room temperature to 169 GPa at 600 °C, as shown in Fig. 2. It can be seen that the Young's modulus of this high strength steel drops by about 5% when the temperature reaches 200 °C from room temperature. Thus experiments performed at over 200 °C may result in substantial error if the room temperature elastic parameters are used in Eqs. (1)–(3). (c) Accurate measurement and control of the specimen temperature. (d) Interpretation of the experimental data.

Various heating methods have been designed for high-temperature SHPB tests. For example, resistance heating [8,10], induction heating [17], infra-red emitter [11], radiant focus heating system [13] and IR image-furnace [18], and tube furnace as we have used in the present work. The most common approach to high-temperature dynamic experiment is simply heating the specimen which is in contact with the incident and transmission bars. As such, part of the bars is in the heating unit or in contact with the hot specimen, resulting in a strong temperature gradient. To the best of our knowledge, Chiddister and Malvern [8] performed the first high-temperature SHPB experiments (at temperatures up to 550 °C) using this approach. To account for the effect of temperature gradient within the bars, they measured the temperature distribution in the bars and corrected their experimental results accordingly. However, their approach has great limitations: the temperature of the specimen has a limit, otherwise the microstructure and the mechanical properties of the elastic bars will change. This is particularly true for repeated thermal cycling of the bars that may render permanent change in their structure and properties. Actually, Galvez et al. [9] found that the yield strength of Rene41 superalloy used to make the input and transmission bars for their set-up decreased to 450 MPa at 900 °C, insufficient for testing very hard samples.

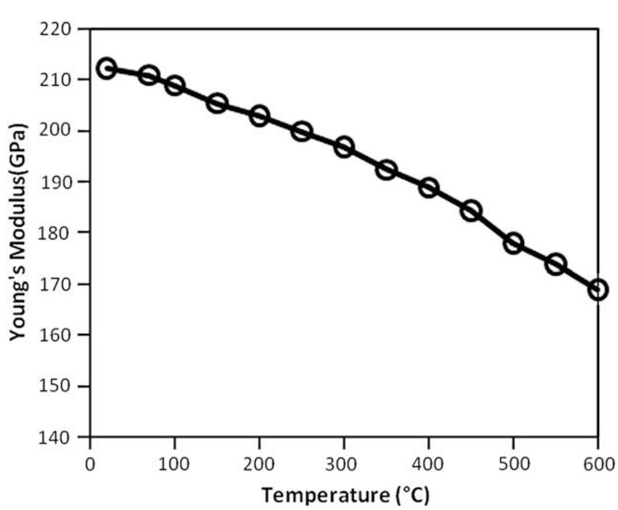

Fig. 2. Young's modulus as a function of temperature for virgin 2.25Cr–1Mo steel, data from [16].

An improved technique for high-temperature high strain-rate test is to preheat the specimen while keeping the incident and transmission bars away from the heating zone of the furnace. After the desired specimen temperature is achieved and homogenized, the bars are brought into contact with the specimen by a synchronically assembled system, immediately before the stress pulse reaches the far end of the incident bar. Since the bars are kept completely away from the heating zone of the furnace, one can avoid the temperature gradient effect and the much involved correction of the experimental results. Furthermore, a higher attainable specimen temperature can be achieved by this technique. Nemat-Nasser and Isaacs [10] used this improved technique (referred to as UCSD technique hereafter), to measure the isothermal flow stress of Ta and Ta–W alloys, and their specimen temperature has reached up to 1000 °C. Lennon and Ramesh [11] have made a simplified version of the UCSD technique by changing the stiff-bar-drive system of the UCSD design into a gas-pressure-drive system. It allows low-cost instrumentation as well as easy integration of the heating unit into conventional SHPB system.

1.3. The role of CCT in high-temperature tests

A vital issue associated with the design and implementation of a high-temperature SHPB apparatus with a synchronically assembled heating system is the cold-contact-time (CCT) [11–13,19]. The CCT is defined as the time of direct contact between the specimen and the bars' ends prior to the arrival of the incident stress wave. It is an extremely important parameter since its length determines the extent of temperature gradient formed in the bars as well as the specimen temperature drop due to the temperature difference between the bars and the heated specimen. For example, one may naturally ask: does the CCT affect the accuracy of the experimental results of high-temperature SHPB testing? If it does, then to what extent? Is there a critical CCT below which the effect could be neglected? Unfortunately, the exact change of temperature in the specimen as a function of CCT is difficult to calculate theoretically, because the thermal conduction at the specimen/bars interfaces is constantly evolving. Lennon and Ramesh [11] have addressed these issues by finite element modeling (FEM). Based on their results, they suggested a critical CCT of 5 ms. That is, if the CCT is longer than 5 ms, the experimental results could not be taken as faithfully representing the intrinsic mechanical properties of the specimen. However, their calculations have ignored the insulation or limited thermal conductivity at the specimen/bar interfaces and it is reasonable to believe that their critical CCT of 5 ms could be an