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THE INFLUENCE OF TEMPERATURE AND RATE DEPENDENCE DURING MESH OBJECTIVE DAMAGE MODELLING OF DUCTILE FRACTURE

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Summary. The modelling and simulation of the manufacturing process based on the finite element method (FEM) is an efficient tool to optimize the process. However, the reliability of the FE tools strongly depends on the constitutive and fracture model utilised. Therefore two damage models for ductile fracture accounting for strain, strain rate and temperature dependence are presented. However, the key feature of the present contribution is that is advances our modelling so that it yields mesh objective fracture dissipation in the context of thermo-mechanical response.

1 INTRODUCTION

The primary task for machining operations is to reach the geometrical dimensions of the final product. During these operations a considerable waste of material- up to 10% of the workpiece volume might be removed[1]. Other difficulties that occur are i.e. variational mechanical properties due to micro-structural phase transformations coupled to temperature. Therefore it is of great importance to maintain control of processing parameters e.g compressive stresses, cutting forces and temperature distribution among others; in order to achieve desired product properties. These issues are generally addressed by implementation of simulation tools based on the finite element method[1 2]. It has been shown that the reliability of the numerical results are strongly coupled to the viability of the adopted constitutive model to accurately describe the material deformation[1 2]. However, it has been observed experimentally that the deformation patterns of the failure mechanisms during machining are highly localised. These localised failure modes can be modelled using a thermo-viscoplastic material model in conjunction with a damage evolution model.

2 DUCTILE DAMAGE MODELS BASED ON THERMO- VISCO-PLASTICITY

As a point of departure, the the response of the effective material is gradually reduced as the "scalar damage" parameter α evolves,

$$\psi = (1-\alpha)\hat{\psi} \quad \text{with} \quad \hat{\psi} = \hat{\psi}\left[\bar{\boldsymbol{b}}, k, \theta\right] \tag{1}$$

where $\hat{\psi}$ is the free energy of the effective (undamaged) material, denoted by a superimposed hat. In the formulation, $\bar{\boldsymbol{b}}$, represents the elastic Finger deformation tensor, k is an isotropic hardening variable while θ represents the temperature. Based on the second law of thermodynamics the Clausius Duhem's Inequality (CDI) is expressed as,

$$\hat{D} = \hat{D}_{mech} + \hat{D}_{therm} \geq 0 \tag{2}$$

It turns out that the total dissipation rate in the dissipation inequality can be formulated in terms of the effective dissipation rate

$$\mathcal{D} = (1-\alpha)\hat{\mathcal{D}}_{mech} + \hat{\psi}\dot{\alpha} \geq 0 \tag{3}$$

The evolution laws for the dissipation are chosen such that the dissipation inequality (2) is fulfilled, hence $D \geq 0$, $\hat{D} \geq 0$ and $\dot{\alpha} \geq 0$. The thermo-visco-plastic JC- constitutive model is adopted for the inelastic continuum response. The yield function is thereby introduced $\phi = \phi\left[\hat{\tau}_e, \hat{\kappa}, \hat{\theta}\right]$ in terms of the the effective von Mises stress $\hat{\tau}_e$, the hardening stress $\hat{\kappa}$ and the homologous temperature $\hat{\theta}$

$$\hat{\theta} = \begin{cases} 0, & \theta < \theta_0 \\ \frac{\theta-\theta_0}{\theta_m-\theta_0}, & \theta_0 < \theta < \theta_m \\ 1, & \theta > \theta_m \end{cases} \tag{4}$$

The plastic multiplier needed for the evolution of the internal dissipative variables $\left\{\boldsymbol{l}_p, \dot{k}\right\}$ is determined by the JC- overstress function

$$\lambda = \dot{\epsilon}_0 \exp\left[\frac{\phi}{C\left(A + Bk^n\right)\left(1-\hat{\theta}^m\right)}\right] \quad \text{for} \quad \lambda > \dot{\epsilon}_0 \tag{5}$$

where the parameters A, B, C, n, m and $\dot{\epsilon}_0$ are JC material parameters. The response becomes visco-plastic (or rate dependent) whenever $\lambda \geq \dot{\epsilon}_0$. To handle the rate independent case $\lambda < \dot{\epsilon}_0$, the plastic multiplier is controlled by the Karush-Kuhn-Tucker (KKT) loading conditions

$$\phi \leq 0, \quad \lambda \geq 0, \quad \lambda\phi = 0 \quad \text{for} \quad \lambda \leq \dot{\epsilon}_0 \tag{6}$$

As for the thermo-mechanical coupling the heat equation is formulated as

$$c^e\dot{\theta} = \eta(\boldsymbol{\tau}\boldsymbol{:}\boldsymbol{l}_p) - 3JK\alpha\theta(2J-1)\mathbf{1}\boldsymbol{:}\boldsymbol{d}_e = \eta w_p - 3JK\alpha\theta(2J-1)tr(\boldsymbol{d}_e) \tag{7}$$

here the *adiabatic condition* is considered where it is assumed that the plastic work is the primary source for the temperature increase besides the contribution from the thermal stress. Additionally, c^e is the heat capacity, w_p is the plastic work rate and η is the inelastic heat fraction parameter determining the amount of plastic work rate that is transfered into heat. To account for damage initiation the JC- fracture criterion is considered based on which two mesh objective ductile damage models are derived. For the sake of simplicity we postulate the final formulation for objectivity[3]. Considering the *progressive damage model*, the damage evolution is controlled as

$$\alpha = \left[\frac{1}{c[L_e]}\left(\frac{A_T}{A_c} - 1\right)\right]^{\frac{1}{m}} \quad \text{where} \quad c[L_e] = \frac{L_c}{L_e}(C_r + m + 1) - (m+1) \tag{8}$$

The next objective model is referred to as,*damage element removal model.* The objective damage evolution for this model is controlled as follows

$$A_T = \frac{L_c}{L_e}A_c \tag{9}$$

This damage model represents the traditional element removal model with the objective addition. Therefore, the damage is either fully developed, $\alpha = 1$, or there is no damage evolution at all $\alpha = 0$. Note that, L_e and L_c represent the current element diameter and the reference element diameter. Additionally, C_r and m represent model parameters while A_T account for the total damage driven energy and A_c is the critical damage driven energy.

