Mechanics of Materials 58 (2013) 84–96

Contents lists available at SciVerse ScienceDirect

Mechanics of Materials

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

The dynamic effect of necking in Hopkinson bar tension tests

Giuseppe Mirone *

Dipartimento di Ingegneria Industriale e Meccanica, University of Catania, Viale A. Doria 6, 95125 Catania, Italy

ARTICLE INFO

Article history:
Received 13 April 2012
Received in revised form 14 September 2012
Available online 2 December 2012

Keywords:
Hopkinson bar
Necking
True strain rate
True strain
Hardening

ABSTRACT

The determination of the stress–strain curves from static and dynamic tension tests is affected by the necking which locally modifies the stress distributions and the stress state, so that uniformity and uniaxiality of the stress state cease to apply and the load-area reduction measurements do not allow anymore to calculate the equivalent plastic strain and the equivalent stress at any material point within the resisting cross-section.

In case of dynamic tension tests, the necking also influences the effective strain rate, causing it to substantially differ from the nominal applied strain rate.

The effects of the necking on the strain rate and on the related material response are investigated here, and it is also checked whether or not a material-independent function previously developed for correcting the post-necking true curves in quasi static tests, can also be used for correcting the stress–strain curves from Hopkinson bar testing and transforming them into equivalent stress vs. equivalent strain curves at a given strain rate.

Finite elements analyses simulating experimental tests are compared to experimental data from the literature so that, from the validated numerical results, stress and strain distributions in the interiors of the specimens can be investigated in detail.

1. Introduction

Material testing at strain rates in the range $(10^2 - 10^4)\,s^{-1}$ is usually conducted by way of the Split Hopkinson Pressure Bar (SHPB) (Gilat et al., 2009; Staab and Gilat, 1991; Lee and Kim, 2003; Meng and Li, 2003), based on the reflection and the transmission of stress–strain waves travelling along two slender bars, elastically loaded, and into the specimen, placed between the two bars and loaded beyond its elastic range and up to failure.

In the SHPB, the compressive strain wave on the input bar is generated by the impact of a projectile launched by a gas-gun or by a similar device (Fig. 1(a), but various other system configurations as in Fig. 1(b) have been developed for inducing tensile and shear dynamic stress states (Gilat et al., 2009; Staab and Gilat, 1991; Lee and Kim, 2003; Kobayashi et al., 2008; Suhadi et al., 2009). Here the attention is focused on the split Hopkinson tension bar (SHTB) which facilitates the attainment of higher strains and the failure of ductile metals.

In typical SHTBs, a cylindrical specimen with threaded ends is mounted between the input and the output bars, and a trapezoidal or approximately rectangular tensile strain pulse is generated at the free end of the input bar by adopting various machine layouts ranging from tubular strikers concentric to the bars (Verleysen and Degrieck, 2004; Verleysen et al., 2005), to the input bar pre-tensioning (Staab and Gilat, 1991), to compression setups with rebound sleeves coaxial to the specimen (Sasso, 2005; Sasso et al., 2007).

The imposed tensile wave (incident wave) travels through the input bar till the bar–specimen interface, where it is partially reflected and partially transmitted according to the impedances of specimen and bars. The imposed tensile wave has an overall wavelength much greater than the specimen's length, so that many successive wave reflections dynamically load the specimen in small discrete load steps, eventually up to failure. The reflections of long waves within a short specimen ensure

* Tel.: +39 0957382418; fax: +39 095337994.
E-mail address: gmirone@diim.unict.it

0167-6636/$ - see front matter
http://dx.doi.org/10.1016/j.mechmat.2012.11.006

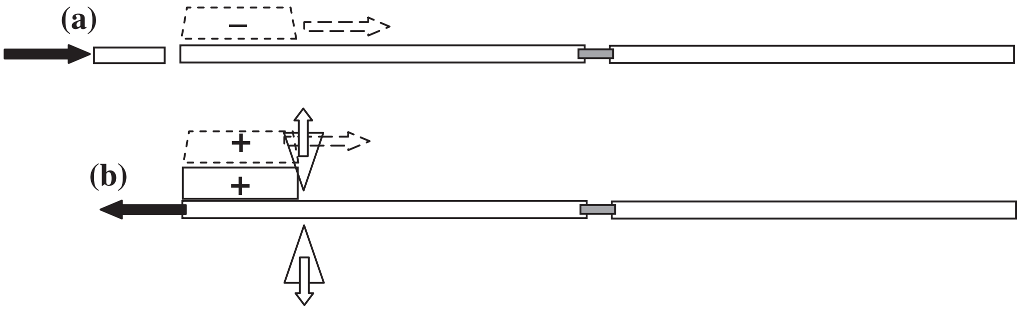

Fig. 1. Hopkinson bar configurations for compression (a) and tension (b) test.

that deformation and strain rate within the specimen can be assumed as almost uniform after a few reflections occurred.

