MATERIAL FAILURE MODELLING IN METALS AT HIGH STRAIN RATES

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Abstract. To account for the physical mechanisms of failure, the concept of thermal activation of damage and failure has been adopted as basis for this material model development. This basic assumption makes the proposed approach compatible with the Mechanical Threshold Stress (MTS) model, which was used as the strength part of the proposed constitutive model. The developments were incorporated into public domain DYNA3D. In order to validate the model, a series of FE simulations of plate impact experiments were performed for OFHC Cu. The numerical analysis results clearly demonstrate the ability of the model to predict the spall process and experimentally observed tensile damage and failure. The model allows simulation of high strain rate deformation processes and dynamic failure in tension for wide range of temperatures. The model is able to reproduce typical longitudinal stress reloading observed in plate impact tests, which is caused by the creation of the internal free surface. Plate impact tests used for model validation were performed on a single-stage gas gun. Longitudinal stresses were measured with stress gauges.

Keywords: Dynamic fracture, Spallation, Plate impact, Damage model, Numerical simulation
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INTRODUCTION

Our main objective was to develop a physically based model with a number of material parameters applicable in engineering practice and capable of modelling tensile failure in Al alloys.

Ductile fracture is a typical mode of failure in aluminium alloys and is characterised by significant plastic deformation prior to material failure. As a consequence of the plastic deformation crack tip becomes blunted and the propagation of the crack requires more energy compared to brittle failure. Ahead of the crack tip, voids develop in the material undergoing plastic deformation that link together, resulting in the extension of the crack. In contrast to quasi-static fracture, dynamic fracture usually nucleates independently at many locations simultaneously.

DYNAMIC FAILURE

The most commonly used failure criteria are based on the assumption that loading time and stress are important variables in predicting both damage and complete failure under dynamic loading conditions.. A good example is the general method presented by Tuler and Butcher [1] and by Gilman and Tuler [2], which proposes the use of a damage function ϕ as a function of the entire stress history $\sigma(t)$:

$$\phi = \int_0^{t_c} f\,[\sigma(t)]dt \tag{1}$$

Where: t is time. When ϕ reaches a critical value, t becomes the failure time or lifetime t_c. One possible interpretation of what ϕ represents could be the total number or volume of microcracks formed in material.

This general criterion based on the concept of cumulative damage has been used by a number of authors. The work presented in the paper followed a number of incremental developments of this basic concept including:

- Energy activation aspects of damage and fracture by Zhurkov [3],
- The rate theory of thermally activated fracture developed by considering the bond-breaking and establishing that this processes is one of fundamental mechanism of fracture initiation by Tobolsky and Eyring [4],
- Modification of the Zhurkov's criterion for spall by Dremin and Molodets [5],
- Modification of the cumulative model for very short loading times by Klepaczko [6] and Hanim and Klepaczko [7].

A step in further development of the research path given above follows the work of Kocks [8], where normalized activation energy u_0 can be defined in the following manner:

$$\Delta U_0 = \mu(T) b^3 u_0 \qquad (2)$$

Where: b is burgers vector, and $\mu(T)$ is temperature dependent shear modulus. One can assume that stress dependent activation energy given by Yokobori can be written in the following form:

$$\Delta U(\sigma) = \mu(T) b^3 u_0 \ln\left(\frac{\sigma_0 / \mu_0}{\sigma / \mu(T)} \right) \qquad (3)$$

Inserting the above expression for activation energy into cumulative damage criterion, modified Klepaczko's cumulative (equation (35) in [9]) failure criterion in the integral form can be written as:

$$\int_0^{t_c} \left(\frac{\sigma(t) / \mu(T)}{\sigma_0 / \mu_0} \right)^{\left(\frac{\mu(T) b^3 u_0}{kT} \right)} dt = t_{c0} \qquad (4)$$

Equation (4) represents the proposed criterion for material fracture. The same equation can be used to define and damage evolution as:

$$D = \frac{t_c}{t_{c0}} \frac{1}{\left(\left(\frac{\mu(T) b^3 u_0}{kT} \right) + 1 \right)} \left(\frac{\sigma(t) / \mu(T)}{\sigma_0 / \mu_0} \right)^{\left(\frac{\mu(T) b^3 u_0}{kT} \right)} \qquad (5)$$

where damage variable D varies between 0 and 1, $\boldsymbol{D} = 0$ corresponds to a virgin material while $\boldsymbol{D} = 1$ corresponds to fully damaged material.

