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Stress state dependence of ductile damage and fracture behavior: Experiments and numerical simulations

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ABSTRACT

The paper deals with new experiments and corresponding numerical simulations to study the effect of stress state on damage and fracture behavior of ductile metals. Different branches of ductile damage criteria are considered corresponding to various mechanisms depending on stress intensity, stress triaxiality and the Lode parameter. New experiments with two-dimensionally loaded specimens have been developed covering a wide range of stress triaxialities and Lode parameters in the tension, shear and compression domains. Scanning electron microscope (SEM) analyses of the fracture surfaces show various failure modes corresponding to different stress states detected by numerical simulations of the experiments.

1. Introduction

Modeling and numerical simulation of inelastic behavior, damage and fracture of materials are important topics in engineering mechanics, for example, in analyses of complex structural components, in prediction of structural reliability, or in development and optimization of structural design. Based on many experimental and numerical studies it is nowadays evident that during loading of ductile metals inelastic deformations occur which are accompanied by damage and local failure mechanisms on micro- and meso-scales. The accumulation of these processes may lead to fracture of structural elements. The damage and failure mechanisms on the micro-level depend on stress state of the material sample. For example, under tension dominated stress conditions (high positive stress triaxialities) damage in ductile metals is mainly caused by nucleation, growth and coalescence of voids whereas under shear and compression dominated stress states (small positive or negative stress triaxialities) evolution of micro-shear-cracks is the predominant damage mechanism. Furthermore, combination of both basic mechanisms occurs for moderate positive stress triaxialities whereas no damage in ductile metals has been observed for finite negative stress states. Therefore, to be able to develop phenomenological ductile material models it is important to analyze in detail and to understand these stress-state-dependent processes and mechanisms of damage and fracture acting on different scales.

Different damage models have been proposed in the literature based on experimental observations as well as on multi-scale approaches [1–5]. In addition, important aspects concerning the choice of mechanical variables characterizing the damage process as well as their experimental identification have been discussed [6]. For example, the advantage of isotropic damage models considering scalar variables is the simple theoretical framework and simple identification of one

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Nomenclature

a/c hydrostatic stress coefficient
c, c_0 yield stresses
E, G, K elastic material parameters
g^{pl}, g^{da} potential functions
f^{da} damage condition
f^{pl} yield condition
F_1, F_2 applied forces
H hardening modulus
$I_1, \bar{I}_1, J_2, \bar{J}_2, J_3$ invariants of (deviatoric) stress tensors
n hardening exponent
$\tilde{T}_1, \tilde{T}_2, \tilde{T}_3$ principal stresses
u displacement
$\mathbf{A}^{el}, \mathbf{A}^{da}$ strain tensors
$\dot{\mathbf{H}}, \dot{\mathbf{H}}^{el}, \dot{\overline{\mathbf{H}}}^{pl}, \dot{\mathbf{H}}^{da}$ strain rate tensors
$\mathbf{M}, \overline{\mathbf{N}}, \mathbf{N}$ normalized stress tensors
$\mathbf{Q}, \mathbf{Q}^{el}, \overline{\mathbf{Q}}^{pl}$ metric transformation tensors
$\mathbf{R}, \overset{o}{\mathbf{R}}, \overset{*}{\mathbf{R}}$ damage tensors
$\tilde{\mathbf{S}}$ deviatoric stress-related tensor
$\overline{\mathbf{T}}, \mathbf{T}, \tilde{\mathbf{T}}$ stress tensors
α, β damage mode parameters
$\bar{\alpha}, \bar{\beta}, \bar{\delta}$ damage rule parameters
$\dot{\lambda}, \dot{\gamma}, \dot{\mu}$ rate of internal variables
ν Poisson's ratio
η stress triaxiality
$\eta_1 \ldots \eta_4$ elastic-damage moduli
σ equivalent damage stress
σ_{eq} von Mises equivalent stress
σ_m mean stress
ω Lode parameter

single parameter [7–10]. However, practical applicability of these isotropic models is very limited because especially in ductile metals anisotropic damage effects occur with large inelastic deformations which cannot be simulated by an isotropic approach. Thus, anisotropic damage models based on tensorial variables have been proposed, for example, by [5,11–15]. However, their practical applicability may be limited by large number of material parameters and difficulties in their identification. Furthermore, on the numerical side there may be remarkable problems to implement these approaches in computer codes and, thus, it seems to be difficult to realistically predict deformation and failure behavior of materials and structures in engineering applications. Therefore, a generalized and thermodynamically consistent, phenomenological continuum damage model has been proposed [16–18] which has been implemented as user-defined material subroutines in commercial finite element programs allowing analyses of static and dynamic problems in differently loaded metal specimens. The continuum model is based on kinematic definition of tensorial damage variables and considers various damaged and corresponding undamaged configurations where respective yield and stress-state-dependent damage criteria as well as constitutive rate equations are formulated.

Furthermore, information on stress-state-dependent damage and failure mechanisms can be obtained by numerical simulations on the micro-level taking into account a large range of different loading conditions [19–26]. A distinct advantage of this microscopic approach is the detailed consideration of individual behavior of voids and micro-shear-cracks as well as their coalescence and accumulation to macro-cracks. With these numerical analyses taking into account a large range of stress states it was possible to detect different damage and fracture mechanisms which have not been exposed by experiments. In addition, the numerical results allowed proposal of equations for damage and fracture criteria as well as damage evolution laws showing remarkable dependence on stress triaxiality and – especially in regions with small or negative triaxialities – additional dependence on the Lode parameter or third deviatoric stress invariant [25,26]. However, the proposed stress-state-dependent criteria and evolution equations for damage and failure as well as the associated identification of material parameters are only based on numerical analyses on the micro-level whereas experimental validation is still required.

In general, constitutive parameters of continuum models have to be identified by experiments with carefully designed specimens. For example, elastic material properties, yield stress and coefficients characterizing plastic hardening are