METAL FORMING PROCESSES IMPROVEMENT BY CONTINUUM DAMAGE MECHANICS

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ABSTRACT

In this work, a fully coupled constitutive equations accounting for both combined isotropic and kinematic hardening as well as the ductile damage is implemented into the general purpose Finite Element code for metal forming simulation. First, the fully coupled anisotropic constitutive equations in the framework of Continuum Damage Mechanics are presented. Attention is paid to the strong coupling between the main thermomechanical fields as thermal effects, elasto-viscoplasticity, mixed hardening, ductile isotropic damage and contact with friction. The associated numerical aspects concerning both the local integration of the coupled constitutive equations as well as the (global) equilibrium integration schemes are presented. The local integration is outlined thanks to the Newton iterative scheme applied to a reduced system of 2 equations. For the global resolution of the equilibrium problem, the classical dynamic explicit (DE) scheme with an adaptive time step control is used. The numerical implementation of the damage is made in such a manner that calculations can be executed with or without damage effect, i.e. fully coupled or uncoupled calculations. For the 2D processes an advanced adaptive meshing procedure is used in order to enhance the numerical solution and to kill the fully damaged elements in order to describe the macroscopic crack propagation.

Various 2D and 3D examples are given in order to show the capability of the methodology to predict the damage initiation and growth during metal forming processes. Finally some aspects related to a going work concerning the non local or damage –gradient formulation in order to overcome the mesh dependency will be discussed.

INTRODUCTION

It is well known that when materials are worked by forming processes, they experience large plastic deformations leading to the onset of internal or surface micro-defects as voids and micro cracks. When these micro-defects initiate and grow inside the plastically deformed metal, the thermomechanical fields are deeply modified, leading to significant modifications in the deformation process. On the over hand, the coalescence of these defects (micro-voids) during the deformation can lead to the initiation of macro cracks or damaged zones, inducing an irreversible damage inside the formed part and consequently it's lose. Accordingly, it is very important for engineers, that the virtual metal forming tools allow the possibility to predict the damage occurrence during the process simulation. This gives a helpful way to improve and optimise, in situ, the process plan in order to avoid or to enhance this damage occurrence. It is worth noting that, taking into account the ductile damage in metal forming necessitates not only the availability of the damage evolution equations, but also its effects (or coupling) on the other thermomechanical fields under concern.

Coupled approaches stands for those models where the damage is introduced directly into the overall constitutive equations and affects all the thermomechanical fields according to the

appropriated coupling theory. Different kinds of coupled approaches have been employed by many authors to predict the damage occurrence in metal forming. The widely used models are based on Gurson's damage theory based of the void volume fraction evolution and its effect on the plastic yielding. Hence, only the effect of damage on the plastic behaviour is taken into account, leaving the elastic behaviour completely insensitive to the damage occurrence [1-6]. Other works are based on the continuum damage mechanics theory (CDM) using the thermodynamics of irreversible processes as can be found in [7, 8, 9]. These fully coupled approaches have shown their ability to « optimise » any process plan, not only to avoid the damage occurrence, but also to enhance the damage in order to simulate any metal cutting processes [10 to 20].
In the present work, an 'advanced' fully coupled approach will be shortly discussed from both the theoretical and numerical point of views. However, various examples will be presented in order to show their capability to predict the damage occurrence during metal forming processes.

1. MECHANICAL AND NUMERICAL MODELLING

In this section the theoretical (constitutive equations), numerical (FEA) and geometrical (adaptive meshing) aspects of the proposed virtual metal forming methodology will be outlined. For the sake of shortness in this paper, we limit ourselves to giving a summary of all these aspects. The reader is referred to the recent introductive chapter written by Saanouni and Chaboche [9] where an exhaustive presentation of the theoretical, numerical and geometrical aspects of the virtual metal forming with ductile damage is given.

1.1 Summary of the fully coupled constitutive equations

In finite deformation mechanics it is useful to assume that the total transformation gradient $\underline{F}$ is multiplicatively decomposed into elastic $\underline{F}^e$ and plastic $\underline{F}^p$ parts giving: $\underline{F}=\underline{F}^e+\underline{F}^p$. Dealing with the forming of metallic materials, it is sound and convenient to suppose that elastic gradient $\underline{F}^e$ is infinitesimal compared to the plastic one. This leads to an additive decomposition of the eulerian strain rate, i.e. $\underline{D} \cong \dot{\underline{\varepsilon}}_J^e + \underline{D}^p$, where the first term represents the Zaremba_Jaumann objective derivatives of the small elastic strain and the second represents the finite plastic strain rate component defined thanks to the appropriated dissipation potential (see Eq. (5)). On the other hand, to fulfil the objectivity requirement at finite strain, the rotational objective rates should be used to calculate the derivatives of any tensorial variable [9]. This rotated description keeps unchanged the basic structure of the constitutive equations as formulated in small strain hypothesis.
Using this 'rotated' objective formulation a complete set of constitutive equations can be formulated for metal forming simulation. In this paper we limit ourselves to giving the simplest isotropic formulation accounting for the nonlinear isotropic and kinematic hardening fully coupled with the isotropic damage under the isothermal condition (see [9] for the general anisotropic and anisothermal formulation). The outline of this model is given here after:

