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Failure by fracture in bulk metal forming

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ABSTRACT

This paper revisits formability in bulk metal forming in the light of fundamental concepts of plasticity, ductile damage and crack opening modes. It proposes a new test to appraise the accuracy, reliability and validity of fracture loci associated with crack opening by tension and out-of-plane shear under loading conditions different from those found in conventional tests for bulk formability based on cylindrical, tapered and flanged specimens.

The new formability test consists of expanding rings of various wall thicknesses with a stepped conical punch and allows investigating the onset of failure by cracking under three-dimensional states of stress subjected to various magnitudes of stress triaxiality.

The presentation is supported by finite element analysis and experimentation in aluminium AA2030-T4 and results show that failure by fracture under three-dimensional loading conditions can be easily and effectively characterized in the space of equivalent strain to fracture and stress triaxiality.

1. Introduction

Failure by surface or internal cracking in bulk metal forming is caused by the accumulation of ductile damage within regions that are highly strained due to extensive plastic flow. Apart from special purpose processes such as the shearing of bars and bar sections, where cracks are needed to cut material, the occurrence of cracks is generally undesirable and should be prevented during process design.

Currently-available finite element computer programs may aid this objective but appropriate input data regarding a relevant fracture locus is crucial for successfully predicting the onset of cracking in bulk metal forming. The conditions at fracture depend on the interaction between plasticity theory, the circumstances under which each crack opening mode will develop and microstructural ductile damage mechanics.

In a recent paper Martins et al. (2014) developed an analytical framework to characterize failure by fracture in metal forming under plane stress conditions and concluded that surface cracking in bulk forming can occur under two different opening modes (i) tensile and (ii) out-of-plane shear, respectively the same as modes I and III of fracture mechanics. The framework allowed concluding that the normalized version of the Cockcroft and Latham (1986) ductile damage criterion is based on a 'hidden' out-of-plane shear-based condition that explains its wide applicability to predict the onset of cracking in opening mode III. The framework also confirmed the link between stress–triaxiality-based damage criteria (McClintock, 1968) and fracture toughness in crack opening mode I, which had been previously established by Muscat-Fenech et al. (1996).

Martins et al. (2014) associated crack opening modes I and III to linear fracture loci with slopes '−1' and '−1/2' observed in the pioneering bulk formability tests that were carried out from the late 1960s to the early 1980s. The investigations by Kudo and Aoi (1967) and Kuhn et al. (1973), for example, showed that the limiting fracture strain pairs on the outside surfaces of upset test specimens fall on a straight line of slope '−1/2' in the principal strain space (that is, a line parallel to uniaxial compression loading under frictionless (homogenous) conditions – refer to 'A' in Fig. 1).

Martins et al. (2014) claimed this fracture locus is associated with crack opening by out-of-plane shear (mode III) (Fig. 1a) in close agreement with the observations by Kobayashi (1970) and Atkins and Mai (1985) who concluded that both the vertical and the inclined surface cracks that are commonly found in upset compression tests do not run radially. Vertical cracks occur in specimens with low friction and larger aspect ratios whereas inclined surface cracks are generally found in specimens with high friction and low aspect ratios.