3 NUMERICAL EXAMPLE

To illustrate the model behavior we present the results for a ballistic impact test[4].

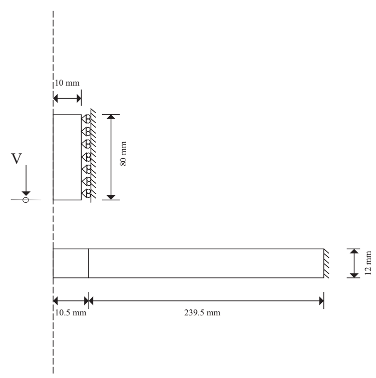
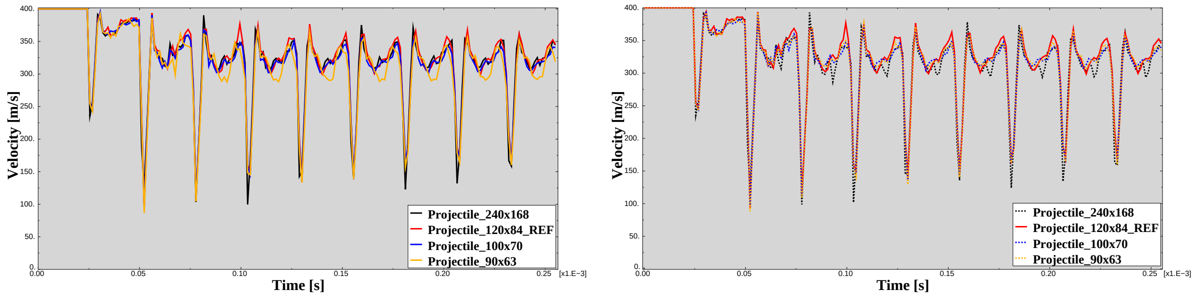


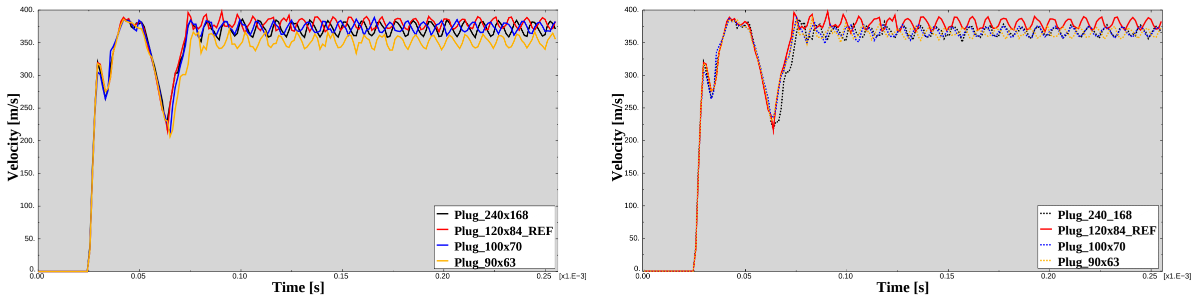
Figure 1: Axisymmetric representation of ballistic impact

The ballistic impact test consists of a circular, Weldox 460 E, steel plate with the nominal thickness of 12 mm and diameter of 500 mm. The blunt-nosed projectile used had a diameter of 20 mm, the length 80 mm and a nominal mass of 197 g as illustrated in Figure 1.



(a) Excluding objective enhancement. (b) Including objective enhancement.

Figure 2: Illustration of the change of velocity for the projectile using a initial velocity V_i = 400 m/s including and excluding mesh objective enhancement.



(a) Excluding objective enhancement. (b) Including objective enhancement.

Figure 3: Illustration of the change of velocity for the plug using a initial velocity V_i = 400 m/s including and excluding mesh objective enhancement.

In Figure 2 - 3 the change of velocity of the projectile and the plug is illustrated. The initial projectile velocity $V_i = 400m/s$ was used ad response was investigated for a set of different element sizes in the perforation zone of the plate. The presented results are based on the response of the progressive damage model. From the previous figures it is clear that neither the projectile and plug velocity change significantly as the mesh size was coarsened or refined when the objective enhancement is excluded. However, including the objective enhancement a better representation with respect to the reference mesh (RED CURVE) response was obtained.

REFERENCES

[1] Arrazola, P., Özel, T., Umbrello, D., Davies, M. & Jawahir, I. Recent advances in modelling of metal machining processes. *CIRP Annals- Manufacturing Technology* **62**, 695–718 (2013).

[2] Vaz, M., Owen, D., Kalhor, V., Lundblad, M. & Lindgren, L. Modeling and simulation of machining processes. *Archives of Computational Methods in Engineering* **38**, 3675–3694 (1995).

[3] Larsson, R., Razanica, S. & B.Josefson. Mesh objective continuum damage models for ductile fracture. *International Journal for Numerical Methods in Engineering.* **106**, 840–860 (2016).

[4] S.Dey, T.Borvik, O.S.Hopperstad & M.Langseth. On the influence of constitutive relations in projectile impact of steel plates. *International Journal of Impact Engineering.* **34**, 464–486 (2007).