Ductile damage in Taylor-anvil and rod-on-rod impact experiment

G Iannitti², N Bonora¹,², A Ruggiero¹,² and G Testa¹

¹ Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, I-03043 Cassino, Italy
² TECHDYN Engineering, I-00199 Rome, Italy

E-mail: g.iannitti@techdyn.it

Abstract. At equivalent impact velocity, pressure in Taylor and ROR impact experiment is not the same and this reflects in the resulting condition for ductile damage development. In this work, finite element parametric simulation was performed to investigate pressure wave development as a function of material and target work hardening curve. Using the Bonora damage model, the impact velocity necessary for generating ductile damage in high purity copper was assessed. Taylor and ROR experiments were performed at different equivalent impact velocities and metallographic investigation were performed on impacted samples in order to validate damage model predictions. Results seems to indicate that ROR configuration is more appropriate for damage model validation while the Taylor anvil is more suitable for strength model assessment.

1. Introduction

In 1948, Taylor proposed a technique for determining the yield stress of a material at high strain rate [1]. The method, named Taylor impact test or Taylor anvil impact, consist in impacting a right circular cylinder against a rigid target and measuring post-mortem the deformed shape. The relation, proposed by Taylor, to calculate the dynamic yield stress is based on the assumption of one-dimensional wave propagation. Later, this assumption was demonstrated to be incorrect [2, 3] due to the bi-dimensional state of stress that develops inside the cylinder during the impact. In recent years, this test was rediscovered to study the mechanical behaviour of materials in the dynamic deformation range [4]. Because of the high complexity of stress, large strain and high strain rate, Taylor impact test is well suited to validate material and, as it will addressed in the paper, damage model.

Numerical simulation of Taylor impact test is affected by several issues such as friction, contact formulation, and mechanical impedance variation at the specimen-anvil interface. To resolve these problem Ertich et al. [5] modified this test by impacting a pair of identical rods, one against the other. This type of test is known as symmetric Taylor impact test or rod-on-rod (ROR) test.

The evidence of ductile damage development in ROR impact test configuration has been reported by several authors. Mayes et al. [6] performed ROR impact on annealed OFE copper with different grain size. For 75 μm initial grain size, they found that near threshold damage occurred at 300 m/s impact while more damage occurred at higher velocity (392 m/s). For 40 μm initial grain size, they reported more damage development at lower impact velocity (233 m/s). Similarly, Radford et al. [7] found evidence of void formation in half-hard copper in ROR tests at 200 and 250 m/s.

On the contrary, for copper, no evidence of ductile damage in Taylor anvil impact, at equivalent ROR impact conditions, is reported in the literature.
In this study the conditions for possible ductile damage development in Taylor anvil and ROR has been investigated using continuum damage mechanics model. In particular, the damage formulation proposed by Bonora [8] was used. Among all features, this formulation allows to account for stress triaxiality effect on material ductility; damage accumulates under tension only and, recently, a pressure dependence of damage model parameters was introduced.

Here, an extensive finite element simulation work was performed in order to estimate the impact velocity at which ductile damage is expected to initiate in high purity copper. Numerical simulation were carried out with the implicit FEM commercial code MSC MARC r2013 using direct integration algorithm. Successively, both Taylor and ROR test were performed in order to validate the damage model. Sectioning and polishing of impacted samples confirmed the accuracy of damage model prediction.

![Figure 1. Annealed copper microstructure.](image1)

![Figure 2. ROR impactor and receiver (a) before and (b) after impact.](image2)

2. Materials and methods
The material under investigation is high purity copper (99.98%) fully annealed at 400 °C for 2h with an average grain size of 40 μm, figure 1. Numerical simulations of ROR and Taylor-anvil impact were performed with the implicit finite element code MSC MARC r2013 using direct integration algorithm. For Taylor-anvil impact configuration, both the impacting cylinder and the anvil were simulated as deformable bodies. The size of the anvil was selected to avoid the reflection of stress waves at the free boundaries (infinite body). Impact cylinders were meshed to have almost square elements when large deformation develops. Alternatively, global remeshing was also used. All 2D simulations have been performed using four node axysimmetric elements with four integration points. Numerical simulations were performed running coupled thermal-elastic-plastic analysis accounting for heat generation during plastic deformation. Large plastic deformation were simulated using large displacement, finite strain and Lagrangian updating formulation. Direct integration algorithm is unconditionally stable. However, in order to follow the stress propagation process, the time step was selected as 0.8 of the time interval required for the stress wave to cross the minimum element size.

