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# MODELING AND SIMULATION OF DYNAMIC FAILURE IN DUCTILE METALS

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**Abstract:** In the present work, we propose a physically based model describing these processes for planar impact. This model combines the Mechanical Threshold Stress (MTS) model for the evolution of the flow stress and a void nucleation and growth model. This paper presents results from numerical simulation of planar impact test and their comparison with experimental results for OFHC copper.

**Key words:** Void Nucleation, Void Growth, Planar impact, Dynamic Plasticity, Dynamic Failure

## 1 INTRODUCTION

It is well established that high rate failure of structural materials takes place by rate processes occurring at the micro level and involving nucleation, growth, and coalescence of voids or cracks. These mechanisms of failure and plasticity in polycrystalline materials is often dislocation controlled. Most of existing failure models are based on phenomenological approaches rather than mechanistic approaches (Tuler-Butcher 68, Cagnoux 85, Zhurkov 65, Klepaczko 90). These have been reviewed by Hanim and Ahzi (2001). The well known mechanistic approaches for dynamic failure are the work of Curran et al (87) where a nucleation and growth model is proposed and the work of Addessio et al (93) where the Gurson model for nucleation and growth is used. The main thrust of the paper is the development of failure model based on microscopic assumptions. We propose a model in which the nucleation and growth processes are linked to the dislocation motion. The new model will be applied to dynamic failure that occurs by spallation during planar impact test. The material used is

OFHC copper. We used various impactor shapes (cylindrical and conical target). In these applications, the new failure model along with the mechanical threshold plasticity model were implemented in the finite element code ABAQUS/Explicit. Results will be compared with the existing experimental results.

## 2 MODELLING OF NUCLEATION AND GROWTH PROCESS

### 2.1 Nucleation process

The mechanism of failure in metallic materials is dislocation controlled (McClintock and Argon, 1966). The process of deformation and failure can therefore be described by plastic glide, which involves the mechanism of dislocation pile-ups. In the work of Stroh (1957), a probability function was suggested for brittle failure due to dislocation pile-up. Since the brittle and ductile nature of failure can be associated to the process of release or non-release of dislocations near a pile up, we assume the brittle and ductile failure are complementary events. So, the probability for ductile failure,  $P$ , can be given by the following equation (Campagne et al 02):

$$P = 1 - \exp\left(-\omega t \exp\left(\frac{-\Delta U}{kT}\right)\right) \quad (1)$$

where  $t$  is the duration of the loading.  $\Delta U$  is the energy of activation that can be related to the shear strain rate by the well-known Arrhenius law. This probability of ductile failure can be expressed in terms of strain rate (eq.2):

$$P = 1 - \exp\left(-\omega t \frac{\dot{\gamma}}{\dot{\gamma}_0}\right) \quad (2)$$

where  $\dot{\gamma}$  is the shear rate and  $\dot{\gamma}_0$  is a pre-exponential factor

We assume that this probability,  $P$ , describes the void nucleation process in the case of ductile failure. Thus, we express the rate of the nucleated sites per unit volume for ductile failure as (Hanim and Ahzi, 2000):

$$\dot{N} = \dot{N}_0 P \quad (3)$$

where  $\dot{N}_0$  is the maximum rate of the nucleated sites per unit volume (Curran and al , 1987). The number of nucleation sites per unit of volume,

$\Delta N$ , which have nucleated during a time interval,  $\Delta t$ , and the associated relative void volume,  $\Delta V_N^{new}$ , are given by the following equations :

$$\Delta N = \dot{N}\Delta t \quad \text{and} \quad \Delta V_N^{new} = \Delta N 8\pi R_0^3 \quad (4)$$

Here,  $R_0$  is the radius of the nucleated voids which are assumed of spherical shape

## 2.2 Growth process based on microscopic assumption

At the sub microscopic level, the growth process can also be explained in terms of dislocation motion. Among the extensive contributions in this area can be found in the book of McClintock and Argon (McClintock and Argon, 1966), and in the recent work of Weertman (1981, 1996). Following the work of Weertman (Weertman, 1981) on the modeling of ductile growth process, we obtain the following growth equation (champagne et al 02):

$$R = R_0 \alpha(t, \sigma_{mean}) = R_0 \exp\left(\frac{3\pi(1-\nu)}{16g^2G^2t^*} \int_0^t \langle \sigma_{mean} - \sigma_{g0} \rangle^+ dt\right) \quad (5)$$

where  $R$  is the radius of spherical void at time  $t$ ,  $\sigma_{mean}$  is the mean stress, and  $\langle \sigma_{mean} - \sigma_{g0} \rangle^+$  is the positive part of  $\langle \sigma_{mean} - \sigma_{g0} \rangle$ . To grow, the void should have nucleated and the mean stress  $\sigma_{mean}$  should exceed growth threshold stress  $\sigma_{g0}$ ,  $t^*$  is time for one loading cycle and  $g$  is a coefficient that depends upon the ratio of the theoretical tensile strength  $\sigma_T$  to theoretical shear strength  $\tau_T$ ,  $\nu$  is the Poisson ratio and  $G$  the shear modulus

