International Journal of Impact Engineering 69 (2014) 149–156

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

An experimental method to measure dynamic stress–strain relationship of materials at high strain rates

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ARTICLE INFO

Article history:
Received 28 June 2013
Received in revised form
27 December 2013
Accepted 20 February 2014
Available online 13 March 2014

Keywords:
Dynamic behavior
Experimental method
Photonic Doppler velocimetry system
Polyvinylidene fluoride thin-film sensor

ABSTRACT

In this paper, an experimental method for measuring dynamic behavior of materials at high strain rates is developed. The strain and stress of a specimen are obtained using a high-precision photonic Doppler velocimetry system and a sensitive polyvinylidene fluoride thin-film sensor respectively. Based on the assumptions of one-dimensional stress state and negligible volume change at plastic deformation stage, the dynamic stress–strain relationship of materials can be determined. Using Al-2024T351 alloy and copper as model materials, the method demonstrates its effectiveness in measuring dynamic behavior of materials at high strain rates.

1. Introduction

The understanding of dynamic behavior of materials plays an important role in many applications such as penetration, explosion and crashworthiness [1]. The split Hopkinson pressure bar (SHPB) technique, first introduced by Hopkinson [2] in 1914 and further developed by Kolsky [3], Davies and Hunter [4], is an effective experimental technique to determine the dynamic stress–strain relationship of materials at strain rates of 50 s^{-1} to 10^4 s^{-1} [5–13]. The SHPB technique is based on the following assumptions: one-dimensional wave propagation theory; uniform stress and strain distribution in axial direction; and negligible inertia effect [3,4,11]. To satisfy these assumptions, the lengths of the incident and transmitted bars can reach up to several meters especially for coarse grain heterogeneous materials [14]. Long bars inevitably introduce imperfect experimental conditions such as un-coaxiality and non-parallelism between bars, which will influence the stress state [15]. On the other hand, the measurement of SHPB technique is based on the wave propagation theory and the superposition principle [2–4]. The incident, reflected and transmitted waves are measured by strain gauges on the bars instead of at the specimen interfaces. The measured strains need to be shifted from the position of the strain gauges to the specimen in time and space. Errors might arise due to the dispersion effect, i.e. the change of the wave shape while propagating along the bar. Additionally, it is difficult to make an exact estimation of the shifting time to ensure the same beginning of the three waves [4,11,16,17].

Many researchers have tried to improve the SHPB technique to broaden its application, including dispersion correction, strain field measurement and data processing methodology [8,11,12,14,16–23]. There are still some aspects needed to be improved. For instance, the digital image correlation (DIC) is one of the most popular methods for obtaining full-field deformation information. However, it is difficult for measuring the out-of-plane displacement, and the measurement of large in-plane displacement is also hard as the great decreasing of image contrast [22,23]. In this paper, we develop an experiment method to characterize high strain-rate behavior of materials. The strain is determined by the radial particle velocity of specimen measured with a high-precision velocimetry, and the stress is measured with a pressure sensor, respectively.

The paper is organized as follows. In Section 2, the measurement concept is described in detail. In Section 3, the experimental based on the method is established. In Section 4, we explain the measurement result and provide discussions relevant to this experimental method.

2. Measurement concept

The schematic diagram of the proposed experimental method is depicted as Fig. 1. The cylinder specimen is sandwiched between

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http://dx.doi.org/10.1016/j.ijimpeng.2014.02.016
0734-743X/

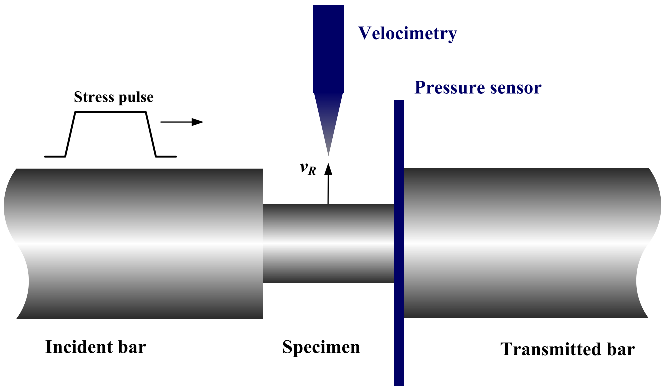

Fig. 1. Schematic diagram of the developed measurement method for stress–strain relationship at high strain rates.

two elastic rods denoted as incident bar and transmitted bar. While a stress pulse propagates through the specimen, the specimen experiences a dynamic compression deformation. The deformation of specimen causes a radial particle velocity at the specimen outside surface, which can be related to the longitudinal deformation of specimen through its deformation law. Therefore, it is possible to obtain the stress–strain response of material if we can measure the stress pulse and the radial velocity.

