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Ductile damage modeling at elevated temperature applied to the cross wedge rolling of AA6082-T6 bars

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ABSTRACT

Formability is one of the critical issues in metal forming processes since it is a limiting factor for the choice of the process parameters as well as for the attainable part quality. This issue is of even higher importance in processes carried out at elevated temperature, in which more variables are involved, and the temperature and strain rate changes can influence the material microstructural behavior, which, in turn, influences the fracture occurrence.

In the paper, a modification of the Oyane–Sato fracture criterion providing the dependency on temperature and strain rate is proposed and applied to a cross wedge rolling process carried out on AA6082-T6 bars at elevated temperature. The modified fracture criterion was calibrated by means of hot tensile tests conducted at varying temperature and strain rate spanning the hot temperature range for the given alloy. Changes in the material formability were identified as a function of the testing parameters and also linked to the material microstructural characteristics. The fracture criterion was then implemented into the calibrated finite element model of the industrial process and validated by comparing the numerical and experimental outcomes.

1. Introduction

Finite element (FE)-based simulations represent a powerful tool for the design and optimization of industrial forming processes, permitting to reduce cost-intensive prototyping steps and to obtain cheaper and high-quality products. However, in order to provide accurate and reliable results, the FE models require a proper calibration of the material rheology and formability as well as of the tribological parameters at the workpiece-die interface, as illustrated by Tekkaya (2005). In particular, the proper modeling of formability is crucial in order to avoid crack formation and, therefore, attain defects-free parts.

The approach to modeling formability in bulk metal forming consists in applying fracture criteria that describe the material damage evolution and are usually calibrated through combined experimental and numerical procedures, as shown by Skrezypek and Ganczarski (1999). Fracture criteria can be classified into two main categories, namely un-coupled and coupled criteria, on the basis of their capability to link the material properties to the damage evolution. Un-coupled fracture criteria are based either on energetic considerations, such as in the pioneering work of Cockroft and Latham (1968), or on the assumption that the triaxiality of the stress state is the driving factor in the voids development, growth and coalescence, which, in turn, will lead to fracture, as showed by Rice and Tracey (1969) and Oyane (1972). Oyane et al. (1980) further developed the criterion for practical application to industrial processes, proving its effectiveness in predicting the formability limits in complex stress and strain conditions such as those arising in an indirect extrusion process. Because of the simplicity of their formulations, un-coupled criteria do not fully characterize the stress state of the material under deformation, and thus they can provide results that may be test-dependent, in particular if low or medium levels of the stress triaxiality are involved, as demonstrated by Bao and Wierzbicki (2004b). On the other hand, the coupled fracture criteria essentially comprise the porosity-based models and the continuum damage mechanics (CDM). The former models are based on the results of Gurson (1977), who considered the material as a porous medium and modeled the voids influence on material damage. The Gurson's approach was then enhanced by Tvergaard (1981), who took into account the close voids coalescence effect in a plane strain case study and by Tvergaard and Needleman (1984), who considered an axisymmetric study case. The CDM, on the other hand, is based on the thermodynamics of the irreversible processes and was first developed in the work of Lemaitre (1985), and later on enhanced by Lemaitre and Desmorat (2005). Coupled criteria provide a more detailed

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Nomenclature

A	Hansel Spittel consistency coefficient
B	Oyane–Sato constant
D_{new}	damage parameter of the proposed fracture criterion
D_{new}^*	damage trigger value of the proposed fracture criterion
$\dot{D}_{new}$	damage rate of the proposed fracture criterion
D_{Oy}	damage parameter of the Oyane–Sato fracture criterion
D_{Oy}^*	damage trigger value of the Oyane–Sato fracture criterion
ε	true strain
$\dot{\varepsilon}$	true strain rate
$\dot{\varepsilon}_{avg}$	average strain rate
$\dot{\varepsilon}_{test}$	test strain rate
$\bar{\varepsilon}$	von Mises equivalent strain
$\dot{\varepsilon}_{nom}$	nominal true strain rate
θ	Lode angle
J_3	third invariant of the deviatoric component of the stress tensor
l_0	specimen initial gauge length
m_1	Hansel Spittel exponential temperature coefficient
m_2	Hansel Spittel strain hardening coefficient
m_3	Hansel Spittel strain rate hardening coefficient
m_4	Hansel Spittel strain softening coefficient
m_5	Hansel Spittel temperature–strain influence coefficient
m_7	Hansel Spittel exponential strain hardening coefficient
m_8	Hansel Spittel temperature–strain rate influence coefficient
m_9	Hansel Spittel temperature coefficient
v	press speed
σ	true stress
$\bar{\sigma}$	von Mises equivalent stress
σ_H	hydrostatic stress
t	time
T	temperature
T_{test}	test temperature
$\o_f$	specimen cross sectional diameter at fracture
$\o_0$	specimen cross sectional initial diameter
X	deviatoric parameter

physical description of the damage phenomenon and its evolution compared to the un-coupled ones, showing less dependency on the calibration test type; on the other hand, they are more mesh size-sensitive than the un-coupled criteria and their calibration and implementation in FE codes appear more complex and time consuming and therefore less suitable to be applied in industry.

