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► **To cite this version:**

Laurence Lambert-Campagne, Loïc Daridon, Saïd Ahzi. Modeling and simulation of dynamic failure in metals. Journal de Physique IV Proceedings, 2003, 110, pp.147-152. 10.1051/jp4:20020685 . hal-00447237

**HAL Id: hal-00447237**

**<https://hal.science/hal-00447237v1>**

Submitted on 30 Sep 2024

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# Modeling and simulation of dynamic failure in metals

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**Abstract.** Computational modeling of planar impact and Taylor impact at different impact velocities have been examined in this paper with a new failure criterion proposed by Campagne et al. [1]. The main result of this work is to show the efficiency of our modeling for the simulation of dynamic plasticity and failure which couples the propose nucleation and growth model with the Mechanical Threshold Stress model. These models have been implemented in a finite element code ABAQUS/ExplicitV6.2 . This implementation is capable of computing the responses of different targets in various geometries at different velocities. Results of these simulations are shown and compared with experimental results.

## I- INTRODUCTION

Modelling the planar impact and Taylor impact problems has been studied with great interest since several years. In these problems, the strain rate and temperature dependency become particularly prevailing at high strain rate where adiabatic plastic flow may produce significant temperature changes in the material. Several constitutive models have been developed to describe the deformation behavior as a function of strain-rate and temperature. Some of these models are based on dislocations overcoming obstacles through thermal activation as in the Mechanical Threshold Stress (MTS) model [2] and the Zerilli-Armstrong model [3]. Another widely used constitutive model is the phenomenological model of Johnson-Cook [4]. The dynamic failure under high strain rate can be divided in two categories: dynamic fracture and dynamic shear localisation. We are interested on the case of dynamic failure by fracture involving nucleation, growth, and coalescence of voids or cracks. These mechanisms of failure in polycrystalline materials are often dislocation controlled. Most of existing failure models are based on phenomenological approaches rather than mechanistic approaches [5-7]. These have been reviewed by Hanim and Ahzi [8]. Among the mechanistic approaches for dynamic failure are the work of Curran et al. [9], Rajendran [10] and Addessio et al. [11]. Computational modeling of planar impact and Taylor impact at different impact velocities have been examined in this paper with a new failure criterion proposed by Campagne et al. [1]. Material used is OFHC copper for the targets and projectiles. Results will be compared with the existing experimental results.

## II- Plasticity models and damage criteria

We considered the “Mechanical Threshold Stress” (MTS) model [2] coupled to a new damage criterion proposed by Campagne et al. [1]. The MTS model connects the macroscopic flow

behavior to the micromechanical behavior. A mechanical threshold stress  $\hat{\sigma}$  is defined as the yield stress for a given structure (of dislocations) and used as internal state variable. It is expressed as a sum of two stresses:  $\hat{\sigma} = \hat{\sigma}_a + \hat{\sigma}_T$  where  $\hat{\sigma}_a$  is the athermal component independent the strain rate and  $\hat{\sigma}_T$  is the component related to the thermal activation and dependent on the strain rate. The relation between the yield stress  $\sigma_y$  and the threshold stress is given by the relation:  $\sigma_y = \hat{\sigma}_a + \hat{\sigma}_T S(\dot{\epsilon}_e^p, T)$ . Thus, the yield stress is a function of the mechanical threshold stress, strain rate and temperature. Hardening results from a balance between accumulation of dislocations and the dynamic recovery. It is expressed in term of a hardening rate:  $\theta = \frac{d\hat{\sigma}}{d\epsilon_e^p} = \theta_o - \theta_r(T, \dot{\epsilon}, \hat{\sigma})$  where  $\theta_o$  is work hardening related to the accumulation of dislocation and is about G/20 for the majority of metals,  $\theta_r$  expresses the dynamic recovery. The term  $\hat{\sigma}_s$  is the saturation stress [2]. A coupling of the MTS model with the new mechanistic criterion of damage [1] was carried out, through the implementation of these two models in the finite element code ABAQUS.