The loading cycle  $t^*$  is evaluated by the shock theory (Meyers, 1994). The initial duration of the peak shock pulse in an impact is approximately equal to twice of travel time of the shock wave through the impactor. Thus, to determine the loading cycle  $t^*$ , we use the following approximate expression:

$$t^* \approx \frac{2d_0}{U_s} \quad (6)$$

where  $d_0$  is the thickness of the impactor and  $U_s$  is the velocity of the shock wave.

The expression for relative void volume by growth of the crown can be expressed by:

$$V_{CG} = 8\pi N_T R_0^3 [\alpha^3(t, \sigma_{mean}) - 1] \quad \text{where } N_T = N_0 + \sum_t \Delta N \quad (7)$$

where  $N_0$  is the initial number of pre-existing void per unit volume. This constant can be expressed in term of initial porosity of the material.

The total relative void volume, denoted  $V_T$ , is the sum of initial relative void volume,  $V_0$ , and of the contributions associated respectively with nucleation and growth processes.

$$V_T = V_0 + \sum_t \Delta V_N^{new} + V_{CG} = 8\pi N_0 R^3 \quad (8)$$

From the total relative void volume, we determine the porosity of the material,  $f$ , and the associated damage parameter,  $d$ , obtained via a self consistent method:

$$f = \frac{V_T}{1 + V_T} \quad \text{and} \quad d = \frac{15(1-\nu)}{7-5\nu} \cdot f \quad (9)$$

To account for the deactivation of the damage in compressive loading and for damage initiation after a threshold porosity, the following expression for the damage law is proposed:

$$\begin{cases} \text{if } f \in [0; f_t] \Rightarrow d = 0 \\ \text{if } f \in ]f_t; f_c[ \Rightarrow d = \frac{15(1-\nu)}{7-5\nu} \cdot f_c \cdot \left( \frac{f - f_t}{f_c - f_t} \right) \cdot \delta(\sigma_{mean}) \\ \text{if } f = f_c \Rightarrow d = 1 \end{cases} \quad (10)$$

where  $\delta(\sigma_{mean}) = 1$  if  $\sigma_{mean} > 0$  and  $\delta(\sigma_{mean}) = 0$  if  $\sigma_{mean} \leq 0$ ,  $f_t$  is the threshold porosity for damage initiation and  $f_c$  the critical porosity for failure.

### 3 APPLICATION TO PLANAR IMPACT

A spall is a material failure produced by the action of tensile stresses developed in the inside of a solid body when two tensile waves collide (Meyer et al). In the following, we show results from our numerical simulations of the planar impact test of OFHC copper. These results are obtained by FEM analysis where our failure model, along with the mechanical threshold stress

model for dynamic plasticity (Kocks, 1987 ; Follansbee and Kocks, 1988), are implemented in Abaqus finite element code. The framework and details of the MTS model are given in the work of Follansbee and Kocks (Follansbee and Kocks, 1988). Determination of the failure model parameters  $f_i$ ,  $\omega$ ,  $\dot{N}_0$ ,  $f_c$ ,  $\sigma_{g0}$  are estimated for the planar impact test with cylindrical geometry and are given in Table 1.

### 3.1 FEM analysis.

The element type used in the FEM analysis is the 4-node, reduced-integration, first-order, with hourglass control, axisymmetric solid element CAX4R. The kinematic predictor/corrector contact algorithm is used with balanced master-slave concept to minimize the penetration of the contacting bodies and we considered no rebound. We studied the planar impact of a cylindrical and conical target with a cylindrical impactor. Both the impactor and target materials are OFHC copper and their respective geometries are shown in figure 1.