In the last decade, the research efforts devoted to model the formability in cold forging have been mostly focused on the comprehension of the stress-state influence on the damage propagation as reported in the work of Bao (2005), who highlighted the strong correlation between triaxiality and equivalent strain at fracture in tensile tests, or again in another work of Bao and Wierzbicki (2004a), who investigated the change of fracture mode at low triaxiality levels. Furthermore, in Xue (2007) and in Xue and Wierzbicki (2008), the authors identified two exponential formability limits, and in Barsoum and Faleskog (2007), it was proved that the fracture mode depends on the deviatoric stress tensor component. Other research efforts were made to take explicitly into account the rheological characteristics of the material into the damage model formulation, with the work of Coppola et al. (2009), or to enhance the capabilities of the coupled criteria, with the work of Bonora (1997), who proposed a non-linear damage computation extension to the Lemaitre's CDM. More recent improvements in damage modeling are in Bai and Wierzbicki (2010), in which the authors investigated the effect of the deviatoric stress tensor component on formability, extending the application of the Mohr–Coulomb criterion to the ductile fracture, while Lou and Huh (2013) and Lou et al. (2014) proposed an extension of the shear controlled fracture model taking into account the effect of stress triaxiality and Lode angle, and Graham et al. (2012) developed a combined tensile-torsion testing apparatus to directly characterize the material fracture locus as a function of triaxiality and deviatoric parameter. It is worth to underline that all the above-mentioned modeling approaches were originally developed to predict the evolution of the ductile damage under cold deformation conditions, neglecting any influence of either the temperature or the strain rate.

In hot forging processes, material formability is usually linked to the idea of *forgeability window* that defines the lower and upper temperature limits suitable to obtain sound components. So, an uncontrolled temperature increase can activate microstructural phenomena that affect the fracture mode (see as reference the ASM Handbook Fractography, 1987), leading to a sudden decrease of the material formability, well known as hot shortness. A survey of literature reveals several researches focused on the ductile damage modeling in hot metal forming processes. Hurtado-Delgado and Morales (2001) investigated the influence of temperature and strain rate on both the material formability and fracture modes of a low carbon steel, while Alexandrov et al. (2004) carried out hot tensile tests on different aluminum alloys to assess the hot shortness onset and the correlation between the formability and the Zenner–Hollomon parameter, finally proposing an extension of the Oyane–Sato fracture criterion to hot conditions. Ghiotti et al. (2009) modified the Lemaitre model to take into account the microstructural non homogeneities of continuously cast steel bars and validated it on a Mannesmann tube piercing industrial process. More recently, Khan and Liu (2012) proposed an analytical approach to model the influence of the temperature and strain rate on the fracture strength, and Zhu et al. (2012) proposed a simple procedure for the prediction of the surface cracking in hot compression tests. He et al. (2013) presented a work in which the Oyane–Sato criterion was extended to high temperatures, modeling also the hot shortness onset, while Deng et al. (2013) presented an investigation on the temperature and strain rate influence on the fracture mode of a magnesium alloy. However, the few works providing experimental validation of the proposed models do not use real industrial processes, but are based on simple cases, such as tensile or compression tests, where the temperature changes during the deformation are almost negligible and do not cause any evident microstructural evolution.

With this in mind, one of the main research challenges in metal forming appears to be the development of new fracture criteria that can take into account the influence of complex phenomena typical of hot metal forming processes, such as the temperature, the strain rate and the microstructure changes but, at the same time, characterized by a formulation and a calibration procedure simple enough for being of industrial interest.

The work presented in this paper proposes a modification of the conventional Oyane–Sato fracture criterion taking into account the influence of the temperature and strain rate on the material damage evolution. The hot cross wedge rolling process of AA6082-T6 alloy round bars was chosen as the reference industrial case, from which the ranges of temperature and strain rate of interest were extracted. Hot compression tests were carried out in order to determine the rheological behavior of the material, while a tensile test