On the use of the symmetric Taylor test to evaluate dynamic ductile compression fracture properties of metals

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Abstract

Failure under dynamic compression of ductile tungsten alloys was examined by conducting symmetric Taylor tests at impacted speeds ranging from 200 to 350 m/s. A fracture parameter consisting of the average surface shear crack length was identified and computed as a function of the impact velocity. From these data, a threshold speed characterizing shear failure was deduced and found to be a mean of differentiating dynamic compression fracture properties of metals.

1 Introduction

The Taylor test has been used over the past fifty years as a mean to evaluate dynamic mechanical property of materials [1]. Because the Taylor test involved stress and strain rate singularities, the Hopkinson pressure bars test generating dynamic stress-strain responses under a constant strain rate is more currently employed [2]. However, the strain rate limitations of the
Hopkinson test of the order of $5 \times 10^3 \text{ s}^{-1}$ [3] motivate today’s use of the Taylor test for which local strain rates up to $7.5 \times 10^4 \text{ s}^{-1}$ [4] can be achieved. The main application of the Taylor test is the validation over the full strain rate range $10^{-4}$ to $10^4 \text{ s}^{-1}$ of constitutive models calibrated with Hopkinson tests. The validation is carried out by performing numerical simulations of Taylor tests. The present work provides another application with regard to the evaluation of dynamic compression failure properties of ductile metals. By varying the impact speed from 200 to 350 m/s, symmetric Taylor testing is shown to be a mean of monitoring dynamic compression failure of ductile tungsten alloys.

2 Experimental Procedure

Taylor testing was performed under symmetric loading conditions using the approach of Erlich et al. [5]. When compared to single Taylor testing, symmetric Taylor testing has the primary advantage to eliminate friction at the loading interfaces therefore facilitating experimental interpretations and numerical simulations of the Taylor experiment. Taylor testing was conducted with as sintered and 25 % swaged 91W-6Ni-3Co alloys of static yield strength of 760 and 1500 MPa and static elongation of 20% and 10%, respectively, provided by Cime Bocuze of Giat Industries.

An improved testing procedure of the symmetric Taylor test involving Teflon sabots was developed, as shown in Figure 1. The loading system consists of a 25 mm caliber gas gun launching up to 600 m/s one Taylor specimen guided with a Teflon sabot against a second Taylor specimen positioned with an identical Teflon sabot in a Taylor guide fitted to the gun muzzle. The use of Teflon sabots facilitates planar and coaxial impacts without interfering with the loading phase. The test implicates two specimens 9 mm in diameter and 35 mm in length. As indicated in the
Figure, velocity measurement was conducted using a 18 mm-base-length two-laser-beams device located 30 mm behind the impact plane. As shown in Figure 2, X ray records were generated prior impact to verify that the Taylor specimen sitting at the gun muzzle did not move prior impact and to identify the impact time, and during loading to provide intermediate specimen profiles.

![Symmetric Taylor test schematic. The launched Taylor specimen is on the right. The speed of the launched specimen, V, is measured with a two-laser-beams device.](image)

3 Numerical Procedure

Numerical simulations were conducted with the Lagrange processor of the finite difference finite element hydrocode AUTODYN-2D [6]. The simulations were conducted with a numerical model simulating the Taylor specimens, the Teflon sabots and the Taylor guide. The mesh of the Taylor specimens is composed of square elements varying in size from 500 μm for the elastically loaded region to 250 μm in the plastically loaded region. An
Figure 2: X ray observations of swaged alloy symmetric Taylor specimens tested at an impact speed of 284 m/s: a) X rays to evaluate the impact time and to verify that the left Taylor specimen sitting at the gun muzzle did not move prior impact, b) X ray taken 20 μs after impact.
elastic shear modulus of 119 GPa was used. High strain rate and temperature was taken into account using Johnson and Cook constitutive models [7]. The models were calibrated to reproduce constant strain rate experimental data at 23°C at a strain rate of 1 and 5 x 10³ s⁻¹, and at 600°C at a strain rate of 1 s⁻¹ under adiabatic conditions. The model expresses the equivalent stress as:

\[
\sigma = (A + B\varepsilon_p^n)(1 + C\ln(\dot{\varepsilon}/1\, s^{-1}))(1-(T-300)/(T_m-300)^m)
\] (1)

with \(\varepsilon_p\), \(\dot{\varepsilon}\), and \(T\) the equivalent plastic strain, the strain rate, and the temperature, respectively. Constant values are provided in Table 1. To calculate the temperature rise due to plastic deformation, a Quinney coefficient of 0.9 was used along with an estimated specific heat coefficient, \(C_{pe}\), of 164 J / (kg °K) corresponding to:

\[
C_{pe} = 0.91 (C_p)_{W} + 0.06 (C_p)_{Co} + 0.03 (C_p)_{Ni}.
\] (2)

