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Ductile damage model for metal forming simulations including refined description of void nucleation

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ABSTRACT

We address the prediction of ductile damage and material anisotropy accumulated during plastic deformation of metals. A new model of phenomenological metal plasticity is proposed which is suitable for applications involving large deformations of workpiece material. The model takes combined nonlinear isotropic/kinematic hardening, strain-driven damage and rate-dependence of the stress response into account. Within this model, the work hardening and the damage evolution are fully coupled. The description of the kinematics is based on the double multiplicative decomposition of the deformation gradient proposed by Lion. An additional multiplicative decomposition is introduced in order to account for the damage-induced volume increase of the material. The model is formulated in a thermodynamically admissible manner. Within a simple example of the proposed framework, the material porosity is adopted as a rough measure of damage.

A new simple void nucleation rule is formulated based on the consideration of various nucleation mechanisms. In particular, this rule is suitable for materials which exhibit a higher void nucleation rate under torsion than in case of tension.

The material model is implemented into the FEM code Abaqus and a simulation of a deep drawing process is presented. The robustness of the algorithm and the performance of the formulation is demonstrated.

1. Introduction

Dealing with metal forming applications, it is often necessary to asses the mechanical properties of the resulting engineering components, including the remaining bearing capacity, accumulated defects, and residual stresses. Thus, a state-of-the-art model for metal forming simulations should account for various nonlinear phenomena. If the residual stresses and the spring back are of particular interest, such a model should include the combined isotropic/kinematic hardening. For some metals, however, the influence of ductile damage induced by plastic deformation should be taken into account as well. In spite of widespread applications involving large plastic deformations accompanied by kinematic hardening and damage, only few material models cover these effects (cf. Simo and Ju (1989); Menzel et al. (2005); Lin and Brocks (2006); Grammenoudis et al. (2009); Bammann and Solanki (2010); Bröcker and Matzenmiller (2014)).

In the current study we advocate the approach to plasticity/viscoplasticity based on the multiplicative decomposition of the deformation gradient. This approach is gaining popularity due to its numerous advantages like the absence of spurious