- **Stress-like variables**

$$\underline{\sigma} = (1-D)\left[\lambda \mathrm{tr}(\underline{\varepsilon}_e)\underline{I} + 2\mu\underline{\varepsilon}_e\right] \tag{1}$$

$$\underline{X} = \frac{2}{3}C(1-D)\,\underline{\alpha} \tag{2}$$

$$R = Q(1-D)r \tag{3}$$

$$Y = \frac{1}{2}\left(\lambda(\underline{\varepsilon}_e : \underline{1})^2 + \mu(\underline{\varepsilon}_e : \underline{\varepsilon}_e)\right) + \frac{1}{3}C\ \ \underline{\alpha} : \underline{\alpha}\ + \frac{1}{2}Q\ \ r^2 \tag{4}$$

- **Evolution equations for the strain-like variables**

$$\underline{D}_p = \frac{3}{2}\frac{\dot{\delta}}{\sqrt{1-D}}\frac{\underline{S}-\underline{X}}{J_2(\underline{\sigma}-\underline{X})} = \dot{\delta}\underline{n} \tag{5}$$

$$\underline{\dot{\alpha}} = \dot{\delta}\left(\underline{n} - a\underline{\alpha}\right) \tag{6}$$

$$\dot{r} = \dot{\delta}\left(\frac{1}{\sqrt{1-D}} - br\right) \tag{7}$$

$$\dot{D} = \dot{\delta}\left(\frac{Y}{A}\right)^{\gamma}\frac{1}{(1-D)^{\beta}} \tag{8}$$

In these constitutive equations (r, R) represents the isotropic hardening, ($\underline{\alpha}$, $\underline{X}$) represents the kinematic hardening and (D, Y) represents the isotropic ductile damage. It is assumed here that all the tensorial variables entering these constitutive equations are rotated by the orthogonal rotation $\underline{Q}$ as discussed above. The material parameters λ and μ are the classical Lame's constants while C, a, Q and b characterize the non linear kinematic and isotropic hardening respectively and A, γ, β characterize the ductile damage evolution. The scalar quantity entering the Eq. (5) is the equivalent stress $J_2(\underline{\sigma}-\underline{X}) = \sqrt{\frac{3}{2}\left(\underline{S}-\underline{X}\right):\left(\underline{S}-\underline{X}\right)}$ in which $\underline{S}$ is the deviatoric stress tensor, and $\dot{\delta}$ is the plastic multiplier given by:

$$\dot{\delta} = \frac{1}{H}\left\langle 2\mu\sqrt{1-D}\,\underline{n} : \underline{D}\right\rangle \tag{9}$$

in which H>0 is the elastoplastic hardening modulus given by:

$$H = 3\mu + Q + C + \frac{\sigma_y}{2(1-D)^{\beta+1}}\left(\frac{Y}{A}\right)^{\gamma} - \left(\frac{bR}{\sqrt{1-D}} + a\underline{n} : \underline{X}\right) \tag{10}$$

The second order deviatoric tensor $\underline{n}$ in Eq. (5) is the outward normal to the yield surface with damage effect defined in the stress space by:

$$f\left(\underline{\sigma}, \underline{X}, R, D\right) = \frac{J_2(\underline{\sigma}-\underline{X}) - R}{\sqrt{1-D}} - \sigma_y \tag{11}$$

In the case of time dependent plasticity this multiplier is given by:

$$\dot{\delta} = \left\langle \frac{f(\underline{\sigma}, \underline{X}, R, D}{K} \right\rangle^{n} \tag{12}$$

where K and n are the classical viscosity parameters characterizing the material sensitivity to the rate effect.

Another phenomenon which can not be avoided in metal forming simulation is the contact with friction between the formed part and the used tools. Generally, the friction models are defined as a relation between the normal stress σ_n, the tangential stress τ_S and the relative tangential velocity $\mathbf{V}_S$ at the contact point between the part (deforming plastically) and the tool (supposed rigid or elastically deforming body). In this presentation we limit ourselves to the isotropic friction models and particularly to the well known Coulomb friction model available in standard fashion within the code ABAQUS.