The proposed damage model allows for spall damage initiation if the mean tensile stress become greater than the specific spall threshold limit stress. Once spall damage is initiated the model calculates the evolution of damage using the proposed cumulative criterion. When an element fails due to accumulated damage, it is removed from the calculations.

PLATE IMPACT SIMULATION

In order to validate proposed model for spall damage and fracture, the model was implemented in the DYNA3D code within the MTS strength model. This strength model is used for the evolution of the flow stress of OFHC Cu under high strain rate deformation, which is described in detail in [10,13]. This model express flow stress as:

$$\sigma_y = \hat{\sigma}_a + (\hat{\sigma} - \hat{\sigma}_a) \left(1 - \left[\frac{kT \ln\left(\dot{\varepsilon}_0 / \dot{\varepsilon} \right)}{\mu(T) b^3 g_0} \right]^{1/q} \right)^{1/p} \qquad (6)$$

Where $\hat{\sigma}_a$ is athermal stress, $\hat{\sigma}$ is the mechanical threshold stress or flow stress at 0K, g_0 is normalized activation energy, $\dot{\varepsilon}_0$ is reference strain rate and p, q are the parameters that characterize the shape of the obstacle profile. MTS model was used in combination with Mie-Grunisen equation of state (EOS) [11].

A series of FE simulations of a plate impact experiment for OFHC Cu were performed. A circular target plate with the diameter d=70.0 mm, was impacted by a 50mm diameter flyer plate at velocity of 304 m/s. The thickness of the flyer and target plate was 5.0 mm and 10.0 mm respectively. The target was supported by a 12 mm block of polymethylmethacrylate (PMMA). Due to radial symmetry, only one quarter of the both plates was modelled. A solid butterfly mesh was created for all parts, using the same mesh desnity. A sliding contact interface was defined between flyer and target.

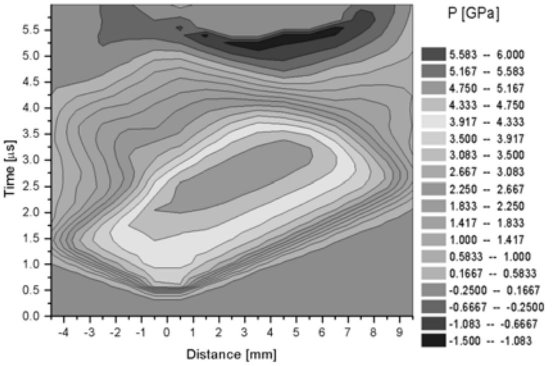

Figure 1. Time distance diagram for OFHC Cu plate impact test simulation with implemented failure criterion

Material data for the OFHC Cu was taken from [12] and used in the proposed failure criterion and damage evolution model. (eq. (4)). Threshold stress $\sigma_0 = 0.95 GPa$, normalized activation energy $u_0 = 0.0508$ and critical time $t_{c0} = 1.4 \mu s$, Boltzmann's constant $k = 1.38 X 10^{-23} J/K$, Burger's vector $b = 0.255 X 10^{-9} m$, and shear modulus $\mu = b_0 - b_1 / \left(\exp(b_2 / T) - 1 \right)$, where $b_0 = 47.3 GPa$ is shear modulus at 0 K, and $b_1 = 2.40 GPa$, $b_2 = 130 K$.

The PMMA backing was modeled as an isotropic–elastic–plastic-hydrodynamic material with the Mie-Grunisen EOS, where a value of 350 MPa was used for the dynamic yield stress.