The damage is characterized by nucleation and growth of spherical cavities. We may express the rate of the nucleated sites per unit volume and per unit time for ductile materials as [8]:

$$\dot{N} = \dot{N}_o \left( 1 - \exp\left(-\omega t \frac{\dot{\gamma}}{\dot{\gamma}_o}\right) \right)$$

where  $\dot{N}_o$  is a material constant,  $\dot{\gamma}$  is the shear rate and  $\dot{\gamma}_o$  is a reference shear rate. Therefore, the number of sites per unit volume which have nucleated during a time interval  $\Delta t$  is written by following expression:

$$\Delta N = \dot{N} \Delta t$$

The total relative void volume by nucleation  $V_N$  corresponds to the addition of the nucleation of new relative void volume during the total loading time and the pre-existing (before deformation) relative void volume  $V_I$ :

$$V_N = V_I + 8\pi R_0^3 \Delta N$$

$R_0$  is the void size parameter (initial void radius) for nucleation.

Based on the ductile crack growth equation proposed by Weertman [12], the relative void volume by growth has been written as a function of the stress[1]:

$$V_G = 8\pi N_T R_0^3 \left[ \exp\left(\frac{3h\pi(1-\nu)}{16g^2 G^2 t^{*2}} \int_0^t \left(\sigma_{mean} - \sigma_{g0}\right)^+ dt\right) - 1 \right]$$

Here,  $\sigma_{mean}$  is the mean pressure and  $\left(\sigma_{mean} - \sigma_{g0}\right)^+$  designates the positive part. The time of the loading cycle,  $t^*$ , is evaluated by the shock theory [14,10].

Finally, we determine the porosity  $f$  of the material by:

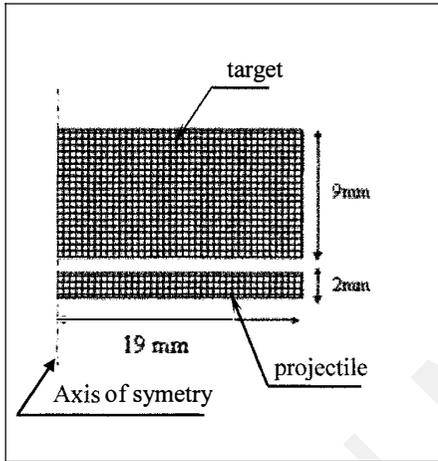
$$f_v = \frac{V_T}{1 + V_T}$$

$$V_T = V_N + V_G$$

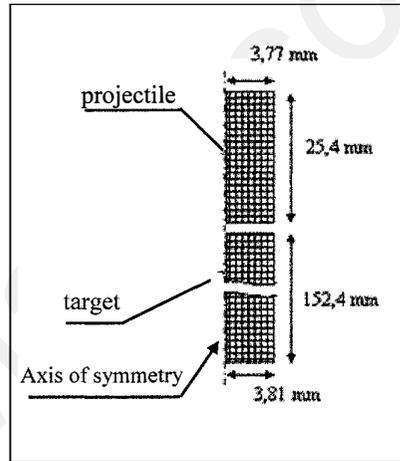
where  $V_T$  is the total relative void volume.

### III- RESULTS AND DISCUSSIONS

To model dynamic failure in various dynamic applications, the constitutive models describe in the previous section were implemented into the commercial hydrocode Abaqus explicit V6.2 via a users material subroutine (vumat). We show results from our numerical simulations of the planar impact test and the Taylor impact test for OFHC copper. To simplify the numerical simulation, we have studied axi-symmetric problems, therefore, axi-symmetric quadrilateral elements are considered to investigate the effect of the porosity. Both the projectile and target materials for the two tests are OFHC copper of cylindrical shapes and their respective dimensions are shown in figure 1 and figure 2. The model parameters and material constants for OFHC copper are those given in [1-2].



**Figure 1.** Geometries of the cylindrical target and impactor for planar impact. Only half of the geometry is shown.



**Figure 2.** Geometries of the cylindrical target and impactor for Taylor impact (Rod on Rod). Only half of the geometry is shown.

