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A physically-based and fully coupled model of elasto-plasticity and damage for dynamic failure in ductile metals

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Abstract. It is well established that spall fracture and other rapid failures in ductile materials are often dominated by nucleation and growth of micro-voids. In the present work, a mechanistic model for failure by cumulative nucleation and growth of voids is fully coupled with the thermo-elastoplastic constitutive equations of the Mechanical Threshold Stress (MTS) which is used to model the evolution of the flow stress. The damage modeling includes both ductile and brittle mechanisms. It accounts for the effects of inertia, rate sensitivity, fracture surface energy, and nucleation frequency. The MTS model used for plasticity includes the superposition of different thermal activation barriers for dislocation motion. Results obtained in the case of uncoupled and coupled model of plasticity and damage from the simulations of the planar impact with cylindrical target, are presented and compared with the experimental results for OFHC copper. This comparison shows the model capabilities in predicting the experimentally measured free surface velocity profile as well as the observed spall and other damage patterns in the material under impact loading. These results are obtained using the finite element code Abaqus/Explicit.

1. INTRODUCTION

At high strain rates most materials commonly fail by nucleation, growth and coalescence of micro-voids. The metallographic observations show that the nucleation is the predominant process at the first stage of damage evolution. During the middle and the last stages of damage evolution, the effect of nucleation is relatively small and can be neglected when compared with void growth and coalescence. Dynamic failure also involves the effects of mass inertia, thermal inertia, thermal activation and viscosity. A detailed knowledge of how loading conditions and microstructural features influence micro-failure (nucleation, growth, and coalescence) would help in designing more failure-resistant structures or tailor structures to have a prescribed toughness. The difficulty is that failure processes are not easily accessible for modeling and analysis. This leads to the development of several engineering models using modern numerical methods to predict failure of different materials at different loading rates and temperatures. A review of these dynamic failure criteria and their extension to include temperature and pressure effects is given in the work of Hanim and Ahzi [1] and Campagne et al. [2].

Nucleation and growth (NAG) based models [3] have sufficient generality to include the statistical distribution of one or more variables such as porosity. However, the model given in [3] is only based on statistical observations so that a number of material constants have to be determined experimentally with the application of statistical methods.

In this study, a fully coupled model of elasto-plasticity and damage is implemented in Abaqus/Explicit [4]. In the first part, the plasticity model is described. This model is based on the Mechanical Threshold Stress (MTS) approach [5-7] for dynamic yielding which was originally developed by Mecking and Kocks [8]. In the second part, our proposed nucleation and growth model is presented. This model is applied to dynamic failure which occurs by spallation during the planar impact

test with cylindrical target. Results from our simulations are compared to the experimental results for the planar impact test using OFHC copper [9].

2. VISCOPLASTIC CONSTITUTIVE RELATION

In this study we will use the MTS model for analysis by spallation in impact-loaded copper plate. The MTS model is implemented in the ABAQUS/Explicit [4] via a subroutine “vumat”. This model uses the basic ingredients of the thermally activated dislocation motion for plastic flow and includes the effect of strain rate and temperature. It is based on the dislocation concepts as proposed by Follansbee and Kocks [5] and was originally developed by Mecking et al. [8]. The mechanical threshold stress (or the flow stress at 0 K) is given by:

$$\sigma_e = \hat{\sigma}_a + \left\{ 1 - \left[\frac{kT}{g_0 G b^3} \ln \left(\frac{\dot{\bar{\epsilon}}_0^p}{\dot{\bar{\epsilon}}^p} \right) \right]^{1/q} \right\}^{1/p} (\hat{\sigma}_t - \hat{\sigma}_a) \quad (1)$$

where the component $\hat{\sigma}_a$ characterizes the rate and temperature independent interaction of dislocations with long-range barriers such as grain boundaries. The component $\hat{\sigma}_t$ characterizes the rate and temperature dependent interactions with short-range obstacles. In the thermally activated regime, the interaction kinetics for short range obstacles are described by an Arrhenius expression.

