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High strain rate tensile testing using a split Hopkinson pressure bar apparatus

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Abstract. A specially-designed specimen is proposed to investigate the tensile response of metals at high strain rates. This specimen may be directly used in a conventional split Hopkinson pressure bar system, thereby overcoming difficulties related to the gripping of traditional tensile specimens in dynamic testing. The specimen geometry has been optimized using finite element analysis. The dominant stress state in the specimen gage section is transverse plane strain. Explicit expressions are given to obtain the equivalent uniaxial stress-strain curve from the force and displacement measurements at the specimen boundaries. Quasi-static experiments have been carried and compared with standard uniaxial tensile tests to evaluate the accuracy of the force-stress and displacement-strain relationships. Using this new specimen, dynamic experiments have been performed on aluminum 2024-T351 showing that strain rates in the range of 1000/s may be obtained without oscillations.

1. INTRODUCTION

The virtual design of engineering structures subject to impact loading requires reliable experimental data for the development and calibration of computational material models. It is common practice to make use of the split Hopkinson pressure bar (SHBP) technique to determine the dynamic behavior of materials under uniaxial compressive loading. In addition to compression testing, the split Hopkinson bar technique has been developed for the torsion testing of cylindrical specimens. Dynamic tensile tests may also be performed by the means of a split Hopkinson bar apparatus. However, due to experimental difficulties, dynamic tensile tests are not very often used to characterize the high strain rate response of engineering materials. Consequently, most existing strain-rate dependent plasticity models have been developed on the basis of experimental data for uniaxial compression and shear.

While the high strain rate deformation response of metals under tension may be estimated within reasonable accuracy based on compression or shear data, dynamic tensile tests are indispensable in characterizing the crack initiation in metals. Most challenges in designing dynamic tensile experiments are related to the gripping of the specimen. When measuring the forces and displacements by the means of bars, the tensile specimen needs to be attached to the respective ends of the so-called incident and transmitter bars. For this, specimens with threaded specimen shoulders are usually directly screwed into the bar ends. As pointed out by Nicholas [1], reliable testing of threaded specimens requires the elimination of all play out of the joints; in addition, perfect alignment of a considerably short tensile specimen is needed (Harding, Wood and Campbell [2]). The threads inside the bar ends generate spurious wave reflections in the vicinity of the bar-specimen interface. Failure to eliminate all gaps will amplify these reflections further, ultimately making it impossible to determine the forces and displacements at the specimen boundaries.

In this paper, we propose a specimen especially designed for the tensile testing in a split Hopkinson pressure bar apparatus. In close conceptual analogy with Luong's tensile specimen for geological materials [3], the specimen converts an incoming pressure pulse into a tensile pulse acting on the specimen gage section. One key advantage of this technique is that those tests may be performed without

attaching the specimen to the bar ends. Instead, the specimen is freely positioned between the flat ends of the incident and transmitter bars. Further, a conventional split Hopkinson pressure bar apparatus may be used to generate the incoming wave, thereby avoiding difficulties related to the generation of a tensile pulse in the incident bar.

2. SPECIMEN

Figure 1(a) shows the front view of the proposed specimen. It is called ‘M-specimen’ because its shape resembles the letter ‘M’. The M-specimen is designed to convert an incoming compression wave into tension within its characteristic gage sections. The section between the points F and E is predominantly under compression. Similarly, the section A-B is subject to compressive loading while the sections B-C and D-E are subject to shear and bending loading. The specimen gage sections C-D on the other hand are predominantly stretched. The key design considerations in choosing the specimen dimensions are:

- (i) *Limit plastic deformation to the gage section.* The geometric dimensions of the specimen must be chosen such that the gage section deforms plastically throughout the experiment while the surrounding specimen structure responds in a purely elastic manner. This must hold true for large deformations and strain hardening within the gage section.
- (ii) *Minimize bending deformation.* In the context of geometrically linear elasticity theory, the bending of sections D-E and B-C would not affect the stress and strain uniformity within the specimen gage section. However, in the case of finite deformations, the bending-induced rotation of points C and D will disturb the otherwise uniform fields within the gage section. To minimize the bending loads, the length of the sections B-C and D-E should be as small as possible. Another efficient technique is the insertion of spacer blocks in the slot between C and F, thereby preventing the bending-induced lateral (inward) motion of point C.
- (iii) *Prevent buckling.* The section A-B is subject to compressive loading and therefore prone to buckling. Its minimal length is determined by the length of the gage section, the height of the bent-sections D-E and B-C, and the displacement to fracture of the gage sections. Here, we make use of an exterior frame that prohibits the lateral (outward) motion of point A. As a result, the effective buckling length of section A-B is significantly reduced, thereby increasing its structural stability.

