International Journal of Plasticity 56 (2014) 19–44

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Effect of strain rate on ductile fracture initiation in advanced high strength steel sheets: Experiments and modeling

Christian C. Roth [a], Dirk Mohr [a,b,*]

[a] Solid Mechanics Laboratory (CNRS-UMR 7649), Department of Mechanics, École Polytechnique, Palaiseau, France
[b] Impact and Crashworthiness Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA

ARTICLE INFO

Article history:
Received 17 October 2013
Received in final revised form 20 December 2013
Available online 31 January 2014

Keywords:
A. Dynamic fracture
B. Viscoplastic material
B. Constitutive behaviour
C. Kolsky bar
Stress-state dependence

ABSTRACT

Low, intermediate and high strain rate tensile experiments are carried out on flat smooth, notched and central-hole tensile specimens extracted from advanced high strength steel sheets. A split Hopkinson pressure bar testing system is used in conjunction with a load inversion device to perform the high strain rate tension experiments. Selected surface strains, as well as local displacements, are measured using high speed photography in conjunction with planar digital image correlation (video extensometer). Through thickness necking precedes fracture in all experiments. A hybrid experimental–numerical approach is therefore employed to determine the strain to fracture inside the neck. To obtain an accurate description of the local strain fields at very large deformations, a plasticity model with a Johnson–Cook type of rate and temperature-dependency and a combined Swift–Voce strain hardening law is used in conjunction with a non-associated anisotropic flow rule. The incremental change in temperature is computed using a strain rate dependent weighting function instead of solving the thermal field equations. The comparison of the computed and measured force–displacement curves and surface strain histories shows good agreement before and after the onset of necking. From each experiment, the loading path to fracture is determined describing the evolution of the equivalent plastic strain in terms of the stress triaxiality, Lode angle parameter, strain rate and temperature. An empirical extension of the stress-state dependent Hosford–Coulomb fracture initiation model is proposed to account for the effect of strain rate on the onset of ductile fracture. The model is subsequently calibrated and successfully validated using the results from fracture experiments on DP590 and TRIP780 steels.

1. Introduction

Advanced high strength steels (AHSS) are widely used in automotive engineering. During stamping, as well as during accidental crash loading, fracture may initiate in AHSS after loading at strain rates as high as 1000/s. Localized necking usually precedes fracture and a significant amount of strain is accumulated inside the localized neck. The strains cannot be measured directly inside a localized neck and a hybrid experimental–numerical approach must be used which requires visco-plasticity models that are accurate at very large strains.

Existing visco-plasticity models can be classified into physics-based models and phenomenological/empirical models. The so-called physics-based models are usually inspired by the thermodynamics and kinetics of slip as summarized in the mono-

* Corresponding author at: Impact and Crashworthiness Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA. Tel.: +1 6172534338.

E-mail address: mohr@mit.edu (D. Mohr).

http://dx.doi.org/10.1016/j.ijplas.2014.01.003
0749-6419/

graph by Kocks et al. (1975). The constitutive equations may be formulated at the slip system level and then used to compute the effective material response using a polycrystal plasticity approach (e.g. Balasubramanian and Anand, 2002). Alternatively, physics-based models may be directly formulated at the macroscopic level by substituting the mechanical variables at the slip system level (e.g. resolved shear stress, shearing rates on slip systems) by their macroscopic counterparts (e.g. von Mises equivalent stress, equivalent plastic strain rate). The Zerilli–Armstrong model (1987) is based on a thermal activation analysis of dislocation motion which results in two different constitutive equations for the macroscopic flow stress of FCC and BCC materials, respectively. A comparison of the performance of the physics-based constitutive models by Bodner and Partom (1975), Zerilli and Armstrong (1987) and Khan and Huang (1992) is included in the review of rate- and temperature-dependent models by Liang and Khan (1999). Good agreement of the predictions of the Khan–Huang–Liang plasticity model with the results from static and dynamic tension experiments has been reported for AHSS (Khan et al., 2012a) and Ti–6Al–4V alloy (Khan et al., 2012b). The Rusinek–Klepaczko model (2001) assumes the additive decomposition of the flow stress into an internal and an effective stress, with an Arrhenius type of law providing the strain rate and temperature dependence of the latter component. Voyiadjis and Abed (2005) present an extended Zerilli–Armstrong model which can accurately describe the adiabatic high strain rate response of both FCC and BCC materials for large strains. A rate- and temperature-dependent plasticity model embedded into a continuum damage mechanics framework (Brünig, 2006) has been applied by Brünig and Gerke (2011). A unified viscoplastic model accounting for the rate-dependent ductile-to-brittle transition during microcracking in polycrystalline materials has been proposed by Shojaei et al. (2013). The effect of strain rate on the plastic anisotropy of advanced high strength steel has been investigated by Huh et al. (2011). Their experiments for strain rates of up to 100/s on TRIP590 and DP780 steels indicated a decrease in plastic anisotropy with increasing strain rate.

