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Damage and failure at negative stress triaxialities: Experiments, modeling and numerical simulations

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Abstract

The paper deals with an anisotropic continuum damage and failure model for ductile metals with focus on negative stress triaxialities. The continuum framework has been generalized to take into account the effect of stress state on damage criteria as well as on evolution equations of damage strains. Different branches of the criteria are considered corresponding to various micro-mechanisms like growth of voids, formation of micro-shear-cracks and their combination which depend on stress intensity, stress triaxiality and the Lode parameter. A series of shear-compression experiments with biaxially loaded specimens and corresponding numerical simulations have been performed to validate the proposed phenomenological approach. Digital image correlation technique has been used to analyze formation of strain fields in critical regions of the specimens for different loading conditions especially in the compression range. Microscopic failure mechanisms are revealed by scanning electron microscopy of fracture surfaces. Based on experimental data and corresponding numerical results the existence of the cut-off value of stress triaxiality is discussed below which fracture never occurs and a stress-state-dependent function of this parameter is proposed.

Keywords: Ductile damage and fracture, stress state dependence, cut-off value of stress triaxiality, experiments, digital image correlation, numerical simulations

1. Introduction

The use of high quality metals like high strength steels, advanced high strength steels and various improved aluminum alloys has been remarkably increased during the last decades. This leads to enhancement of material properties to avoid early localization of inelastic strains as well as damage and failure of structural components under complex loading conditions. For example, phenomenological modeling and numerical analyses for optimization of forming processes currently receive remarkable attention. Caused by increasing demands of customers products of modern metal forming processes have to fulfill economic, environmental and material strength requirements. There are claims to lightweight design leading to improved energy consumption or cost efficiency and, at the same time, to enforce the safety demands. Therefore, numerical simulation of various metal forming processes becomes an indispensable tool in modern engineering technologies. This requires development of elaborate experiments and of accurate, highly predictive and practically applicable constitutive theories as well as of efficient corresponding numerical methods. Their main object is to analyze and to understand large inelastic deformation behavior as well as damage and fracture mechanisms acting on different scales in materials and structures especially during metal forming processes.

It has been observed in many experiments and forming operations with ductile metals that during elongation or forming of material samples large, often localized inelastic deformations occur which may be accompanied by different damage and failure mechanisms on the micro- and macro-scales. Especially, at negative stress triaxialities these damage and failure mechanisms in ductile metals are of very special interest since many industrial processes like rolling and forging involve significant compressive hydrostatic stresses. Formation of damage and failure on the micro-level may then lead to macro-cracks and, thus, to final failure of structural elements. In this context, a large number of widely used elastic-plastic constitutive models including damage and failure prediction have been