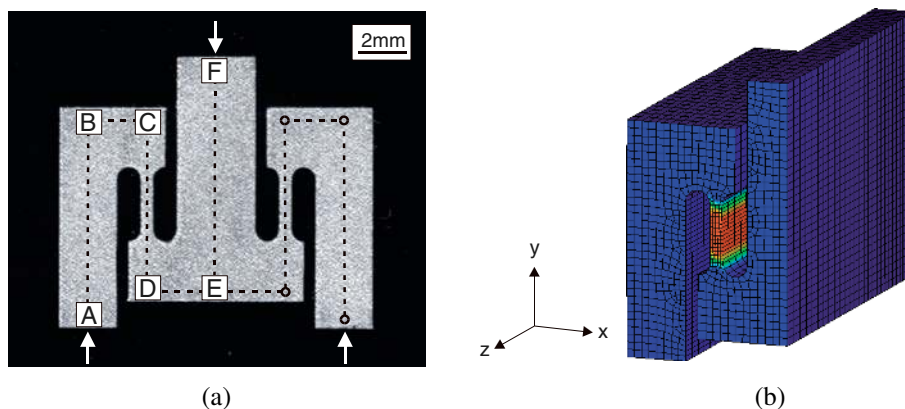


Figure 1. (a) Photograph of the EDM machined specimen, (b) 3D finite element model representing one quarter of the M-specimen (symmetry planes x - y and y - z); the contour plot indicates the intensity of the equivalent plastic strain.

- (iv) *Minimize the distance of wave travel.* The maximum acceptable loading velocity is limited by the time it takes for an incoming stress wave to travel from the top to the bottom boundary of the specimen. Clearly, this duration is directly related to the distance of wave travel. It is important that the specimen is in equilibrium throughout the dynamic experiment, i.e. the duration of wave travel must be small as compared to the duration of the loading pulse. Consequently, the total distance of wave travel along the path F-E-D-C-B-A must be short.
- (v) *Achieve transverse plane strain conditions.* The stress and strain fields also depend on the specimen width (the dimension in z-direction, Fig. 1b). The stress state within the gage section is uniaxial when the specimen width is of the order of the gage section thickness. However, in view of problems related to the specimen alignment (with respect to the loading platens) and the force measurement accuracy, the chosen specimen width should be large as compared to the gage section thickness and gage length which ultimately results in transverse plane strain conditions within the gage section. In other words, the strains along the z-direction are approximately zero.

Based on these considerations, we conclude that the gage section should be as thin as possible for optimal specimen performance in terms of maximum strain rate and field uniformity within the gage section. For the present specimen, we chose a gage section thickness of 0.5mm which results in overall specimen dimensions that can still be manufactured within reasonable accuracy using a computer-controlled wire EDM. A fully three-dimensional finite element model of the specimen (Fig. 1b) has been used to assess the stress and strain field uniformity within the specimen gage section.

3. DETERMINATION OF THE STRESS-STRAIN CURVE

Throughout the experiment, the forces and displacements are measured at the specimen boundaries, i.e. at the top and bottom surfaces of the M-specimen. Assuming that the specimen is in equilibrium ($F_{top} = F_{bot}$), the resulting experimental output is a single force-displacement curve $F(u)$ where $u = u_{top} - u_{bot}$. In the following, we determine the stress-strain curve for specimens made from Levy-Mises materials. For small to moderate deformations, we assume the additive decomposition of elastic and plastic deformation at the displacement level,

$$u = u_e + u_p \quad (1)$$

Moreover, it is assumed that the elastic displacements u_e depend linearly on the applied force F ,

$$F = Ku_e \quad (2)$$

where the stiffness K accounts for the elastic stiffness of the specimen and the testing device. We have the nominal stress along the gage length, Σ_{yy} ,

$$\Sigma_{yy}(t) = \frac{F(t)}{A_0} \quad (3)$$

where A_0 denotes the total initial cross-sectional area of the gage sections. Assuming a constant effective gage section length l_0 , the corresponding nominal plastic strain, E_{yy}^p , reads:

$$E_{yy}^p(t) = \frac{u_p}{l_0} = \frac{u(t)}{l_0} - \frac{F(t)}{Kl_0} \quad (4)$$

Further, we calculate the true stress

$$\sigma_{yy} = (1 + E_{yy}^p)\Sigma_{yy} \quad (5)$$

and the logarithmic plastic strain

$$\varepsilon_{yy}^p = \ln(1 + E_{yy}^p) \quad (6)$$

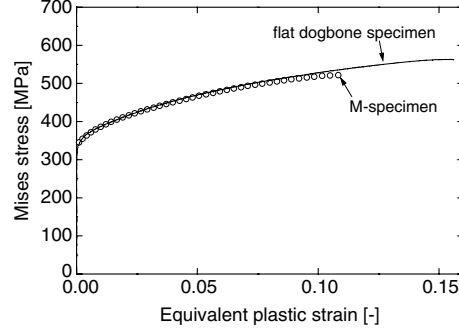


Figure 2. Stress-strain curve for static loading as obtained from the testing of a flat dogbone specimen and the M-specimen.

Assuming transverse plane strain conditions, we have the corresponding equivalent plastic strain:

$$\bar{\epsilon}^p(t) = \frac{2}{\sqrt{3}} \epsilon_{yy}^p(t) \quad (7)$$

and the equivalent Von Mises stress

$$\bar{\sigma}(t) = \frac{\sqrt{3}}{2} \sigma_{yy}(t) \quad (8)$$

Thus, using Eqs. (7) and (8), the stress-strain curve $\bar{\sigma} = \bar{\sigma}(\bar{\epsilon}^p)$ can be determined based on the experimental measurements $F(t)$ and $u(t)$.

