SHOCK WAVE EFFECTS IN COPPER: DESIGN OF AN EXPERIMENTAL DEVICE FOR POST RECOVERY MECHANICAL TESTING

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Abstract. The mechanical behavior of metals may prove high changes with strain rate and pressure loading history. In order to investigate the effect of a shock on the ulterior mechanical behavior of high purity copper, we set up an experimental device inspired from G. T. Gray Ill’s works. This device, based on the trapping of shock waves after a plane plate impact is validated by numerical simulations. The aim of these simulations is the evaluation of the heterogeneity of plastic deformation. Shock pressures up to 10 GPa have been investigated. The plastic strain levels subsequent to the shock are between 0.08 and 0.15 in the sample.

INTRODUCTION

The mechanical behavior of metals depends on the thermomechanical conditions they are submitted to. From a macroscopic point of view, the modeling of this behavior is rather well known for many metals when the loading conditions don’t change during the test. In fact, the microstructural defects such as dislocations, twins... steadily evolve during the test in a rather gentle way, these evolutions depending on the loading. However, when a sudden change in the loading conditions is observed, the microstructure evolution reveals to be different from what it used to be in “quasi monotonic conditions”. In particular, when we consider a shock, the changes in terms of pressure, strain rate, temperature lead to a drastically different behavior [1–3].

In order to investigate the effect of a shock on the mechanical behavior of copper, we have performed several numerical simulations with Hesione, a CEA hydrodynamic code used in its Lagrangian version. The goal of this work is to check that no damage will affect the sample and to estimate the deformation path the sample encounters during the loading in terms of cumulated deformation, strain rate and homogeneity.

NUMERICAL CONDITIONS

Geometry

The initial geometry is presented in a companion paper [4]. The device is composed by a flying target whose composition and velocity are described in table 1 and by an assemblage of several elements:

- a cover plate (copper 40 mm in diameter, 3.5 mm thick)
- a sample (copper 40 mm in diameter, 7 mm thick)
- a cone shaped confinement (copper)
- a spall plate which traps the release waves (copper)
- a surrounding aluminum ring to maintain the assemblage on the launcher.
TABLE 1. Test conditions

<table>
<thead>
<tr>
<th>Test number</th>
<th>Flyer plate</th>
<th>Impact velocity</th>
<th>Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Cu φ 58 mm thickness 3 mm</td>
<td>450 m.s⁻¹</td>
<td>0.1 mm gap around the sample</td>
</tr>
<tr>
<td>T2</td>
<td>Ta φ 55 mm thickness 3 mm</td>
<td>450 m.s⁻¹</td>
<td>0.1 mm gap around the sample</td>
</tr>
<tr>
<td>T3</td>
<td>Cu φ 55 mm thickness 2 mm</td>
<td>400 m.s⁻¹</td>
<td>0.1 mm gap around the sample</td>
</tr>
</tbody>
</table>

The global mesh density is 2 meshes per mm. Three test conditions are presented in this paper (cf. Table 1). The simulations are made in 2 dimensional axisymmetrical conditions. (Fig. 1). We have found it important to introduce a gap of 0.1 mm around the sample which is consistent with the machining configuration to have a better evaluation of these effects.

Constitutive equations

Several constitutive models were tested for copper (Steinberg–Cochran–Guinan, Johnson–Cook, Zerilli–Armstrong). The final result is not significantly affected by the model. We present results obtained with a modified Zerilli–Armstrong constitutive law [6].

\[ \sigma = C_0 + C_3 \varepsilon^{1/2} \exp(-C_1 T + C_4 T \ln \dot{\varepsilon}) \]  

The following coefficients have been optimized from compression test in the range of temperature 77 – 700 K and 10⁻³ to 10³ s⁻¹ [7].

TABLE 2. ZA coefficients for copper

<table>
<thead>
<tr>
<th></th>
<th>C₁</th>
<th>C₂</th>
<th>C₃</th>
<th>C₄</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>69.58 MPa</td>
<td>936.64 MPa</td>
<td>0.00176 K⁻¹</td>
<td>5.77 10⁻³ K⁻¹</td>
</tr>
</tbody>
</table>

Damage

In order to simulate the effect of damage, we considered a spall stress of 1.2 GPa.

RESULTS

Figure 3 presents the evolution of pressure of a copper plate impacting the assemblage (T1). The pressure level reaches 8.5 GPa. Almost all the energy due to the impact is trapped in the back plate. Thus, there is no tension shock wave coming back to the sample (Fig. 4) and we can consider that no ulterior phenomenon affects the sample after 50 μs (Fig. 4 and 5).
In the sample, three different stages can be considered:

- a sudden rise in strain due to shock compression,
- a release that brings the sample dimensions very close from the initial geometry,
- two-dimensional waves that bring the sample in its final configuration.

<table>
<thead>
<tr>
<th></th>
<th>( T_1 )</th>
<th>( T_2 )</th>
<th>( T_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Pressure</td>
<td>8.5 GPa</td>
<td>10 GPa</td>
<td>9 GPa</td>
</tr>
<tr>
<td>Shock duration</td>
<td>1 ( \mu )s</td>
<td>1 ( \mu )s</td>
<td>1.5 ( \mu )s</td>
</tr>
<tr>
<td>Axial deformation in the sample</td>
<td>1.0%</td>
<td>3.0%</td>
<td>7.5%</td>
</tr>
</tbody>
</table>

In all three cases, the mean pressure in the sample is of the same kind and thus, the axial strain after the elastic loading and the Hugoniot is roughly the same (4%). The subsequent unloading is also the same but, according to the shock pressure level and duration, the importance of the third stage is more or less important. This level of deformation in the third stage appears to be of the same level in the case of a “Cu+Ta” flyer (T3) as the deformation obtained after the compression stage. On the contrary, in the case of the “Cu flyer” (T1), the influence of the radial waves on the amplitude of the third stage is small.

Thus, the deformation path to reach the residual deformation is highly non monotonous. These phenomena have been very clearly been analyzed by Gray and al. [2]. The levels of axial strain depicted in their paper is of the same kind as the ones we find. One has to be aware that the final deformation does not correspond to the total plastic deformation the sample is submitted to.

In order to check the homogeneity of the deformation, we followed the deformation level of lagrangian points at different diameter and thickness position. Figure 6 shows the cumulated strain at different positions in the sample which is the most pertinent parameter to estimate the shock loading effects. It can be noticed that in configurations T1 and T2, the deformation is rather homogeneous. However, configuration T3 exhibits high dispersion.
In this paper, we have investigated the ability to recover a copper sample submitted to shock pressures around 10 GPa. We have noticed that the reflected waves do not damage the sample and that the deformation is rather homogeneous in the sample in the case of a single flyer plate. However, one has to be much more careful for the interpretation of results coming from the third configuration.

We have to be aware that if this assemblage gives good results for shock pressure around 10 GPa, it has to be improved for higher impact velocities, the radial waves bringing the sample to decay. Two dimensional simulations are necessary for a good estimation of these radial waves. Numerical simulations proves to be a very important tool for the ulterior interpretation of post shock mechanical testing.

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REFERENCES