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Modeling of shear ductile fracture considering a changeable cut-off value for stress triaxiality

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ABSTRACT

A macroscopic ductile fracture criterion is proposed based on micro-mechanism analysis of nucleation, growth and shear coalescence of voids from experimental observation of fracture surfaces. The proposed ductile fracture model endows a changeable cut-off value for the stress triaxiality to represent effect of micro-structures, the Lode parameter, temperature, and strain rate on ductility of metals. The proposed model is used to construct fracture loci of AA 2024-T351. The constructed fracture loci are compared with experimental data covering wide stress triaxiality ranging between −0.5 and 1.0. The fracture loci are constructed in full stress spaces and plane stress conditions to analyze characteristics of the proposed fracture loci. Errors of the equivalent stress to fracture are calculated and compared with those predicted by the MSV model (Khan and Liu, 2012a) and series of the modified Mohr–Coulomb criteria. The comparison suggests that the proposed model can provide a satisfactory prediction of ductile fracture for metals from compressive upsetting tests to plane strain tension with slanted fracture surfaces. Moreover, it is expected that the proposed model reasonably describes ductile fracture behavior in high velocity perforation simulation since a reasonable cut-off value for the stress triaxiality is coupled with the proposed ductile fracture criterion.

1. Introduction

Failure prediction is one of the most important issues in analysis and design of metal forming processes. In sheet metal forming, necking has been viewed as a major failure mechanism since it is the dominant reason for the loss of load capability during forming. Several effective models were proposed for the accurate prediction of necking, such as the Hill's localized necking model (Hill, 1952), the Swift's diffuse necking model (Swift, 1952), the imperfection-based Marciniak–Kuczynski model (Marciniak and Kuczynski, 1967), the vertex theory (Stören and Rice, 1975; Zhu et al., 2001) and the modified maximum force criterion (Hora et al., 1996). Recently, advanced high strength steels, aluminum alloys and magnesium alloys were extensively employed in automobile industry to satisfy the increasing requirement for high fuel efficiency and improved safety. These advanced metals, however, fail as ductile fracture with little necking compared with conventional steels of SPCC and SPRC in Fig. 1. In addition, ductile fracture is also observed in shear and compression at low or negative stress triaxiality in bulk metal forming (Bao and Wierzbicki, 2004; Børvik et al., 2010; Khan and Liu, 2012a, 2012b). Thus, ductile fracture criteria instead of various necking models are more suitable to predict failure of these advanced metals in wide loading conditions from tension, shear to compression.

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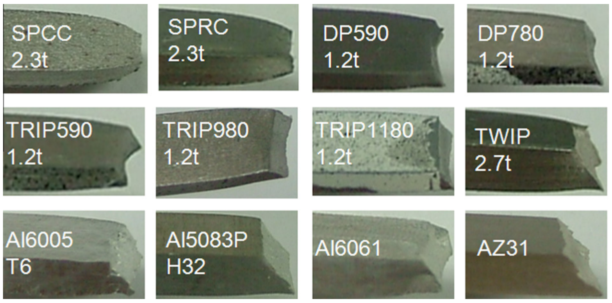

Fig. 1. Two failure mechanisms: necking for SPCC and SPRC and ductile fracture for other metal sheets.

From the microscopic point of view, ductile fracture of metals is the integral processes of nucleation, growth and coalescence of micro-cavities or voids. Ductile fracture of these microscopic mechanisms was modeled by dozens of fracture criteria. These ductile fracture criteria can be classified into two branches: coupled fracture criteria and uncoupled fracture criteria. Coupled fracture criteria assume that strength of metals is affected by accumulated damage induced by nucleation, growth and coalescence of voids while damage predicted by uncoupled fracture criteria has no effect on the load capability of metals before final fracture.