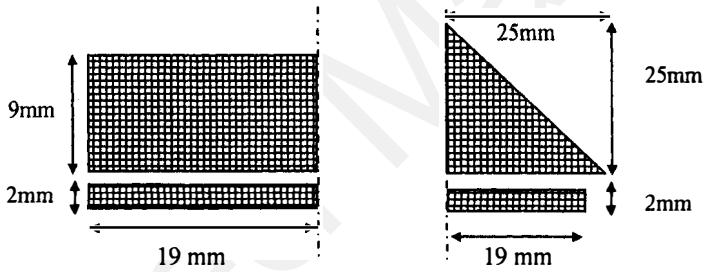


Fig. 1.a. Geometries of the cylindrical target and impactor

Fig. 1.b. Geometries of the conical target and cylindrical impactor

Parameters	Mechanistic approach
Nucleation coefficient $\dot{N}_0$ [no./cm <sup>3</sup> -s]	$3.2 \times 10^{24}$
Frequency $\omega$ [1/s]	$10^6$
Hydrostatic stress $\sigma_0$ [Mpa]	5
Critical porosity $f_c$	0.44
Threshold porosity $f_i$	0.0

Table 1: Parameters for the mechanistic failure model for OFHC Copper

### 3.1.1 Cylindrical geometry

For this test where the impactor velocity is  $185 \text{ ms}^{-1}$ . According to Meyers (1994), we use for this test the value for loading cycle  $t^* = 0.98 \cdot 10^{-6} \text{ s}$ . The predicted curve of the free surface velocity history for a node located on the free surface in the target is shown in Figure 2. in comparison with the experimental results of Rajendran et al. (Rajendran and al, 1988).

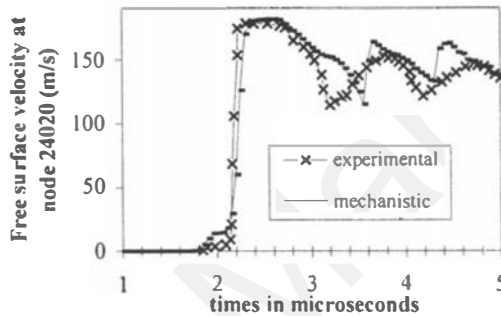


Fig. 2. Comparison between numerical result and the experimental results of Rajendran and al, 1988

The agreement of this numerical simulation with the experimental data shows that the choice of the model parameters is fair. Now, considering the failure map in the target. Our approach predict the spalling plane at a distance equal the height of the projectile from the free surface velocity,(see Fig 3). This is in good agreement with both the experimental observations and the elastic shock wave analysis. Note the figure 3 shows damage evolution at time  $2.5 \text{ } \mu\text{s}$  and  $3.0 \text{ } \mu\text{s}$ . Dark area is highly damaged and corresponds to the value of the critical porosity  $f_c$ .

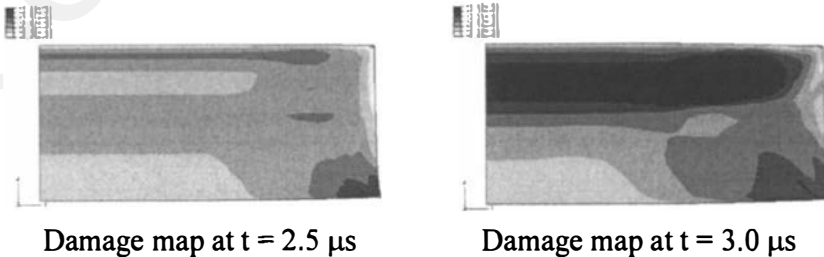


Fig3. Damage map for cylindrical target

### 3.1.2 Conical geometry

For this test where the impactor velocity is  $183 \text{ ms}^{-1}$ . According to Meyers (Meyers, 1994), we use for this test the value for loading cycle  $t^* = 0.98 \cdot 10^{-6} \text{ s}$ , all of the other parameters of our model are the same as in the previous test. We present in figure 4 damage map at different times. These results are qualitatively in good agreement with the elastic shock wave analysis, but the lack of experimental data, for OFHC Copper with this geometry, does not allow us to evaluate the quantitative side of the results.



Damage map at  $t = 3.6 \mu\text{s}$

Damage map at  $t = 4.8 \mu\text{s}$

Fig4. Damage map for conical target

## 4 CONCLUSION

In this work we have proposed a new physically based dynamic failure model. The new Nucleation and Growth model (NAG) also takes into account the initial porosity of the material. This model is valid 3 dimensional analysis (conical target) The advantage of a NAG approach is that it predicts damage evolution in the target as well as in the impactor. For the cylindrical test, the numerical damage map is in good agreement with the experimental observations

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