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Nomenclature

$\mathbf{1}$	identity tensor
$\mathbf{F}$, $\overset{\text{por}}{\mathbf{F}}_{\text{ep}}$	deformation gradient and its elasto-plastic part (cf. (1))
$\overset{\text{por}}{\mathbf{F}}_{\text{i}}$, $\overset{\text{por}}{\mathbf{F}}_{\text{ii}}$	dissipative parts of deformation (cf. (3), (4))
$\widehat{\mathbf{F}}_{\text{e}}$, $\breve{\mathbf{F}}_{\text{ie}}$	conservative parts of deformation (cf. (3), (4))
$\mathbf{C}$, $\overset{\text{por}}{\mathbf{C}}_{\text{ep}}$	total and elasto-plastic right Cauchy-Green tensors (cf. $(7)_1$)
$\overset{\text{por}}{\mathbf{C}}_{\text{i}}$, $\overset{\text{por}}{\mathbf{C}}_{\text{ii}}$	(dissipative) tensors of right Cauchy-Green type (cf. $(7)_2$, $(8)_1$)
$\widehat{\mathbf{C}}_{\text{e}}$, $\breve{\mathbf{C}}_{\text{ie}}$	(conservative) tensors of right Cauchy-Green type (cf. $(7)_3$, $(8)_2$)
$\mathbf{L}$	velocity gradient tensor
$\widehat{\mathbf{L}}_{\text{i}}$	inelastic velocity gradient (cf. $(10)_1$)
$\breve{\mathbf{L}}_{\text{ii}}$	inelastic velocity gradient of substructure (cf. $(11)_1$)
$\mathbf{D}$	strain rate tensor (stretching tensor)
$\widehat{\mathbf{D}}_{\text{i}}$	inelastic strain rate (cf. $(10)_2$)
$\breve{\mathbf{D}}_{\text{ii}}$	inelastic strain rate of substructure (cf. $(11)_2$)
s, s_{d}, s_{e}	inelastic arc-length and its parts (cf. (12))
$\mathbf{T}$, $\widetilde{\mathbf{T}}$	Cauchy stress and 2nd Piola–Kirchhoff stress
$\mathbf{S}$, $\mathbf{S}_{\text{ep}}$	Kirchhoff stress and Kirchhoff-like stress (cf. (13))
$\widehat{\mathbf{S}}_{\text{ep}}$, $\overset{\text{por}}{\mathbf{T}}_{\text{ep}}$	pull-backs of $\mathbf{S}$ to $\widehat{\mathscr{K}}$ and $\overset{\text{por}}{\mathscr{K}}$ (cf. (14), (16))
$\widehat{\mathbf{X}}$, $\overset{\text{por}}{\mathbf{X}}$, $\breve{\mathbf{X}}$	backstresses on $\widehat{\mathscr{K}}$, $\overset{\text{por}}{\mathscr{K}}$, $\breve{\mathscr{K}}$ (cf. (18), (19), $(28)_2$)
$\widehat{\mathbf{\Sigma}}$, $\breve{\mathbf{\Xi}}$	effective stress on $\widehat{\mathscr{K}}$ and Mandel-like backstress on $\breve{\mathscr{K}}$ (cf. (21), (20))
R	isotropic hardening (stress) (cf. $(28)_3$, (42))
f	yield function (rate-dependent overstress) (cf. (42))
$\mathbf{A}^{\text{D}}$	deviatoric part of a second-rank tensor
$\overline{\mathbf{A}}$	unimodular part of a second-rank tensor (cf. (25))
$\mathbf{A}$	transposition of a second-rank tensor
$\text{sym}(\mathbf{A})$	symmetric part of a second-rank tensor
$\|\|\mathbf{A}\|\|$	Frobenius norm of a second-rank tensor
$\mathbf{A} : \mathbf{B}$	scalar product of two second-rank tensors
ρ_{R}, ρ_{por}	mass densities in $\widetilde{\mathscr{K}}$ and $\overset{\text{por}}{\mathscr{K}}$
Φ	damage-induced volume change (cf. (2))
N	void number per unit volume in $\widetilde{\mathscr{K}}$

shear oscillations, the absence of non-physical dissipation in the elastic range and the weak invariance under the change of the reference configuration (Shutov and Ihlemann, 2014). The main purpose of the current publication is to promote the phenomenological damage modeling within the multiplicative framework. Toward that end, the model of finite strain viscoplasticity proposed by Shutov and Kreißig (2008a) is extended to account for ductile damage. The original viscoplastic model takes the isotropic hardening of Voce type and the kinematic hardening of Armstrong–Frederick type into account. The model is based on a double multiplicative split of the deformation gradient, considered by Lion (2000).[1] Both the original model and its extension are thermodynamically consistent. We aim at the simplest possible extension which takes the following effects into account:

- nonlinear kinematic and isotropic hardening;
- inelastic volume change due to damage-induced porosity;
- damage-induced deterioration of elastic and hardening properties.

In this vein, we assume that the elastic properties deteriorate with increasing damage and remain isotropic at any stage of deformation. The assumption of elastic isotropy is needed to exclude the plastic spin from the flow rule, thus reducing the flow rule to six dimensions.

[1] The seminal idea of the double split was already used by several authors to capture the nonlinear kinematic hardening (Helm, 2001; Tsakmakis and Willuweit, 2004; Dettmer and Reese, 2004; Hartmann et al., 2008; Henann and Anand, 2009; Brepols et al., 2013, 2014; Zhu et al., 2013). It was also implicitly adopted by Menzel et al. (2005); Johansson et al. (2005). A simple extension to distortional hardening was presented by Shutov et al. (2011).