Static experiments on specimens machined from aluminum 2024-T351 have been performed to validate the proposed relationships for the stress-strain curve. For this, the M-specimen is placed between the flat loading platens of a screw-driven universal tensile testing machine (Model G45, MTS). The measured force-displacement history follows closely that obtained from numerical simulations. Subsequently, the Mises stress versus equivalent plastic strain curve has been calculated using the equations above. It was found that the calculated stress level is about 2% too low due to perturbations in the plane-strain stress field near the boundaries of the cross-section. Furthermore, the measured stress-strain curve needed to be corrected by a very small offset of about $\Delta\bar{\epsilon}^p = 0.0025$ in order to match with that obtained from uniaxial tensile testing. This effect could be attributed to some initial bending-induced deformation which precedes the plastic deformation due to uniform stretching of the gage section. The resulting stress-strain curves as obtained from static testing are shown in Fig. 2.

4. DYNAMIC EXPERIMENTS

A SHPB apparatus consisting of two straight aluminum bars and an aluminum striker bar is used to subject the specimen to dynamic loading conditions. All bars are of cylindrical cross-section of 40mm diameter. The lengths are 1203mm for the striker bar, 2991mm for the incident bar, and 1850mm for the transmitter bar. Strain gages are positioned near the center of the incident bar (at a distance of 1493mm from the specimen/bar interface) and on the transmitter bar (at a distance of 335mm from the corresponding specimen/bar interface). The amplified signals of the strain gages are recorded at a sampling frequency of 1MHz.

After testing, the recorded incident, reflected and transmitted waves are ‘transported’ to the respective bar/specimen interfaces while correcting for geometrical dispersion (using the DAVID software). Consequently, the force and velocity histories are determined at both the top (incoming) and bottom (outcoming) specimen boundaries.

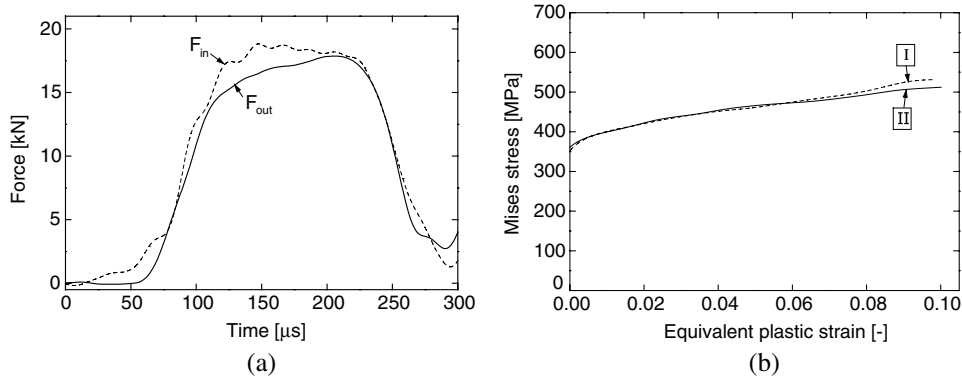


Figure 3. Experiments at an equivalent plastic strain rate of about $\dot{\epsilon}^p = 1075/s$: (a) Plot of the measured force histories $F_{in}(t)$ and $F_{out}(t)$ at the top and bottom boundary, respectively; (b) Stress-strain curves for two dynamic experiments (striker velocities $v_I = 4.10m/s$ and $v_{II} = 4.33m/s$).

The incoming and outgoing force histories for a selected experiment performed at a striker impact velocity of 4.33m/s are shown in Fig. 3a. The small deviation of the two curves indicates that the specimen is still under quasi-static equilibrium during the present experiment. The corresponding stress-strain curve is plotted in Fig. 3b. The same curve is shown for another experiment which has been performed at a similar velocity. Both curves are very close, which demonstrates the repeatability of the present experiment. Throughout the experiment, the equivalent plastic strain versus time curve (not shown) increases in a considerably linear manner at an average strain rate of about 1075/s.

Nonlinear finite element simulations of the split Hopkinson pressure bar experiment (FEA model including specimen and bars) have been performed to assess the quasi-static equilibrium at higher strain rates. Preliminary results have indicated that for impact velocities of up to 10m/s, the hypothesis of quasi-static equilibrium still holds approximately true. However, for very high loading velocities, the duration of the real experiment is only little longer than the rise time of the incoming wave (about 50μs). Therefore, perturbing transient effects related to the Pochhammer-Chree oscillations following the initial rise are likely to limit the strain rate range of reliable material characterization for the present experimental technique.

5. CONCLUSION

A new specimen has been proposed to characterize the high strain rate response of bulk metals under tensile loading. The specimen converts compression at its boundaries into tension within its gage section. Consequently, it can be used in conjunction with a split Hopkinson pressure bar apparatus, thereby circumventing difficulties associated with the gripping of specimens in conventional dynamic tensile testing devices. It is shown experimentally that this M-shaped specimen provides reliable results for strain rates of up to 1000/s.

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