One of the most popular coupled ductile fracture criteria is the Gurson–Tvergaard–Needleman (GTN) ductile fracture criterion which considers all damage sources of nucleation, growth and coalescence of voids (Gurson, 1977; Tvergaard, 1982; Tvergaard and Needleman, 1984). The accumulated damage is represented by void volume fraction. The void volume fraction is coupled by the constitutive equation to induce softening effect. Recently, Xue (2008) and Nahshon and Hutchinson (2008) as well as Nielsen and Tvergaard (2010) modified the GTN model to describe fracture behavior at zero or low stress triaxiality in shear. Xue et al. (2013) applied an extended GTN model to simulate the tension–torsion tests of two steels, Weldox 420 and 960, to investigate the Lode dependence of ductile fracture. Another popular coupled ductile fracture criterion is the continuum damage mechanics (CDM) initially introduced by Kachanov (1958) and further improved by Lemaitre (1985, 1996), Chaboche (1981, 1988a, 1988b), Saanouni and Chaboche (2003), Brünig (2003a, 2003b, 2006), and others. CDM considers the mechanics of material damage and its mechanical effects within the framework of continuum mechanics. CDM introduces a continuous damage variable by establishing an additional damage evolution equation for representing the local distribution of micro-defects. Brünig and Gerke (2011) implemented a generalized and extended version of Brünig's damage model to simulate damage evolution in ductile metals under dynamic loading.

Meanwhile, uncoupled ductile fracture criteria were developed based on microscopic mechanisms, various hypotheses or experimental observations of ductile fracture. McClintock (1968) analytically investigated the growth of a cylindrical void while Rice and Tracey (1969) analyzed void growth using a single spherical void in an infinite solid under remote loading. Both their results stated that void growth was mainly controlled by the stress triaxiality. LeRoy et al. (1981) considered nucleation, shape change and coalescence of voids in the Rice–Tracey model. Besides, many phenomenological ductile fracture criteria (Freudenthal, 1950; Cockcroft and Latham, 1968; Brozzo et al., 1972; Oh et al., 1979; Oyane et al., 1980; Clift et al., 1990; Ko et al., 2007) were developed and widely employed to solve engineering problems (ex. compressive upsetting tests, axisymmetric extrusion, strip compression and tension, drawing and hub-hole expanding) due to their simplicity and few fracture parameters to be evaluated experimentally.

Although extensively utilized in industrial application, ductile fracture criteria reviewed above cannot fully describe ductile fracture behavior in wide loading conditions partially due to few numbers of fracture parameters in these criteria. Also it is because experimental results were not available to schematically illustrate the shape of a fracture locus at their proposals until Bao and Wierzbicki (2004) carried out fifteen tests of AA 2024-T351 with stress triaxiality ranging from -0.3 to 1.0. These tests provided a schematic clue to the effect of the stress triaxiality on the equivalent plastic strain to fracture. Soon after the report of these experimental results, several phenomenological fracture models were proposed including Bao and Wierzbicki (2004) and Bai and Wierzbicki (2008). Brünig et al. (2008, 2011a, 2011b) classified damage mechanisms as microshear crack at negative stress triaxiality, void-growth-dominated modes at large positive stress triaxiality, and mixed modes for low positive stress triaxiality and proposed ductile fracture models for different damage mechanisms. Xue (2007) and Xue and Wierzbicki (2008) observed that the equivalent plastic strain to fracture in pure shear was less than that in uniaxial tension for AA 2024-T351 (Bao and Wierzbicki, 2004) and 4340 steel (Halford and Morrow, 1962). This observation is conflicted with the prediction by ductile fracture criteria solely considering the effect of the stress triaxiality such as the Rice–Tracey model. They attributed this confliction to the omission of the Lode dependence in modeling of ductile fracture and proposed two Lode dependent fracture functions in a heuristic way without exploring the underlying physical mechanisms of Lode dependent ductile fracture behavior (Li et al., 2011). The Lode dependence of ductile fracture were also confirmed by combined torsion-tension experiments (Barsoum and Faleskog, 2007a, 2007b, 2011; Haltom et al., 2013; Xue et al., 2013; Faleskog and Barsoum, 2013). Bai and Wierzbicki (2010) modified the Mohr–Coulomb (MMC) criterion and successfully applied the MMC criterion to describe ductile fracture behavior