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Improved fracture criterion to chain forming stage and in use mechanical strength computations of metallic parts – Application to half-blanked components

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ABSTRACT

Forming processes stages usually affect final components mechanical properties. Accounting for material processing effect is required to analyze final component's mechanical strength and optimize products design. Accounting for both the forming stage and the structural analysis of the final product requires dealing with complex multi-stages and non-proportional loading configurations. The development of improved material models and numerical methods is needed. In the present paper, in-use mechanical behavior of half-blanked components is modeled by means of the finite element method. The complete methodology to chain metal forming computations (Forge® software) and in-use parts mechanical loading computations (LS-Dyna® software) is described. An improved fracture criterion, suited for the non-proportional loading observed during products lifecycle, was developed and used to model fracture of high-strength low-alloy steel S420MC. Ductility is modeled by a damage variable which can grow during the forming stage allowing the modeling of the relative loss of ductility induced by this step. The proposed fracture criterion is based on the definition of stress state functions, by parts in the stress states space, which allows modeling fracture under a wide range of loading conditions. Laboratory tests and industrial case computations results are assessed by comparison with experiment. Influence of forming stage and ductile fracture is analyzed. It is shown that accounting for the manufacturing process and modeling fracture are mandatory if one wants to predict accurately the observed failure modes as well as the load-carrying capacity of half-blanked components.

1. Introduction

Computer aided engineering (CAE) tools are now widely used to develop industrial processes and products. Especially, finite element method allows engineers to compute local variables (as strain and stress states) and global variables (as resulting displacements and loads) to analyze the mechanical behavior of structures submitted to external loadings. To ensure accurate results, material behavior, initial conditions and boundary conditions have to be modeled properly. In the case of structures, made of ductile metals and submitted to high external loadings in quasi-static and isothermal conditions, the following phenomena have to be taken into account: plasticity, ductile damage and ductile fracture.

Ductile fracture is the occurrence of macroscopic cracks after significant inelastic deformations. Predicting ductile fracture is of prime interest in the design of processes since customers often specify to manufacturer delivering crack free products. Predicting ductile fracture is also of interest in the design of mechanical products. Fracture decreases the material load carrying capacity. Then fractured components generally cannot ensure anymore their mechanical linkage or power transmission functionalities.

Mechanical behavior of metals and ductile fracture are mainly influenced by the stress state. In the present paper, stress and strain states are characterized by the stress triaxiality ratio η, the Lode angle θ_L and the equivalent plastic strain ε_{pl}. Expressions of the stress triaxiality ratio η and of the Lode angle θ_L, function of the principles stresses (σ_I, σ_{II}, σ_{III}), are given respectively by Eqs. (1) and (4). For convenience, the stress triaxiality ratio will be referred as the "stress triaxiality" in the following.