Plastic strain is implicitly represented through the term representing structure evolution $\hat{\sigma}_t$. The specific form of the equivalent plastic strain ($\bar{\epsilon}^p$) is dependent on the strain-hardening rate description. The strain-hardening response is given by Voce behavior for which the material constants are given by Follansbee and Kocks [5].

At high strain rates which are considered in this study, adiabatic conditions are assumed and the temperature is calculated assuming that 90% of the plastic work is converted into heat which results in a temperature rise according to:

$$\Delta T = T_0 + \frac{0.9}{\rho c_v} \int_0^{\bar{\epsilon}^p} \sigma_e d\bar{\epsilon}^p \quad (2)$$

where T_0 is the initial temperature, ρ is the mass density and c_v the specific heat.

The basic input data used in the modeling for polycrystalline copper are given as follows. The elastic modulus, $G = 124 \text{ GPa}$. Poisson's ratio, $\nu = 0.34$. Specific heat, $c_v = 500 \text{ J/(kg.K)}$. Thermal conductivity $k = 54 \text{ W/(m.K)}$ and volume density $\rho = 7860 \text{ kg/m}^3$.

3. NUCLEATION AND GROWTH MODEL

The damage can quickly reach its critical value for failure due to the rapid void growth at high strain rate. Therefore the void coalescence process can be neglected. In the present work, we briefly address the constitutive equations for damage criterion since the details can be found in [2]. The material porosity f is determined from the total relative void volume V_T and given by:

$$f = \frac{V_T}{1 + V_T} \quad (3)$$

The total relative void volume V_T which can be expressed as the sum of preexisting nucleation and growth relative void volumes :

$$V_T = 8\pi R_0^3 [N_I + N_\epsilon + N_\sigma] \exp \left(\frac{3h\pi(1-\nu)}{16g^2G^2_{eff}t^*} \int_0^t (\langle \sigma_m - \sigma_{g0} \rangle^+)^2 dt \right) \quad (4)$$

Here N_I is the initial number of voids, N_ϵ and N_σ are respectively the number of voids nucleated and controlled by the strain and the stress. The creation of cavities inside a material domain modifies the mechanical properties of this domain. A damage parameter d is introduced so that the elastic modulus and shear modulus are reduced with increasing damage.

We introduce the notion of effective elastic modulus to account for damage effects on the elastic properties during loading. The effective Young modulus E_{eff} and shear modulus G_{eff} are thus given by:

$$E_{eff} = E(1 - d) \quad \text{and} \quad G_{eff} = G(1 - d) \quad \text{in tensile loading} \quad (5)$$

$$E_{eff} = E \quad \text{and} \quad G_{eff} = G(1 - d) \quad \text{in compressive loading} \quad (6)$$

where E and G are their corresponding initial (undamaged) values.

The failure criterion is based on a critical porosity f_c :

$$\begin{cases} f < f_c & \Rightarrow \text{Damage} \\ f = f_c & \Rightarrow \text{Failure} \end{cases} \quad (7)$$

The damage parameter d can be derived as function of the effective porosity f^* , from a self-consistent approach [10]:

$$d = \frac{15(1 - \nu)}{7 - 5\nu} f^* \quad (8)$$

Here, isotropy is assumed and the porosity f is supposed uniformly distributed. The effective porosity f^* is defined such that damage initiates at a threshold porosity f_i , and that failure occurs when d reaches a critical value d_c corresponding to the critical porosity f_c . The damage evolution in ductile metals begins after a threshold strain [11,12] associated in our case to threshold porosity f_i . The effective porosity f^* is defined by the following relation [2]:

$$\begin{cases} f^* = 0 & \text{if } f \in [0, f_i] \\ f^* = f_i \left(\frac{f - f_i}{f_c - f_i} \right) & \text{if } f \in [f_i, f_c] \\ f^* = f_c & \text{if } f \geq f_c \end{cases} \quad (9)$$

The material parameters for the mechanistic damage model are given in [13].