The material strength was modelled using a voce type low for the flow curve and strain rate and temperature effects were modelled using Johnson-Cook terms. Model parameters were identified based on quasi static and Hopkinson bar dynamic traction tests.

Both Taylor anvil and ROR tests were performed using an 11 mm gas gun bore. All tests were performed in vacuum and helium was used as propeller gas. Impact (and ROR receiver) cylinders were 10.8 mm in diameter and 50 mm long, figure 2. Cork sabot was used in all tests. Receiver cylinders in ROR were suspended using four fish rods and positioned near the gun exit in order to ensure normal impact conditions. Soft recovery was performed using a Gelita® ballistic gel block. In figure 3 an example of the alignment check for the ROR test is shown. For each test the deformed profile was
measured using optical comparator. Successively, deformed cylinders were sectioned and polished for optical microscopy analysis.

![Experimental setup of RoR test.](Image)

**Figure 3.** Experimental setup of RoR test.

3. Ductile damage analysis

The damage model used in this work is the CDM model proposed by Bonora [9]. This model formulation predicts ductility reduction with stress triaxiality, the accumulation of damage under tension only and does not introduce softening in the material flow curve making this formulation insensitive to mesh effects. The model predicts non-linear damage accumulation with plastic strain and is well suited for describing damage evolution in different classes of metals and alloys. The model requires four material parameters only: uniaxial plastic threshold strain \( \varepsilon_{th} \) at which damage initiates, the uniaxial failure strain \( \varepsilon_f \), the critical damage \( P_f \) and the shape parameter \( \alpha \).

For low stress triaxialities, which are usually experienced in shaped geometry such as notched bar or cracked sample, the damage threshold strain does not show a significant dependence on pressure or stress triaxiality. Investigation on spall fracture revealed that under very high stress triaxiality, such as those occurring in the flyer plate experiment, the damage threshold is reduced. Bonora et al. [8], assuming that the total damage energy dissipation is constant and independent on the load path, derived an expression for the stress triaxiality dependence of the damage threshold strain. According to this, under the assumption of proportional loading the damage threshold strain and the failure strain are given respectively by,

\[
\begin{align*}
P_{th} &= \varepsilon_{th}^{m/3} \left( \varepsilon_f^{2m} - \varepsilon_{th}^{2m} \right) \frac{1}{2m} \\
P_f &= \varepsilon_{f}^{m/3} \left( \varepsilon_f^{2m} - \varepsilon_{th}^{2m} \right) \frac{1}{2m}
\end{align*}
\]

(1)

(2)

where \( R_u = \left( \frac{2}{3} \right) (1 + \nu) + 3(1 - 2\nu)T^2 \) is a function of stress triaxiality \( T = \sigma_m / \sigma_{eq} \); \( \nu \) is the Poisson ratio; \( m \) is the strain hardening exponent in a power law approximation of the flow curve. For the uniaxial stress case, \( T = 1/3 \) and \( R_u = 1 \), \( p_{th} = \varepsilon_{th} \) and \( p_f = \varepsilon_f \). Equation (1) still predict that \( p_{th} \) does not vary significantly for low or moderate stress triaxiality. At larger stress triaxiality both \( p_{th}, p_f \) are reduced becoming closer and closer. This means that at large stress triaxiality ductile rupture occurs immediately after damage initiation [10].

