International Journal of Impact Engineering 81 (2015) 1–7

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

A novel intermediate strain rate testing device: The serpentine transmitted bar

W.R. Whittington [a], A.L. Oppedal [a,*], D.K. Francis [a], M.F. Horstemeyer [a,b]

[a] Center for Advanced Vehicular Systems, Mississippi State University, MS 39762, USA
[b] Department of Mechanical Engineering, Mississippi State University, MS 39762, USA

ARTICLE INFO

Article history:
Received 18 July 2014
Received in revised form
21 December 2014
Accepted 25 February 2015
Available online 12 March 2015

Keywords:
Intermediate strain rate
High strain rate
Kolsky bar
Split Hopkinson pressure bar

ABSTRACT

A material's stress–strain behavior at intermediate strain rates (between 5 s^{-1} to 500 s^{-1}) is essential for characterization of important events such as a car crash or a metal forming process. In addition, a material's stress–strain behavior can be strongly strain rate dependent, such that calibrating and validating the constitutive model at the actual strain rate of interest are important if finite element analyses are used for components that experience these strain rates. Testing of materials below 5 s^{-1} is easily accomplished with conventional electro-mechanical or servo-hydraulic load frames. Rates above 500 s^{-1} are typically performed with the split Kolsky/Hopkinson pressure bar (SHPB) and other devices depending upon the strain rate. However, the intermediate strain rate regime is a demanding test regime in which researchers have extended the use of specially instrumented servo-hydraulic load frames or very long Hopkinson bars. We describe a novel design of a serpentine Hopkinson transmitted bar that allows for accurate and robust load acquisition at intermediate strain rates in a compact form. Our new design produces repeatable stress–strain results without stress oscillations typical of a specially instrumented servo-hydraulic load frame and produces data for a longer loading time than a conventional Kolsky/Hopkinson bar of the same length. We demonstrate the intermediate bar's stress–strain response on a 6061-T6 Al alloy in which low rate and high rate data from the literature bounded the intermediate bar's response.

1. Introduction

The mechanical response of engineering materials is widely known to depend on the applied strain rate [1]. In high strain rate testing (500 s^{-1} to 5000 s^{-1}), the split Hopkinson pressure bar (SHPB) is widely used to gather the stress–strain behavior [1–6]. In these experiments, a single shock wave is imparted to the specimen and using one dimensional stress wave theory, stress–strain relations can be extracted from monitoring the bars. The drawback of SHPB testing is that the time duration of the test is limited to the length of the bars. To achieve strain rates in the intermediate strain rate regime (5 s^{-1} to 5500 s^{-1}), the testing apparatus would become too large to fit in conventional laboratories. Nevertheless, some laboratories have created intermediate strain rate bar systems in the order of 30 m length to achieve intermediate strain rates [7,8]. Some researchers have modified conventional SHPBs to provide a long loading duration with hydraulic or other means with load acquisition using two or more strain gages on each bar to monitor the stress–strain relationship. In these systems, a multi-gage solution to the stress wave propagation allows stress–strain measurements to be captured after the stress wave has traversed the short transmitted bar multiple times [9,10]. This method, however, presents a new problem as the strain rate jumps at every instance that the initial transmitted wave comes into contact with the specimen, and the reduced data may have many oscillations at intermediate strain rates.

Another approach to testing materials in the intermediate strain rate regime is to modify existing low strain rate testing equipment [11–14]. The desired loading rate of the specimen is realized by servo-hydraulics, while the sample grips and fixtures are modified to improve the load acquisition [11,12]. The most common goal in modifying the fixtures is to design the load train with a high natural frequency such that the test frame reaches equilibrium along with the specimen. The load then can be measured by a strain gage mounted on the fixture or grip section of the specimen or by using a small piezoelectric load washer [15]. Data from these test setups,

* Corresponding author.
E-mail address: aoppedal@cavs.msstate.edu (A.L. Oppedal).

http://dx.doi.org/10.1016/j.ijimpeng.2015.02.009

with careful consideration, have been used to calculate stress–-strain responses up to approximately 100 s^{-1} [11,12]. Shown in Fig. 1 is a comparison of the as-received high rate testing apparatus from a manufacturer (Fig. 1a) and the best case improvement to the system (Fig. 1c). Although modified servo-hydraulics are typically rated for higher loading rates (10 m s^{-1}), at strain rates above 100 s^{-1} these systems become unreasonably difficult to acquire load data. Therefore, experimentalists are forced to perform data filtering and curve fitting techniques [12].

With bar systems having a minimum strain rate limitation in the intermediate regime and modified servo-hydraulic systems having a maximum strain rate limitation also in this regime, improvements to one or both systems must be made to provide significant strain rate overlap between the testing practices. The objective of this paper is to provide an intermediate strain rate solution that acquires accurate load data without unreasonable difficulty in providing laboratories with a common of load acquisition method.