4. MODEL VALIDATION

There are several possibilities for coupling plasticity and damage effects in a single constitutive relation. The yield stress is affected by the damage according to $\sigma_e^D = \sigma_e \sqrt{1 - d}$. To test the implementation of the MTS model we used a mesh of one element under plane strain loading. The element type used is plane strain CPE4R. In figure 1 we give the corresponding predicted uncoupled response together with the coupled responses obtained with a strain rate equal to $10^4 s^{-1}$. We note that in both cases the elastic constants are affected by damage. As we can see in figure 1 the flow stress drops drastically, in the coupled case, which shows that the damage is accounted for correctly in this case

5. APPLICATION TO THE PLANAR IMPACT WITH CYLINDRICAL TARGET

The planar impact of a copper cylindrical target with a copper cylindrical impactor is modeled. The thickness ratio of the target to the impactor is 9/2. In this application, the stress-controlled nucleation is

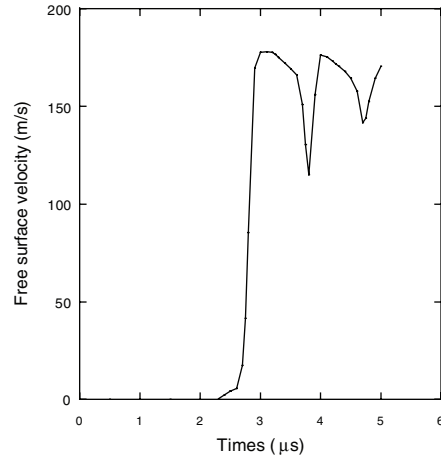
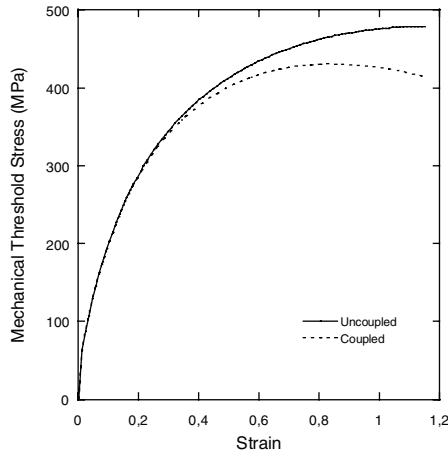


Figure 1. Stress-strain response, coupled and uncoupled for OFHC copper ($\dot{\epsilon} = 10^4 s^{-1}$). **Figure 2.** Predicted free surface velocity profile.

neglected since it is not activated even when we account for it in this particular test. All the boundaries, except for the axis of symmetry, are taken as free boundaries.

To perform the simulation of planar impact, the loading cycle t^* is evaluated by the shock theory [14]. The initial duration of the peak shock pulse in an impact is approximatively equal to twice the travel time of the shock wave through the projectile.

The occurrence of spalling can be interpreted from the free surface velocity profile. If there is no damage there will be a complete unloading of the velocity history. But, if the tensile stress pulses during the course of the planar impact simulations are sufficiently high, spalling is bound to occur in the target. A new free surface is therefore created in the target at a distance from the free surface that is almost equal to the thickness of the impactor. Figure 2 shows the computed free-surface velocity profiles of the spalled element in copper cylindrical target with full coupling of the MTS and the damage model. It should be noted that the same results are obtained if there is no coupling between plasticity and the damage. That is explained by the brittle character of fracture in the case of spall phenomenon. To highlight the importance of the coupling, problems would have to be considered where the mechanism of rupture is rather ductile.

Considering the failure distribution in the target, both approaches predict the spalling plane at a distance, from the free surface velocity, equal the thickness of the projectile (see Figures 3 and 4). This is in good agreement with the experimental results for both models.