Unlike the above models, the widely used Johnson–Cook model (1983) has no physical basis and is purely empirical. It postulates the multiplicative decomposition of the flow stress into three functions that depend on the strain, the strain rate and the temperature, respectively. Many studies in impact engineering demonstrate that the simple J–C plasticity model provides reasonable predictions of the temperature-dependent viscoplastic response of metals up to very high strains (e.g. Johnson and Cook, 1983; Johnson and Holmquist, 1988; Clausen et al., 2004; Smerd et al., 2005; Verleysen et al., 2011; Erice et al., 2012; Kajberg and Sundin, 2013). However, it shows serious limitations when an accurate description of the hardening at large strains is required. An important example is the prediction of the necking and post-necking response of sheet metal. Under static and isothermal loading conditions, the J–C model reduces to a power-law which is known to overestimate the strain hardening capacity of automotive steels (e.g. Dunand and Mohr, 2010). This shortcoming has been addressed by Sung et al. (2010) through a constitutive model that makes use of a temperature-dependent combination of power and saturation hardening.

The effect of stress state on the ductile fracture of advanced high strength steels has been studied extensively at low strain rates (e.g. Sun et al., 2009; Mohr et al., 2010; Luo and Wierzbicki, 2010; Kim et al., 2011; Gruben et al., 2011; Chung et al., 2011; Lou et al., 2014; Lian et al., 2013). The reader is referred to Lecarme et al. (2011), Malcher et al. (2012) and Lou et al. (2014) for reviews of the current literature on ductile fracture of non-AHSS materials. Using a high speed hydraulic testing machine, Huh et al. (2008) performed uniaxial tensile tests of four different advanced high strength steels (TRIP600, TRIP800, DP600 and DP800) for pre-necking strain rates ranging from 0.003/s to 200/s. They report an increase of the fracture elongation (engineering strain over a length of 30 mm) for the TRIP600 steel, and an approximately rate-insensitive elongation for the other three materials. Curtze et al. (2009) performed static and intermediate strain rate tensile experiments on a servohydraulic testing machine and high strain rate experiments using a tensile Hopkinson bar system. In their experiments at room temperature, the elongation at fracture (over a length of 6 mm) for a DP600 steel and a TRIP700 steel were approximately the same irrespective of the strain rate. It is worth noting that necking preceded fracture in all of the above high strain rate tensile experiments, but the strain to fracture inside the localized neck has not been determined.

Estimates of the local strain at the onset of fracture in high strain rate experiments are available for bulk materials. The results from dynamic experiments on axisymmetric notched tensile specimens have been the basis for the formulation of the empirical Johnson–Cook failure model (Johnson and Cook, 1985). Unlike for flat specimens, the local strains at fracture in round specimens may be conveniently estimated from cross-section measurements in combination with FEA-based or analytical correction formulas (e.g. Bridgman, 1952). Johnson and Cook (1985) reported an increase in ductility as a function of the strain rate for OFHC copper, ARMCO iron and 4340 steel. A positive strain rate sensitivity of the strain to fracture has also been determined from static and dynamic notched tension experiments on aluminum 5083-H116 (Clausen et al., 2004) and martensitic stainless steel FV535 (Erice et al., 2012). Khan and Liu (2012a,b) incorporated the effect of strain rate and temperature into their stress-based ductile criterion. Their model captures the significant increase in ductility observed during high strain rate torsion experiments on aluminum 2024-T351.

In the present work, low, intermediate and high strain rate experiments are performed on flat specimens with a central hole and different notches. The strain to fracture is determined inside the neck using detailed finite element analysis in conjunction with digital image correlation. To obtain a highly accurate description of the post-necking response of specimens extracted from DP590 and TRIP780 steel sheets, the Johnson–Cook plasticity model is coupled with a combined Voce–Swift strain hardening function and a non-associated anisotropic flow rule. The loading paths up to the onset of fracture are identified from all experiments, including the evolution of stress triaxiality, Lode angle parameter, temperature, strain rate and equivalent plastic strain. Subsequently, an empirical extension of the Hosford–Coulomb fracture initiation model is proposed and validated to account for the effect of strain rate on ductile fracture.