In order to validate implemented failure criterion, Langrangian time-distance diagrams for the centre of the flyer and target plates were plotted from pressure-time data (see figure Fig. 1). For the chosen set of elements, the coordinate through the

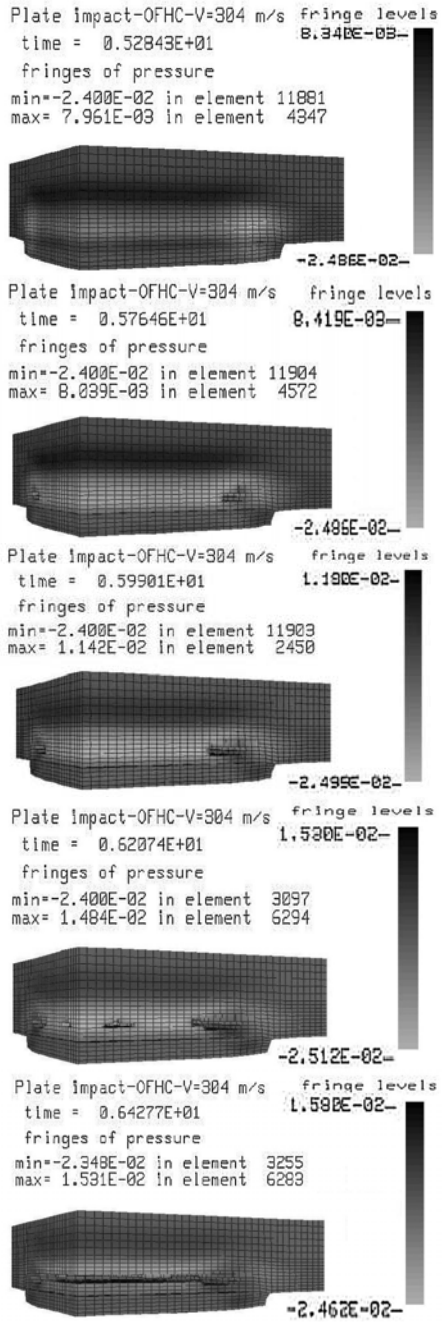

Figure 2. The pressure plots for response times t=5.3 μs (a), 5.8 μs (b), 6.0 μs (c), 6.2μs (d) and 6.4 μs (e) for impact velocity 304 m/s

thickness of the material represents distance in the time-distance diagram. Figure Fig. 1 shows the time-distance diagrams for the 6 μs response time. The dark regions indicate tensile loading followed by reloading due to opening of the free surface.

Contour plots of pressure at different stages of spalling for incident velocity of 304 m/s are presented in Fig. 2. Spall starts near the external diameter, where the lateral tensile release waves interact with the plane incident wave. The opening of the free surface is almost instantaneous, as it can be seen from the longitudinal stress history.

The longitudinal stress time history measured in the 304 m/s plate impact experiment and the equivalent stress time history from the numerical simulations are shown in Fig. 3. There is a reasonable agreement between the experimental and numerical data.

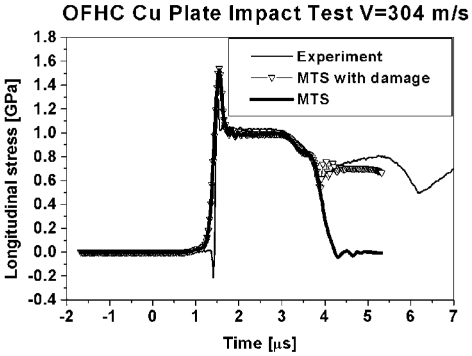

Figure. 3 Longitudinal stress histories for 304 m/s plate impact

SUMMARY

The presented results demonstrate that the proposed cumulative damage and failure model based on the assumption that damage and fracture processes occurs with the assistance of thermal activation can model dynamic tensile failure. The damage model, combined with the MTS strength part of the constitutive relation and EOS, can simulate high strain rate shock induced deformation processes. Numerical analysis predicted the occurrence of spall, including the location of initiation and evolution of the free surface development for the plate impact test considered.

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