$$\eta = -\frac{p}{\sigma_{eq}} \quad (1)$$

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Nomenclature

b	tensile specimens gage section width
d	tensile specimens reduced section length
d_{BH}	inner diameter of the blank holder
d_d	inner diameter of the die
d_{isp}	tool displacement
d_g	internal diameter of the groove of the hat shape specimens
d_h	diameter of the blind hole of the hat shape specimens
d_p	punch diameter
D	damage variable
D_1	material parameter of the Xue and Wierzbicki fracture criterion
D_2	material parameter of the Xue and Wierzbicki fracture criterion
D_3	material parameter of the Xue and Wierzbicki fracture criterion
D_4	material parameter of the Xue and Wierzbicki fracture criterion
D_5	material parameter of the Xue and Wierzbicki fracture criterion
D_d	outer diameter of the die
D_{BH}	outer diameter of the blank holder
e	sheet thickness
$\vec{e}_r$	radial axis
$\vec{e}_R$	rolling direction
$\vec{e}_x$	tensile specimens longitudinal direction
F_{BH}	blank holder load
Fel	experimental tensile load at yield stress
F_{max}	maximum load carrying capacity
h	height of the formed cylinder of the half-blanked specimens (half-blanking height)
hr	resulting height of the wrenched specimens
hw	clearance between the specimens sheet plane and the shearing tool (wrenching height)
j	clearance between the punch and the die
k	material parameter of the Xue and Wierzbicki fracture criterion
K	material parameter of the power hardening law
l	tensile specimens gage section length
n	material parameter of the power hardening law
p	hydrostatic pressure
p_g	groove depth of the hat shape specimens
p_h	blind hole depth of the hat shape specimens
r	radial coordinate
r_l	lankford ratio
r_d	edge radius of the die
r_p	edge radius of the punch
R	tensile specimens groove radius
R_s	tensile specimens shoulder radius
Rel	experimental yield stress
α	angle between the tensile specimen longitudinal direction and the rolling direction
ε_0	material parameter of the power hardening law
ε_1	equivalent plastic strain met at the end of the first stage of a non-monotonic mechanical test
ε_f	function defining the equivalent plastic strain at fracture
ε_{pl}	equivalent plastic strain
ε_{pl}'	equivalent plastic strain met during the first stage of a non-monotonic mechanical test
$\dot{\varepsilon}_{pl}$	rate of the equivalent plastic strain
$\bar{\bar{\varepsilon}}$	strain tensor
$\dot{\bar{\bar{\varepsilon}}}_{pl}$	plastic strain rate tensor
η	stress triaxiality ratio
η'	stress triaxiality ratio met during the first stage of a non-monotonic mechanical test
$\eta_{\lim}$	material parameter of the Xue and Wierzbicki fracture criterion
θ_L	Lode angle
θ_L'	Lode angle met during the first stage of a non-monotonic mechanical test
γ	material parameter of the Xue and Wierzbicki fracture criterion
μ_η	function of the stress triaxiality of the Xue and Wierzbicki fracture criterion
$\mu_{\theta L}$	function of the Lode angle of the Xue and Wierzbicki fracture criterion
σ_0	yield stress
σ_I	first principal stress
σ_{II}	second principal stress
σ_{III}	third principal stress
σ_{eq}	von Mises equivalent stress
$\bar{\bar{\sigma}}$	Cauchy stress tensor

with the hydrostatic pressure p and the von Mises equivalent stress σ_{eq}:

$$p = -\frac{1}{3}(\sigma_I + \sigma_{II} + \sigma_{III}) \quad (2)$$

$$\sigma_{eq} = \left(\frac{1}{2}\left((\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_I - \sigma_{III})^2\right)\right)^{\frac{1}{2}} \quad (3)$$

$$\theta_L = \arctan\left(\frac{\sqrt{3}}{3}\frac{2\sigma_{II} - \sigma_I - \sigma_{III}}{\sigma_I - \sigma_{III}}\right) \quad (4)$$

The rate of equivalent plastic strain $\dot{\varepsilon}_{pl}$ is defined by the rate of plastic work given by Eq. (5):

$$\bar{\bar{\sigma}} : \dot{\bar{\bar{\varepsilon}}}_{pl} = \sigma_{eq}\dot{\varepsilon}_{pl} \quad (5)$$

where $\bar{\bar{\sigma}}$ is the Cauchy stress tensor and $\dot{\bar{\bar{\varepsilon}}}_{pl}$ is the plastic strain rate tensor. Equivalent plastic strain ε_{pl} is then given by Eq. (6).

$$\varepsilon_{pl} = \int \dot{\varepsilon}_{pl} dt \quad (6)$$

From a microscopic point of view, ductile fracture is the consequence of voids nucleation, growth and coalescence at higher stress triaxiality and by shear bands at lower stress triaxiality. These changes in the materials microstructure induce at macroscopic scale a decrease of stiffness followed by final fracture.

Based on the work of Gurson (1977) and Tvergaard and Needleman (1984) developed the GTN model that accounts for voids evolution (nucleation, growth and coalescence) and for evolution of the yield stress due to porosity. More recently Nahshon and Hutchinson (2008) modified the GTN model to account for damage increase due to voids rotation and elongation for shear loading. In another way, ductile damage and fracture phenomena can be modeled using the continuum damage mechanics (CDM) approach mainly developed by Lemaitre (1985). Lemaitre defined a phenomenological damage variable which evolution is given by a dissipative potential within a consistent thermodynamic framework. The effect of damage on mechanical properties is taken into account by the definition of the effective stress (Kachanov, 1986). Lemaitre model was recently improved to account for complex