1.2 Numerical aspects

The Finite Element Analysis is required in virtual metal forming in order to solve numerically, for each external applied load increment, the equilibrium equations together with the fully coupled constitutive and friction equations discussed above. Appropriated initial and boundary conditions including the evolving contact arising from the moving contact between the deformed part and the tools should be taken into account. This defines a highly nonlinear IBVP which needs to be incrementally linearized and solved on each load step using either an iterative or non iterative implicit or explicit scheme. Practically, solving this kind of IBVPs needs both the spatial discretization of the body using the FEM and the time discretization using an appropriated finite difference method. A considerable work has been done in this field aiming to solve many kinds of IBVPs with various kinds of constitutive equations applied to different kinds of nonlinear mechanical structures. In this work a Dynamic Explicit scheme without any iteration procedure nor the tangent stiffness matrix is used. However, it is conditionally stable requiring an automatic time step control (see Abaqus users manual).
For the local integration of the fully coupled constitutive equations (see Eq. (1 to 12), a fully explicit return mapping algorithm is used together with an exponential (asymptotic) development applied to the hardening Eq. (6) and (7). Moreover, special developments have been made in this fully isotropic case in order to reduce the ODEs number to only two scalar equations coming from the time discretization of the yield function and the damage equation.

2. SOME APPLICATIONS

To be short, hereafter are given without detailed information and discussion, some results concerning the numerical simulation of some 2D virtual metal forming processes. More complete information together with other 3D processes will be shown during the oral presentation.
The first example concerns the hot forging of the axisymmetric wheel starting from an initial cylindrical part. The circular upper punch moves with the controlled displacement rate of 0.05 mm/s while the lower one is fixed. Both the punch and the die are supposed rigid bodies. The wheel is obtained in one operation. The initial or reference temperature in the hot cylindrical part is T_0=1000°C.

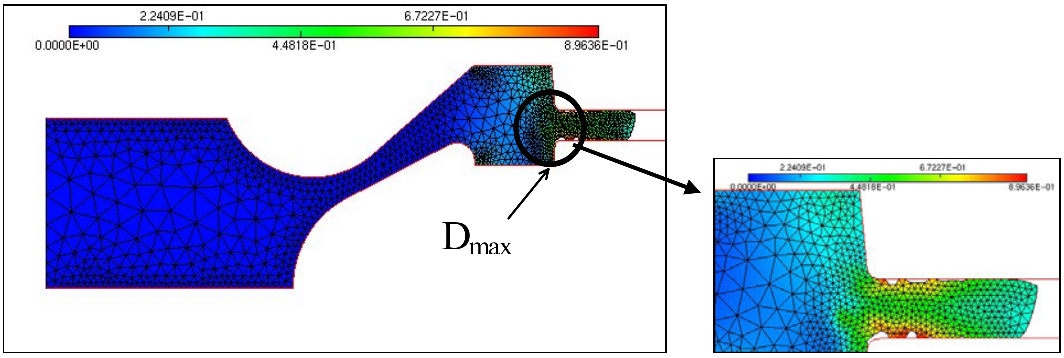
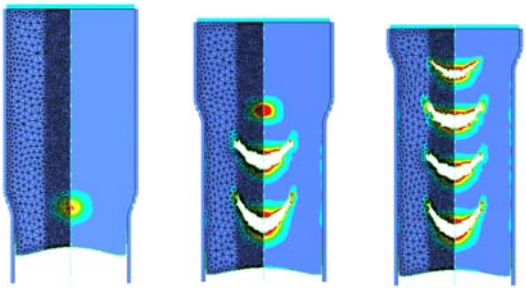


Figure 2 : Damage distribution at the end of the operation for u=14.75 mm

Figure 1 shows the ductile damage distribution together with the mesh adaptation at the end of the process. It is worth nothing that the process is terminated without any significant damage (D < 10%) in the wheel expecting the area around the burr indicated in Figure 1 where the damage exceeds 40% with some fully damaged elements as shown in the zoom of Figure 2. The maximum forging force is F=4500 kN observed at the process end for u= 14.75 mm.

The second example aims to predict the chevron-shaped cracks along the central axis of a cylindrical bar subject to a cold forward extrusion. The initial bar has 75 mm length and 50 mm diameter to be reduced to 44.5 mm using a die cone angle of 30°. Figure 2 shows a realistic predicted discontinuous chevron cracks thanks to the fully coupled approach.



(a) d=0 mm (b) d=24 mm (c) d=70 mm

Figure 2. Numerical prediction of the discontinuous chevron cracks in forward cold extrusion of a cylindrical bar without adaptive remeshing but with kill element procedure.

Acknowledment

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