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Ductile fracture experiments with locally proportional loading histories

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

[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
[c] ETH Zurich, Department of Mechanical and Process Engineering, Zurich, Switzerland

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Basic ductile fracture experiments for sheet metal (or flat coupons extracted from bulk material) are presented to characterize the onset of fracture at different stress states. Special emphasis is placed on designing the experiments such that the stress triaxiality and the Lode angle parameter remain constant while the specimen is loaded all the way to fracture. A new in-plane specimen with two parallel gage sections is proposed to determine the strain to fracture for approximately zero stress triaxiality. A FEA based methodology is shown to identify the optimal specimen geometry as a function of the material's ductility and strain hardening. A tension specimen with a central hole is investigated in detail with regard to determining the strain to fracture for uniaxial tension. It is found that the required hole-to-ligament width ratio decreases as a function of the material ductility and increases as a function of the strain hardening exponent. The bending of a wide strip is pursued to prevent the necking prior to fracture under plane strain tension conditions, while an Erichsen-type of punch test is used to characterize the material response for equi-biaxial tension. It is worth noting that the strain to fracture can be directly determined from surface strain measurements in the cases of shear, plane strain tension and equi-biaxial tension loading, thereby removing the need to perform finite element simulations for extracting the loading path to fracture.

1. Introduction

There is a constant quest for reliable experimental data characterizing the effect of stress state on ductile fracture. Different stress states may be achieved through different initial specimen geometries or by applying different combinations of loading to the specimen boundaries. Examples for the first approach are the works of Bao and Wierzbicki (2004), Brünig et al. (2008), Gao et al. (2010) or Driemeier et al. (2010). Example for the second approach are the tension-torsion experiments of Barsoum and Faleskog (2007a), Faleskog and Barsoum (2013), Haltom et al. (2013) and Papasidero et al. (2015), the internal pressure-tension testing of tubes (Kuwabara et al., 2005; Korkolis and Kyriakides, 2009), the tension-shear loading of butterfly specimens (Wierzbicki et al., 2005; Mohr and Henn, 2007; Mae et al., 2007; Dunand and Mohr, 2011, Abedini et al., 2015) and the biaxial loading of cruciform-like specimens (e.g. Abu-Farha et al., 2009; Brenner et al., 2014).

* Corresponding author. ETH Zurich, Department of Mechanical and Process Engineering, Zurich, Switzerland.
E-mail address: dmohr@ethz.ch (D. Mohr).

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The main result of ductile fracture experiments on isotropic materials is the so-called loading path to fracture, i.e. the evolution of the equivalent plastic strain as a function of the stress triaxiality and the Lode parameter. The mechanical fields within the specimen gage section are heterogeneous (at the macroscopic level) in most experiments and the local stress state cannot be calculated based on force measurements using analytical formulas. A hybrid experimental-numerical approach is therefore often required (e.g. Mohr and Henn, 2007; Bai and Wierzbicki, 2008; Dunand and Mohr, 2010; Gruben et al., 2011; Brünig and Gerke, 2011; Lou et al., 2012, 2014; Fourmeau et al., 2013; Malcher et al., 2012). This introduces additional uncertainty in the determined loading paths to fracture related to the employed finite strain plasticity model. A noteworthy predicament of ductile fracture experiments is that their outcome is often no longer a direct experimental observation, but a combined numerical-experimental result.

In micromechanical studies, ductile fracture has been thoroughly investigated for monotonic proportional loading, i.e. for loading histories during which the stress state remains constant up to the point of fracture initiation (e.g. Tvergaard, 1981; Koplik and Needleman, 1988; Barsoum and Faleskog, 2007b, 2011; Scheyvaerts et al., 2011; Danas and Ponte Castaneda, 2012; Tekoglu et al., 2012; Dunand and Mohr, 2014; Brünig et al., 2014). Moreover, knowledge of the strain to fracture as a function of the stress state for proportional loading is also a main ingredient of fracture initiation models that fall into the category of damage indicator models (e.g. Wilkins et al., 1980; Bai and Wierzbicki, 2010; Lou et al., 2014; Mohr and Marcadet, 2015). Another important predicament of ductile fracture experiments is that proportional loading conditions at a material point are extremely difficult to achieve. In most ductile fracture experiments, the local stress state actually evolves throughout loading even if the ratios of the forces acting on the specimen boundaries are kept constant. This stress state evolution is due to changes in the specimen geometry that are almost inevitable in experiments involving large deformations. For example, Ebnoether and Mohr (2013) have shown that in a conventional flat uniaxial tension specimen, the stress triaxiality can increase after the onset of necking from 0.33 to values as high as 0.8 at the instant of fracture initiation.

The above experimental predicaments partially prohibit the progress in the field since the direct validation of fracture models for proportional loading through experimental results becomes almost impossible. Early works represented the results from fracture experiments in terms of either the average stress triaxiality (e.g. Bao and Wierzbicki, 2004) or the stress state at the instant of fracture initiation (Barsoum and Faleskog, 2007a). However, more recent considerations for non-proportional loading (Benzerga et al., 2012; Marcadet and Mohr, 2015; Papasidero et al., 2015) raise doubt about the meaningfulness of the representation of experimental data in terms of average or final stress triaxialities.

In this work, an attempt is made to present fracture experiments that feature (i) a constant stress state up to the onset of fracture, and (ii) that allow for the direct determination of the strain to fracture from experimental measurements without any numerical simulations. In addition, we focus on stress states that are particularly useful for identifying the plane stress fracture envelope for proportional loading: (1) pure shear, (2) uniaxial tension, (3) plane strain tension, and (4) equi-biaxial tension. New specimen geometries are identified for the first two stress states through constrained shape optimization, while V-bending and punch experiments are considered for the latter two stress states. To facilitate the fracture characterization in an industrial environment, all experiments are designed such that they can be performed in a universal testing machine.

It is emphasized that we take a 3D continuum mechanical point of view on failure. We are interested in determining the intrinsic failure response at a material point which is assumed to depend on the history of the local mechanical field variables only. For mechanical reasons, all specimens are flat and are thus extracted from steel sheets. However, we are not concerned with sheet metal mechanics where it is common practice to distinguish between in-plane and bending properties. To avoid any confusion, it might be worth thinking of all proposed fracture specimens as thin specimens that have been extracted from a bulk material.

2. Plasticity model

Numerical simulations play a central role in developing, analyzing and validating ductile fracture experiments. We therefore begin our presentation with a brief summary of the plasticity and fracture initiation models that are employed in the sequel. We calibrated both models based on experiments on specimens extracted from a 1 *mm* thick dual phase steel DP780 provided by US Steel. The material serves as model material in the present work; it is composed of a ferrite matrix with martensite inclusions and features an average grain size of about 8 μm.

2.1. Plasticity model formulation

A rate-independent non-associated quadratic plasticity model (Mohr et al., 2010) is used to model the material response. This particular model had been proposed based on the results from combined tension-shear experiments on DP590 and TRIP780 steels. It also provided a remarkably accurate description of multi-axial experiments on DP780 steel specimens (Mohr and Marcadet, 2015). Its isotropic yield function is written in terms of the von Mises equivalent stress, $\bar{\sigma}$, and a deformation resistance k,

$$f[\boldsymbol{\sigma}, k] = \bar{\sigma} - k = 0. \tag{1}$$