#### III-1 Result of planar impact

In the problem of planar impact, the failure in the material is created by a spall process. A spall is a material failure produced by the action of tensile stress developed in the inside of a solid body when two decompression waves collide. The spall plane is obtained at a distance from the free surface equals the thickness of the impactor. In our simulations, the used impact velocity of the projectile is 185m/s. Considering the porosity map in the target as shown in figure 3, our failure criterion predicts the production of high porosity at a distance, from the free surface velocity, equal the height of the projectile. The spall plane is represented by the zone A. The second zone B of high porosity results from the action of the radial relief wave with decompression wave coming from the projectile. Dark areas are highly damaged and correspond to the value of the critical porosity  $f_c = 44\%$ . This is in fair agreement with the experimental results and the shock wave analysis. Figure 4 shows the compression of our simulated results to the experimental ones [10] for the free surface velocity profile. Our simulations are in fair agreement with the experiments for OFHC copper.

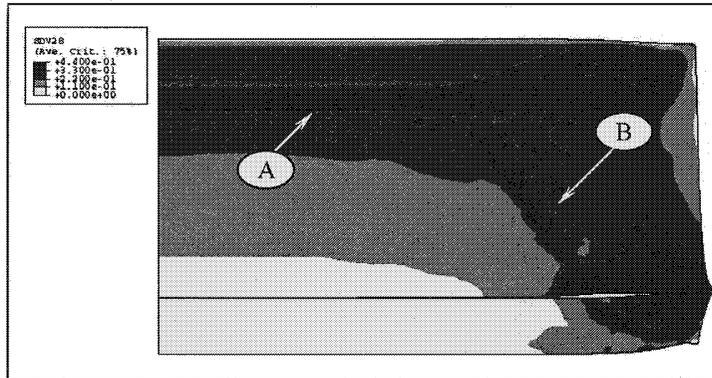


Figure 3. Damage map for cylindrical target at 3,40 $\mu$ s

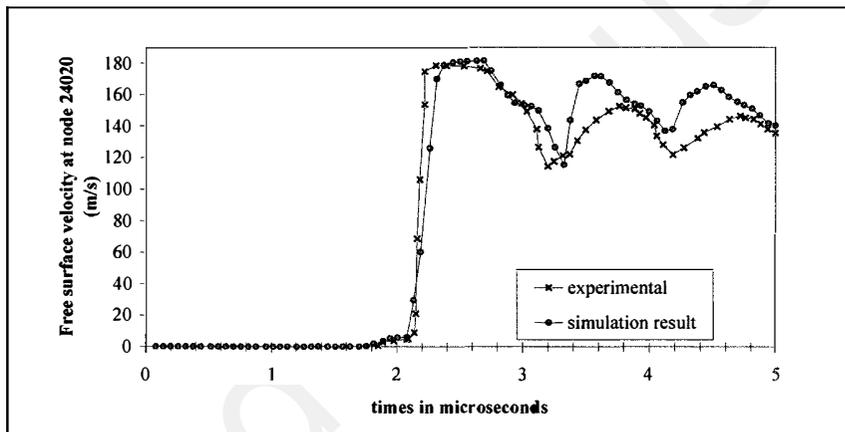
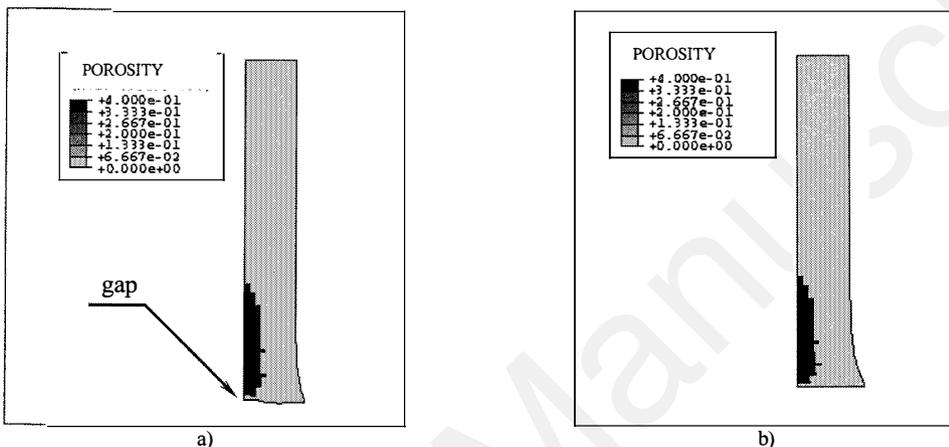