Input and output bars have a low D/L ratio for ensuring uniformity and uniaxiality of stress and, in turn, minimising radial strains and wave dispersion. At the same time, the bars' cross section cannot be too small for avoiding yielding.

The impulsive character of the loading causes typical incident waves to have a large number of harmonics with different frequencies, travelling into the bars at different speeds. This means that the wave distorts its shape as it travels along the bars, and various ways are available for preventing, reducing, correcting or compensating this effect (Verleysen et al., 2005; Meng and Li, 2003; Sasso, 2004; Ramirez and Rubio-Gonzalez, 2006; Sasso, et al., 2007).

A very well known phenomenon introducing significant approximations in SHTB experiments is the necking, whose effect, investigated here, is usually neglected or only partially accounted for.

Experimental data available in literature (Johnson and Cook, 1983; Noble et al., 1999; Ruggiero, 2005) are used for validating finite elements simulations of four SHTB tests (Balokhonov et al., 2009). The validated numerical data are then used for calculating local distributions of stresses and strains in meaningful zones within the specimen, also during the post-necking phase.

The numerical simulations confirm that, in case of dynamic straining, the necking introduces one more effect than it does for quasi-static tests. In fact, while for static tests the only necking-induced modification of ideal conditions is the gradually increasing triaxiality and non-uniformity of stress enforced all over the minimum cross section, when it comes to high strain rate tests, the neck localization also induces very sharp peaks of strain rate.

This result is in perfect agreement with recent experimental results (Gilat et al., 2009), and also constitutes a quantitative analysis of the strain rate amplification which can be expected in SHTB tests due to the necking.

The usual strain gauge recordings from Hopkinson Bar tests allow to derive the current specimen load (averaged on the two specimen–bars interfaces), and the current total specimen elongation; these two variables are easily transformed in engineering stress and engineering strain, respectively, by simply referring to the dimensions of the undeformed specimen.

However, for identifying the elastoplastic response of metals, the hardening functions relating the equivalent von Mises stress σ_{Eq} to the equivalent plastic strain $\varepsilon_{\mathrm{Eq}}$ must be determined. Before the necking initiation, σ_{Eq} and $\varepsilon_{\mathrm{Eq}}$ coincide with the true stress (σ_{True}, current ratio of load to cross section) and the true strain ($\varepsilon_{\mathrm{True}}$ logarithmic strain based on the area reduction), both easily obtainable from the engineering stress and strain data.

After the necking initiates, the true stress and the true strain cannot be derived anymore from the engineering stress–strain data, and also if other means are adopted for their derivation (e.g. neck diameter measurement by fast cameras and image analysis), σ_{True} and $\varepsilon_{\mathrm{True}}$ cannot accurately represent the post-necking material curve; in fact, the necking induces a gradually increasing triaxiality of the stress state and the consequent departure of the true stress from the Mises stress.

Ductile metals may be subjected to pronounced necking during more than 90% of their straining life so that, at failure, the error in approximating the Mises stress with the true stress may be greater than 15% or 20%.

Then a correction is needed in the post necking strain range for eliminating the effect of the necking-induced triaxiality from the true stress (Bridgman, 1956; Alves and Jones, 1999; Zhang et al., 1999; Ling, 1996; La Rosa et al., 2003; Mirone, 2004).

Such a correction was found to be material-independent for the quasi-static response of metals, and it allows converting the post-necking true stresses into accurate estimations of the von Mises stress all over the post-necking strain range (Mirone, 2004, 2007; Mirone and Corallo, 2010).

The suitability of this corrective function for determining the hardening response of metals at high strain rates (SHTB tests) is also evaluated in the next sections.

2. Stress and strain calculations for SHTB

In SHTB experiments, the engineering axial strain ε_Z, strain rate $\dot{\varepsilon}_Z$ and stress σ_Z can be calculated as follows as long as their distributions are uniform within the specimen volume:

$$\varepsilon_Z = -2 \cdot c_0/L_0 \cdot \int_0^t \varepsilon_r dt \tag{1}$$