Table 1: Johnson and Cook constitutive model constants.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>A</th>
<th>B</th>
<th>n</th>
<th>C</th>
<th>m</th>
<th>(T_m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As sintered</td>
<td>500</td>
<td>2500</td>
<td>0.31</td>
<td>0.023</td>
<td>0.770</td>
<td>1485</td>
</tr>
<tr>
<td>25% swaged</td>
<td>1948</td>
<td>1875</td>
<td>0.95</td>
<td>0.030</td>
<td>0.835</td>
<td>1485</td>
</tr>
</tbody>
</table>

4 Results

Figure 3 shows the swaged alloy tested at impacted speeds of 207 and 301 m/s. For the lower impact speed, large plastic deformation is observed at the impact site without any evidence of cracking. At the highest impact
Figure 3: Swaged alloy symmetric Taylor specimens tested at a) 207 m/s and b) 301 m/s.
Figure 4: Swaged alloy symmetric Taylor specimens tested at 301 m/s showing 45° failed shear bands.

Figure 5: Impact speed of the launched Taylor specimen function of the average shear crack length $a_s$. The F symbol indicates that complete fracture of the specimens occurred.
speed, shear cracks were observed and found from observations of sectioned specimens to originate from shear bands [8]. For the as sintered microstructure, shear cracks were also generated but without evidence of shear banding.

By conducting Taylor testing at intermediate speeds, the amount of surface shear cracks was found to steadily increase with the increase of the impact speed. To quantify the amount of shear fracture, shear crack lengths, $a$, were measured, see Figure 4, and used to calculate an average shear crack length, $a_s$, equal to the sum of the shear crack lengths divided by the number of shear cracks. Figure 5 shows the fracture parameter, $a_s$, as a function of the impacted speed. A threshold speed of 250 m/s can be deduced for shear band initiation of the swaged microstructure while a threshold speed of 290 m/s has been identified for shear fracture initiation of the as sintered microstructure.

Simulations of the Taylor test were conducted to describe the strain and stress states at the threshold speeds of 250 and 290 m/s for the swaged and as sintered alloys, respectively. Figure 6 compared the effective plastic strains. Large plastic deformation on both sides of the shear band path for the swaged alloy and of the fracture path for the as sintered configuration are reported with maximum deformations of 0.8 at the loading side zones. The shear band path of the swaged alloy is characterized by effective plastic strains varying from 0.3 to 0.5. Shear band and fracture paths for the swaged alloy involve pressure of 500 Mpa and effective plastic strain of 0.4. Shear fracture in the as sintered alloy occurs at lower pressures of the order of 200 MPa and at an average effective plastic strain of 0.5.

Differences between the loading histories of the two microstructures were identified through the temperature calculations for material points
Figure 6: Equivalent plastic strain distribution in the Taylor specimens a) at 250 m/s for the swaged alloy and b) at 290 m/s for the as sintered alloy. The shear failure paths, SFP, are indicated.
within the maximum shear stress zones. Comparisons were performed at an effective plastic strain of 0.35. A higher temperature, 276 °C, was calculated at the onset of shear banding for the swaged alloy when compared to 228°C at the onset of shear fracture for the as sintered alloy. Similar temperature differences were calculated from simulations of Hopkinson pressure bars tests conducted at $5 \times 10^3$ s$^{-1}$, for which shear banding was only observed with the swaged alloy [8]. These differences in temperature were found to be associated to the non hardening behavior of the swaged alloy implying greater plastic work. The larger generated plastic work results in a higher heat production, therefore in higher temperatures. These results indicate that shear band formation in tungsten alloys is temperature dependant.

5 Conclusions

Symmetric Taylor testing was found to be a mean of evaluating dynamic failure properties of ductile as sintered and swaged tungsten alloys. Critical threshold impact speeds characterizing compression failure involving shear cracks were deduced. The lower threshold impact speed for the swaged alloy was associated to the alloy capability of generating shear bands. The swaged alloy ability to form shear bands was found to be related to higher local temperatures reached during plastic deformation.

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References