The proposed experimental method is based on two assumptions:

i. The stress in the specimen quickly reaches its equilibrium and is in one-dimensional state;
ii. The volume change at the plastic deformation stage is negligible.

The one-dimensional stress state is usually satisfied when the friction effect is negligible [2–4]. As pointed out by Davies and Hunter [24], the stress can reach an equilibrium state after the stress pulse experiences approximately π reverberations within the specimen, i.e., the time for reaching an equilibrium state is approximately

$$t_{\text{equil}} = \frac{\pi L_0}{c_L} \tag{1}$$

where L_0 is length of specimen and c_L is longitudinal wave speed in specimen. For a 5-mm-thick specimen, taking $c_L = 5000$ m/s, the equilibrium time is expected to approximately 3 μs. Therefore, the specimen will deform uniformly quickly after the impact. At this stage, the stress at the back-surface where the pressure sensor is placed can be regarded as the stress at the position where the radial velocity is measured. According to Bridgman [25], the volume change at the plastic deformation stage is negligible for metals when the applied pressure is not very high. With this assumption, the longitudinal strain can be determined from the radial particle velocity through the deformation law.

The analysis of longitudinal strain can be divided into stages of elastic deformation and plastic deformation respectively. For the *elastic deformation stage*, the radial strain is related to the longitudinal strain owing to the Poisson's effect,

$$\varepsilon_r = \frac{\partial u_r}{\partial r} = -\nu\varepsilon_l, \tag{2}$$

where ε_r, ε_l denote radial strain and longitudinal strain respectively, u_r is radial displacement, and ν is the Poisson's ratio.

Considering longitudinal strain ε_l as a function of Lagrange coordinate X and transient time t, $\varepsilon_l = \varepsilon_l(X,t)$, at the specimen surface ($r = R$, R is the radius of the cylinder specimen), the radial displacement u_R can be expressed using the longitudinal strain $\varepsilon_l(X,t)$ as

$$u_R = -\nu R\varepsilon_l(X,t). \tag{3}$$

Consequently, the longitudinal strain $\varepsilon_l(X,t)$ can be solved by the radial particle velocity v_R,

$$\varepsilon_l(t) = -\frac{1}{\nu R}\int_0^t v_R(t)dt. \tag{4}$$

For the *plastic deformation stage*, the volume change is negligible. Assuming the longitudinal particle velocities at two positions with infinitesimal length Δl of specimen are v_1 and v_2 respectively, the volume of the Δl-length specimen at time t is

$$V_t = \pi R_t^2 \cdot \Delta l_t, \tag{5}$$

where R_t and Δl_t denote the radius and length of the Δl-length specimen at time t respectively.

At time $t + \Delta t$, the volume of the Δl-length specimen is

$$V_{t+\Delta t} = \pi R_{t+\Delta t}^2 \cdot \Delta l_{t+\Delta t} = \pi[R_t + v_R(t)\cdot\Delta t]^2 \cdot [\Delta l_t + (v_2 - v_1)\cdot\Delta t]. \tag{6}$$

Moreover, the strain rate of the specimen can be written as

$$\dot{\varepsilon}_l(t) = (v_2 - v_1)/\Delta l_t. \tag{7}$$

Therefore, the relationship between the longitudinal strain and the radial particle velocity can be deduced as

$$\varepsilon_l(t) = -\int_0^{t_C} \frac{v_R(t)}{\nu R}dt - \int_{t_C}^{t} \frac{2v_R(t)}{R_t}dt, \tag{8}$$

where t_C is the critical time, at which the specimen transits from the elastic deformation to plastic deformation. As will be shown later, this critical time can be approximately obtained from the stress profile measured by the pressure sensor. The radius of the specimen at time t, R_t, is derived as

$$R_t = R_0 + \int_0^t v_R(t)dt. \tag{9}$$

From Eqs. (4) and (8), the longitudinal strain of the specimen can be calculated. Meanwhile, the related strain rate can also be determined,

$$\dot{\varepsilon}_l(t) = \left|\frac{d\varepsilon_l(t)}{dt}\right|. \tag{10}$$

Finally, the dynamic stress–strain relationship of the specimen can be obtained.

3. Experimental

3.1. Experimental setup

Even though a new experimental set-up can be established to validate the proposed method according to Fig. 1, the proposed experimental method is performed in a traditional SHPB