6. CONCLUSION

The main results of this work are to show the efficiency of the presented NAG model, which is based on the process of release and no-release of dislocations near a pile-up. The advantage of a NAG approach is that it predicts damage evolution until failure. Our computed damage distribution is in good agreement with the experimental results for the planar impact with cylindrical target. We show that the strong coupling between plasticity and damage model does not have an influence on the free surface velocity. Indeed, the numerical results show brittle behavior for OFHC copper at high strain rate.

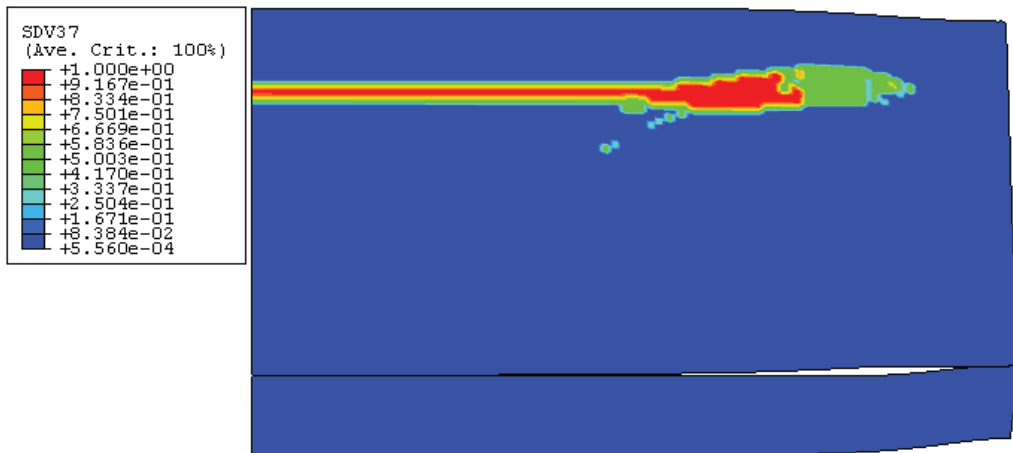


Figure 3. Damage parameter, d , distribution for cylindrical target at $3.4 \mu\text{s}$; when plasticity is coupled with damage model.

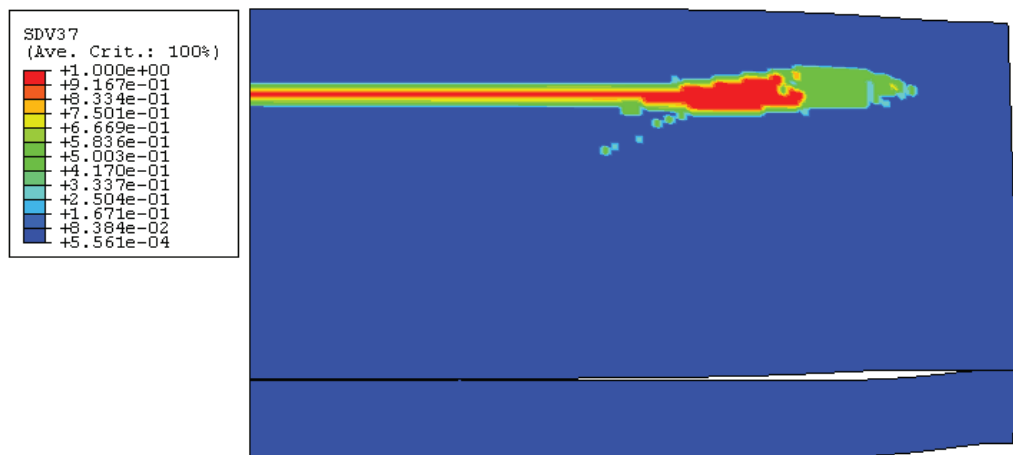


Figure 4. Damage parameter, d , distribution for cylindrical target at $3.4 \mu\text{s}$; when only elasticity is coupled with damage model.

To improve the predictive capability of the NAG model with a strong coupling with plasticity other impact test where the fracture is caused by ductile failure is need.

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