2. Materials and methods

2.1. Bar system methodology

As discussed in the introduction, the issue with bar testing at intermediate rates is due to the bar size constraint along with the wave speed. These constraints arise, because the stress wave propagates along the bar length, reflects off of the free end, and returns to the specimen [9]. Once the stress wave reaches the specimen, the energy applied to the specimen changes and can subsequently change the applied strain rate, commonly known as a strain rate jump. Typical Hopkinson bar experiments are performed at such a high strain rate that the experiment is completed before the stress wave traverses the bar so as to eliminate this strain rate jump effect. Because of this size constraint, the Hopkinson bar has a lower strain rate limit for the bar setup. The minimum strain rate that can be achieved with a single continuous applied load in any bar system is described by the following:

$$\dot{\varepsilon}_{min} = \frac{\varepsilon_{max} c}{2L} \tag{1}$$

where L is the length of the transmitted bar, c is the longitudinal wave speed of the bar material, and ε_{max} is the maximum strain incurred by the specimen. To reduce the minimum strain rate achievable in the test, the maximum strain could be reduced without changing the bar properties at all. However, reducing the maximum specimen strain preempts an experiment from achieving specimen failure. The longitudinal wave speed of the bar could be reduced by changing the bar material. However, materials with a significant reduction in wave speed, such as polymeric materials, also have a significant reduction in strength; this reduction in strength cannot be used for testing metals that are stronger than the bars themselves. The final parameter that is possible to change is the bar length. Changing the bar length can be performed only to the extent that a laboratory can accommodate such a testing apparatus. As previously mentioned, some researchers [7,8] have adopted this practice by increasing their length (~30 m). However, other laboratories would have to undergo infrastructure changes to acquire the ability to use these systems.

Packaging the bar in an economical way that allows conventional laboratories to perform intermediate strain rate tests would be optimal and that is the purpose of our design. Typical laboratories that perform SHPB experiments can house a system of 6 m but need the capabilities of a longer transmitted bar (>18 m) for smooth load acquisition durations in the intermediate strain rate range. The time duration of a bar with length of 18 m would be enough for testing nominal strain rates of about 70 s^{-1} for a specimens tested to 0.50 strain if a metallic bar (c = 5000 m s^{-1}) was used. Because modified servo-hydraulics are capable of strain rates up to 100 s^{-1}, our proposed technique provides enough overlap for complete testing throughout the intermediate strain rate regime if a laboratory had acquired both systems.

2.2. The serpentine bar approach

Fig. 2 shows the structure of a serpentine bar that can provide increased time duration to achieve large strains. A serpentine bar has the advantage over a conventional long bar in that the stress wave, propagating from the sample, can be transferred into a series of tubes. These tubes are impedance matched to the original solid bar to eliminate the reflection due to the added tubes, and the joints are made small and stiff to reduce the joint reflections. Tubes have been used previously to trap the stress wave energy in "recovery" Hopkinson bar setups [17]. The recovery Hopkinson bar uses a tube that is located near a flange on the bar free end to admit bar movement before the stress wave enters the tube and is trapped from returning to the specimen. This process allows a precise amount of strain to be applied to the sample without repeated loading from the stress waves. This setup transmits the stress wave very well when designing the transfer flange is carefully considered. Here, we adapt this concept for increasing the stress wave duration possible in a given bar length, rather than trapping a shorter stress wave inside a detachable tube. The main difference with the serpentine bar setup is that a series of tubes are rigidly connected at alternating ends of the bar. Fig. 2 shows a serpentine bar with two attached tubes, which multiplies the effective length of the bar by a factor of three. As manufacturing techniques permit,

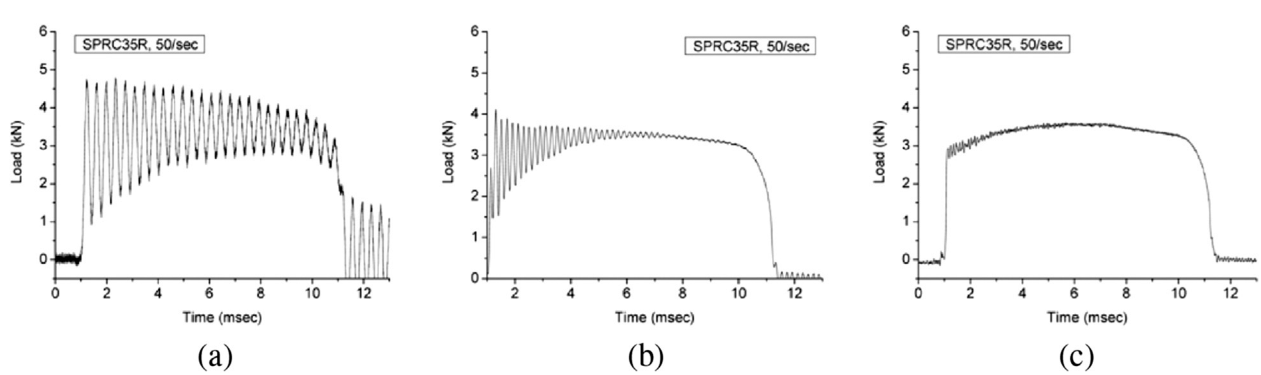

Fig. 1. Tensile load ringing in three different modified servo-hydraulic specimen fixtures at three different natural frequencies: (a) 2500 Hz, (b) 4800 Hz, (c) 13 000 Hz. Reproduced with permission from Huh et al. [16].