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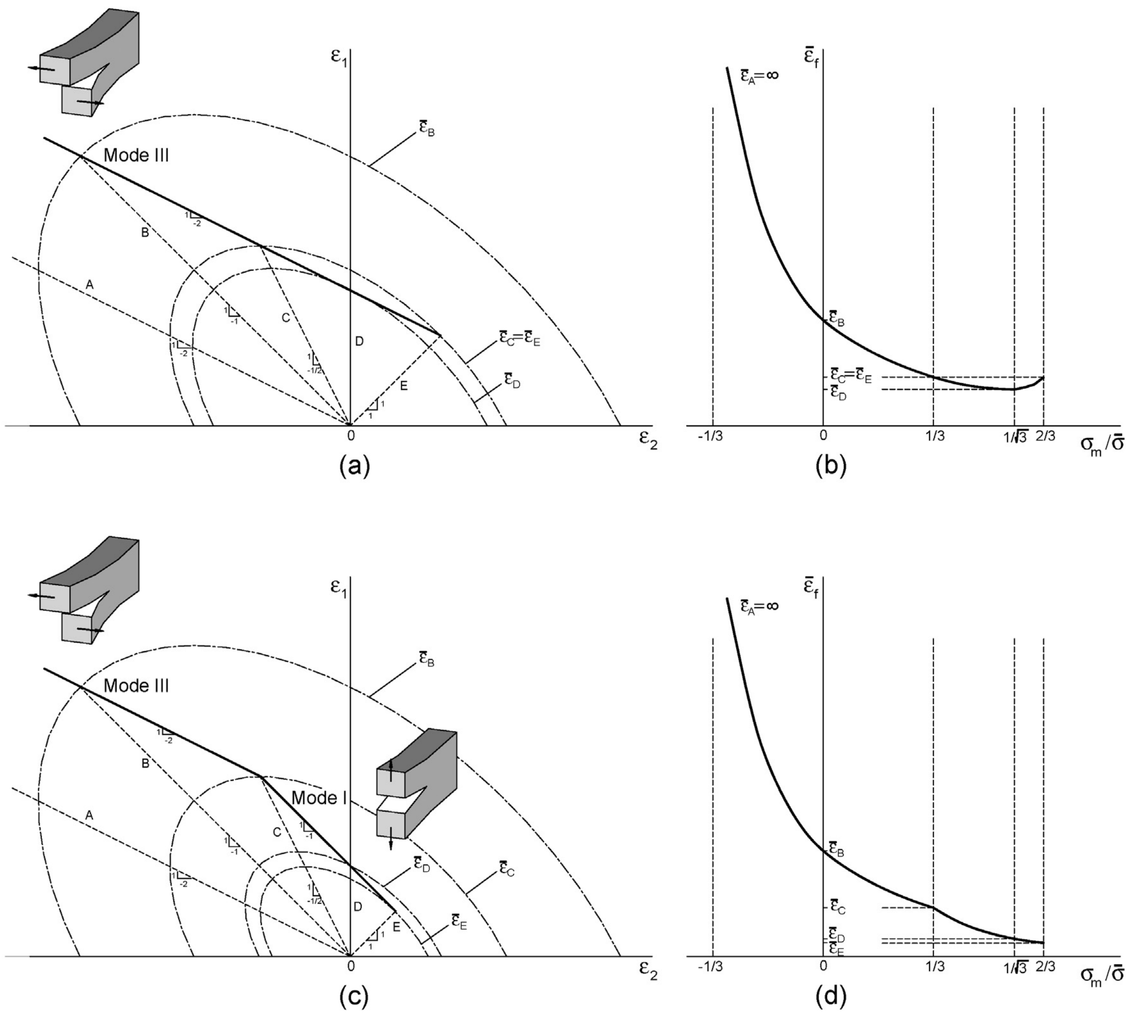

Fig. 1. Schematic representation of fracture loci in bulk metal forming in the (a and c) principal strain space and in the (b and d) space of equivalent strain to fracture and stress triaxiality. (a and b) Linear fracture locus associated to crack opening by out-of-plane shear (mode III); (c and d) bilinear fracture locus resulting from combination of crack opening by out-of-plane shear (mode III) and by tension (mode I).

Subsequent investigations by Erman et al. (1983) disclosed the possibility of the limiting fracture strain pairs on the outside surfaces of bulk formability test specimens to fall on a bilinear locus resulting from combination of the previously mentioned straight line of slope '$-1/2$' (mode III) with a straight line of slope '-1′, parallel to pure shear loading conditions (Fig. 1c). Martins et al. (2014) claimed the fracture locus corresponding to a straight line of slope '-1' parallel to pure shear loading conditions (refer to 'B') to result from crack opening by tension (mode I). In connection to Fig. 1a and c it is worth noting that 'C', 'D' and 'E' refer to loading paths corresponding to pure tension, plane strain and equal biaxial stretching and that ellipses refer to isolines of constant effective strain $\bar{\varepsilon}$.

The transformation of fracture loci in bulk metal forming from principal strain space (Fig. 1a and c) to the space of equivalent strain to fracture ε_f and stress triaxiality $\sigma_m/\bar{\sigma}$ is schematically shown in Fig. 1b and d.

The space of equivalent strain to fracture and stress triaxiality was originally proposed by Vujovic and Shabaik (1986) as a 'forming limit criterion for bulk metalworking processes, based on the magnitude of the hydrostatic component and the effective stress of the stress state (the first invariant of the stress tensor and the second invariant of the deviatoric stress tensor)'. However, its widespread acceptance only came after Bao and Wierzbicki (2004) utilization for investigating the capability of several well-known ductile fracture criteria to predict failure by fracture in metal forming. The utilization of the space of equivalent strain to fracture and stress triaxiality was further developed by Wierzbicki and co-workers in several other publications that were focused on the development of ductile fracture criteria for metal forming (for example, Li et al., 2010).

In a subsequent publication Bai and Wierzbicki (2010) proposed the utilization of an enhanced version of this space where the axes are the equivalent strain to fracture, the stress triaxiality and the normalized Lode angle parameter.

A review of the literature on the experimental determination of fracture loci and on the development of non-coupled ductile damage criteria for predicting the onset of cracking in metal forming reveals (i) that most of the investigations treat sheet and bulk forming separately and (ii) that free surface normal strains causing cracking are exclusively characterized by means of plane stress loading conditions.

The first conclusion may be attributed to fundamental differences in plastic flow that result from two and three dimensional stress loading conditions that are typical of sheet and bulk metal forming and to its influence on the circumstances under which different processes fail by fracture. The need to treat sheet and bulk metal forming separately also copes with the overall aims and scope of a recent keynote paper by Bruschi et al. (2014) that is exclusively focused on formability in sheet metal forming.