Figure 4. Comparison between numerical results and the experimental results of Rajendran [10]

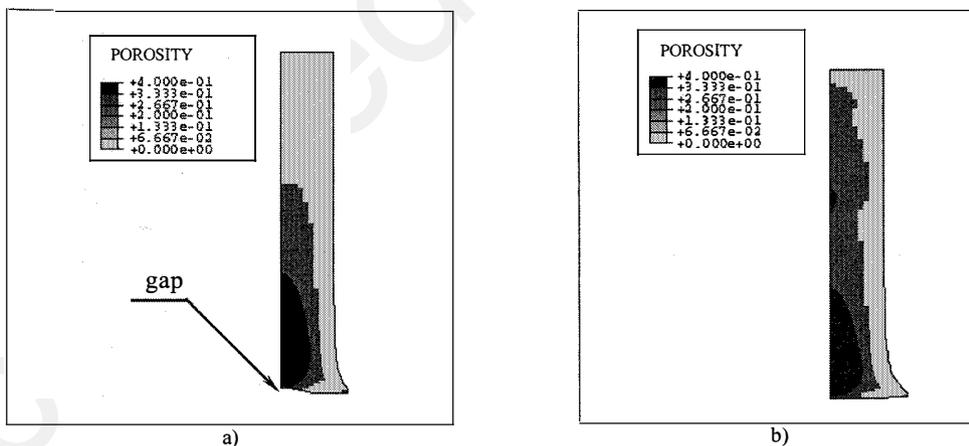
### III-2 Result of Taylor impact

In the Taylor impact test, a radial relief wave is generated at a lateral surface of the target cylinder. At high projectile velocities when the relief wave reaches the center line of the target, it results in a region of tension where the magnitude of the tensile wave is sufficiently high to produce porosity in the material. This failure occurs at the center line of the cylinder. Two initial velocities of the projectile have been considered: 260m/s and 390m/s. Figure 5 and figure 6 show damage contours for Taylor impact test at 260m/s and 390 m/s at time of 5  $\mu$ s and 10  $\mu$ s. Figure 5 (a) and figure 6 (a) show that shortly after the radial release wave have reached the center line of the projectile a gap appears at the projectile base. This gap is closed at 10  $\mu$ s as showed in figure 5 (b) and figure 6 (b). The failure at the center line is essentially governed by growth of cavities. At 390m/s impact velocity, we note a large

increasing of the porosity compared to the case of 260m/s. The nucleation contribution governed by strain is essentially located at the projectile based and is a negligible compared to the growth contribution porosity. The value of the critical porosity is  $f_c = 40\%$ . This numerical result is qualitatively in fair agreement with the experimental and numerical results of Addressio et al. [11]. We note that in order to obtain these numerical results for the Taylor impact test, we slightly modified the growth model (by increasing the parameter  $N_T$ ). This is a simplified way to including stress controlled nucleation of voids.



**Figure 5.** Porosity contours for the impact velocity 260m/s  
a)  $5 \mu s$ ; b)  $10 \mu s$



**Figure 6.** Porosity contours for the impact velocity 390m/s  
a)  $5 \mu s$ ; b)  $10 \mu s$

### III-3 Conclusion

We proposed to combine the MTS model for the evolution of the flow stress with a new damage model for the simulation of dynamic plasticity and failure in OFHC copper. The damage model is a mechanistic approach where nucleation and growth of voids are considered. The application to the planar impact test and to the Taylor impact test yielded results that are in agreement with the experimental results.

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