This modified version of Bonora damage model was implemented into the commercial finite element code MSC MARC. For a generic material point, \( p_{th} = \varepsilon_{th} \) is assumed. During the load history, the
stress triaxiality and the corresponding $p_{th}$ is calculated. If the current accumulated plastic strain is lower than the current value of the damage threshold, no damage accumulation occurs. If the accumulated plastic strain is equal or higher than the current $p_{th}$, then damage accumulation starts and that threshold strain value remains constant for the remaining loading history for that specific material point. Numerical simulation of Taylor test and ROR were performed. Several impact velocities were investigated. For each simulation the point along the axis of the impacting cylinder where the stress triaxiality builds up most was identified. This point is located along the symmetry axis below the impacting surface and it is determined by the arrival of the release wave, starting at the free surface edge of the cylinder, and travelling toward the cylinder axis. For this point, the history of the stress triaxiality vs the accumulated plastic strain was extracted and plotted on the stress triaxiality vs ductility plot.

**Figure 4.** Stress triaxiality vs ductility plot: load path for ROR at different velocities.

**Figure 5.** Stress triaxiality vs ductility plot: load path for ROR and Taylor anvil at equivalent velocity.
According to the proposed model if the load path crosses the damage initiation/failure locus then ductile damage can occur. In figure 4 the failure locus for OFHC copper is given. The vertical axis is given in log scale in order to enhance differences between the damage initiation and failure curves. Here dots are relative to different experimental data (quasi static tractions and flyer plate). The load path at the most critical point in the ROR experiment are also shown for three impact velocity: 200, 293 and 328 m/s respectively. According to the proposed model, at 200 m/s no damage is expected to occur, while at 293 m/s and beyond ductile damage is expected to develop in the ROR.

Numerical simulation performed on Taylor anvil impact at equivalent ROR velocity, 150 m/s, indicated that although the impact velocity is the similar as well as the active plastic strain, the stress triaxiality that is generated is much lower than that obtained in the ROR, giving no possibility to the ductile damage to initiate, as shown in figure 5.

4. Results and discussion
Based on numerical simulation, ROR and Taylor anvil test were planned and executed. ROR tests were performed at 200, 293, and 328 m/s. Samples deformed profiles were acquired and successively, samples were sectioned and polished. Deformed profiles were compared with numerical results. The agreement found was very good confirming the accuracy and the correctness of the proposed strength model, figure 6. For what concerns damage, microscopy investigation revealed no damage for the 200 m/s impact, some damage at 293 m/s and fully developed damage at 328 m/s. Damage on the impact surface was visible at naked eyes, figure 7. Experiment on Taylor anvil confirmed the complete lack of damage. Damage model predictions were found to be in a very close agreement with experimental findings.

![Figure 6. Comparison between experimental and numerical profiles at different impact velocities.](image)

![Figure 7. Ductile damage in ROR.](image)

5. Conclusions
In the present work the Bonora damage model at high stress triaxiality was verified. Numerical simulations performed on both ROR and Taylor-anvil impact configuration confirm that using the active plastic strain and stress triaxiality concept allows to predict and explain the conditions for ductile damage development at different velocities. To confirm the numerical analysis ROR tests have been carried out. The ROR configuration seems to be more appropriate for damage model validation while the Taylor anvil it is for the strength model.
References
[1] Taylor G 1948 P. Roy. Soc. Lond A. Mat. 194 289-299
[2] Wilkins M L and Guinan M W 1973 J. Appl. Phys. 44 1200-1206
[3] Papirno R P, Mescall J F and Hansen A M 1980 P. Army. Sol. Mech. 20
[4] Gray G, Maudlin P, Hull L, Zuo Q K and Chen S-R 2005 J Fail. Anal. and Preven. 5 7-17
[5] Erlich D C, Shockey D A and Seaman L 1982 AIP Conf. Proc. 78 402-406
[6] Mayes J L, Hatfield S L, Gillis P P and House J W 1993 Int. J. Impact Eng. 14 503-508
[7] Radford D D, Willmott G R, Walley S M and Field J E 2003 J. Phys. IV 110 687-692
[8] Bonora N, Ruggiero A, Esposito L and Iannitti G 2009 AIP Conf. Proc. 1195 107-110
[9] Bonora N 1997 Eng. Fract. Mech. 58 11-28
[10] Ruggiero A and Bonora N 2004 AIP Conf. Proc. 706 1355- 1358