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International Journal of Impact Engineering 34 (2007) 784–798
INTERNATIONAL JOURNAL OF IMPACT ENGINEERING
www.elsevier.com/locate/ijimpeng

An optical technique for measurement of material properties in the tension Kolsky bar

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Received 8 March 2005; received in revised form 8 December 2005; accepted 8 December 2005
Available online 7 February 2006

Abstract

In this paper, a simple and effective technique is described for measurement of the viscoplastic tensile strains of specimens in the tension Kolsky bar experiment. The technique uses a Laser Occlusive Radius Detector (LORD) to directly measure the local diametral strain. To verify the accuracy of this technique, comparative tests of an A359 aluminum alloy were performed in which the strains in the specimens were simultaneously determined using the LORD approach and on-specimen strain gauges. Full numerical simulations of the tension Kolsky bar experiment were also performed for a variety of specimen geometries and material properties to evaluate the domains of accuracy of each measure of specimen strain. The experimental and numerical results show that (i) the strain measured using the LORD approach is in very good agreement with that measured using on-specimen strain gauges; (ii) the LORD approach continues to provide strain measurements after failure of the on-specimen strain gauges; (iii) the strain measured using conventional approaches is different from the strain measured using either the LORD or the on-specimen strain gauges.

Keywords: High strain rate; Tension; Kolsky bar; Split-Hopkinson bar; Non-contact measurements

1. Introduction

The Kolsky bar (or split-Hopkinson pressure bar) is widely used to determine the behavior of materials at high strain rates. Over the last 50 years, a number of improvements have been made to the compression Kolsky bar in specimen design [1,2], dispersion correction [3–6], pulse shaping [7,8], stress wave separation and so forth. However, the tension Kolsky bar technique has not been improved as much as the compression Kolsky bar since the nature of the tension test requires the use of a gripping technique for the connection of the specimen to the bars. Computational simulations easily demonstrate that the conventional analysis procedure leads generally to inaccurate estimates of specimen strain, except in fairly specific cases. The primary difficulty arises because a fillet transition is required between the specimen gauge length and the grips

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0734-743X/$ - see front matter
doi:10.1016/j.ijimpeng.2005.12.002

to avoid failure due to stress concentrations at the specimen ends, and so the specimen length is no longer well-defined.

Harding et al. [9] noted this problem in their original development of the tension Kolsky bar experiment and used a characteristic length of 0.35″ in their data analysis, instead of either their specimen gauge length (0.28″) or the larger distance between the two bar ends. Quasistatic [10] and dynamic [11] calibrations have been used to determine the characteristic length, assuming that the calibrations would hold irrespective of differences in material behavior. High-speed photography coupled with a Bridgman-type analysis has been used to estimate the stress and strain in the necking region [12]. Gilat and co-workers [13,14] studied the effects of specimen geometry using both experiments and computational analysis, considering in particular specimens that had negligible transition regions between the gauge length and the flanges, and concluded that valid experiments could be performed with specimen gauge length to diameter ratios greater than 1.6. However, the corresponding complex stress states at the corners may make it difficult to use such specimens to evaluate the tensile failure strains of materials. The dynamic tension experiments of Rodríguez et al. [15] on aluminum alloys and stainless steel showed that the average strain obtained from the conventional Kolsky bar approach deviated from the strain measured using on-specimen strain gauges when the strain was larger than 2% (these workers used a specimen gauge length to diameter ratio of 2.5, larger than the minimum ratio suggested by Staab and Gilat [13]). Rodríguez et al. [15] also performed finite element analysis and demonstrated that the necessary specimen effective length to gauge length ratio is a function of specimen geometry and material behavior. More recently, Verleysen and Degrieck [16] used a streak camera with a grid on the specimen to measure the specimen strain, and found that good agreement with the optical measurement could achieved if an effective gauge length of 8.8 mm was be used in the conventional method. This effective gauge length was different from both the specimen gauge length (6 mm) and the distance between the two bar ends (16 mm).

The difficulties that arise in determining the specimen strains from the tension Kolsky bar are similar to those that arise in any tension experiment, but are compounded by the wave propagation problem in the Kolsky bar arrangement. The issues are most easily understood using a computational approach.

2. Numerical simulations

Typical tension specimens for Kolsky bar experiments are of the types shown in Fig. 1(a) and (b). Specimens of the type shown in Fig. 1(a) are glued to the bars, while specimens of the type shown in Fig. 1(b) are attached to the bars using threaded ends. Both types of specimens were used in the experiments described here, but for purposes of simulation we choose to focus on the more complex specimens of Fig. 1(b) (these are the more common, since the threaded grips can carry higher loads). A schematic of such specimens is shown in Fig. 1(c) (note the actual dimensions are shown in Fig. 1(b)). The distance between the bar ends (i.e. the exposed segments outside the threaded ends) is denoted by L_1, and the corresponding axial strains (i.e. strains which are estimated using L_1 as the specimen length) will be denoted as L_1-strains. The defined specimen gauge length itself (the parallel sides beyond the fillet radius) is denoted by L_0, and the corresponding axial strains (i.e. strains which are estimated using L_0 as the specimen length) will be denoted as L_0-strains.

Full numerical simulations of the dynamic tension of the specimen have been performed, using the ABAQUS explicit finite element code to deal with this nonlinear dynamic boundary value problem. Using the axisymmetric nature of the problem, half of the input bar is divided into 3088 elements, half of the specimen into 1208 elements and half of the output bar into 2288 elements. Contact pairs are used between specimen threads and bar threads. The mesh used for the specimen, together with the two bar ends is shown in Fig. 1(d). The integration time step was chosen automatically (it is forced to always remain below the Courant limit with respect to the smallest element), and the total simulation time amounted to 1.5 ms after the transmitted pulse passed the gauge station on the output bar. The axial displacements at both ends of the bars connected to the specimen and the radial displacement at the middle of the specimen are also calculated.

Both the input and output bars were assumed to be made of 7075-T6 aluminum alloy and to deform elastically, with a Young's modulus $E = 70\,\text{GPa}$, a Poisson's ratio $\nu = 0.33$ and a density $\rho = 2700\,\text{kg/m}^3$. The specimen material was characterized as an isotropically hardening, rate-dependent elastic–plastic solid that