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Prediction of ductile fracture for advanced high strength steel with a new criterion: Experiments and simulation

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ABSTRACT

This paper is concerned with prediction of the onset of ductile fracture by a newly proposed micro-mechanism-motivated macroscopic ductile fracture criterion in various stress states from shear to plane strain tension where most ductile fracture takes place in sheet metal forming processes. The new ductile fracture criterion (Lou et al., 2012) is calibrated by the equivalent plastic strain to fracture measured by the hybrid experimental–numerical method from four types of specimens manufactured from DP980 sheet whose fracture locus is eventually constructed. The calibrated criterion is utilized to construct the fracture locus of DP980. The constructed fracture locus is then implemented into the ABAQUS/Explicit code to predict the onset of ductile fracture for these three types of specimens. Three types of notched specimens are further designed for the validation of the ductile fracture criterion from uniaxial tension to plane strain tension by comparison of experimental results to those numerically predicted by the ductile fracture criterion. Three types of shear specimens are then utilized to validate predictability of the ductile fracture criterion between shear and uniaxial tension. The validation demonstrates that the ductile fracture criterion can accurately predict the onset of ductile fracture for these specimens. The comparison result with high accuracy reveals that the criterion can correctly describe ductile fracture behaviors of metals in various stress states from shear to the plane strain tension.

1. Introduction

Advanced high strength steels, aluminum alloys and magnesium alloys are extensively employed in automobile industries to satisfy the increasing requirement of both crashworthiness and fuel efficiency. Different from conventional low strength steels, these metals fail as ductile shear fracture before severe necking in sheet metal forming processes as illustrated in Fig. 1 for fractured dog-bone specimens of various metals with different strength. While a large amount of thickness reduction is observed for two conventional steel sheets of SPCC and SPRC, the thickness reduction before ductile fracture is negligible for other materials such as dual phase steel sheets, aluminum alloys and AZ31 magnesium alloy. Provided that slight necking takes place before ductile fracture, various analytical models based on necking (e.g. the localized necking model proposed by Hill, 1952; the diffuse necking model developed by Swift, 1952; a theoretical model with initially geometrical inhomogeneity proposed by Marciniak and Kuczynski, 1967; the vertex theory proposed by Stören and Rice, 1975 and Zhu et al., 2001; the modified maximum force criterion introduced by Hora et al., 1996) are no longer suitable for the failure prediction of these advanced metals.

Instead of common necking failure models, various ductile fracture criteria have gained increasing attentions to assess the onset of failure in metal forming processes. From microscopic viewpoints, ductile fracture is the integral manifestation of nucleation, growth and coalescence of voids. These three procedures have been extensively studied experimentally, analytically and numerically. Argon et al. (1975) and Goods and Brown (1979) argued that void nucleation takes place when the interfacial stress reaches a critical value and proposed two separate functions to calculate the critical interfacial stress. On the other hand, Gurland (1972) observed that the number of cracked particles increases with strain for a spheroidized 1.05% carbon steel. As to the growth of voids, Rice and Tracey (1969) formulated the enlargement of a single spherical void in an infinite solid subjected to remote normal stresses. McClintock (1968) also described the void growth using a cylindrical void analytically. Weck and Wilkinson (2008) reported two coalescence mechanisms based on experimental observation of model materials: the necking of ligaments between voids caused by the highest principal stress; shear-linking up of voids along the direction of the maximum shear stress. Ghosh (1976) emphasized that the necking of ligaments was not found in sheets and developed a simple probabilistic approach

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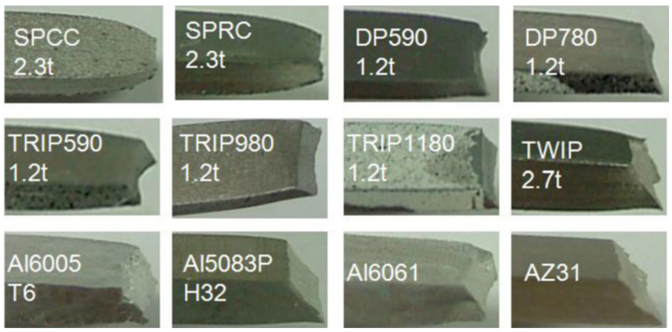

Fig. 1. Two failure mechanisms: necking for SPCC and SPRC and ductile fracture for other metal sheets.

for ductile fracture in sheets under biaxial loading based on the process of shear linking-up of voids.

Considering damage accumulation induced by nucleation, growth and coalescence of voids, Gurson (1977) and Tvergaard and Needleman (1984) developed a damage model, which is referred as the GTN model, to describe both plasticity and ductile fracture of porous materials. The GTN model is classified as a coupled ductile fracture criterion since the GTN model took account of the effect of damage on the plastic flow. After the proposal of the GTN model, numerous modifications were carried out based on various hypotheses since the glamorous physical mechanisms were considered in the GTN model. One of the remarkable modifications was proposed by Xue (2008) to incorporate void shear effect in the GTN model by introducing dependency of the damage evolution on the third stress invariant. Nahshon and Hutchinson (2008) proposed an extension of the Gurson model to incorporate damage growth under low triaxiality straining for shear-dominated states by making use of the third stress invariant to distinguish shear dominated states. The extended Gurson model can predict ductile fracture in shear-dominated states such as projectile penetration. Nielsen and Tvergaard (2010) modified the Nahshon-Hutchinson model to activate the damage accumulation under shear only in the low stress triaxiality. The Gurson model and three recent shear modifications cannot work well at negative stress triaxiality such as uniaxial compression or plane strain compression since the void volume fraction does not increase due to the fact that void growth was suppressed in negative stress triaxiality. To predict ductile fracture by GTN family models in negative stress triaxiality, one possible approach is to record the shape change of voids and take the interaction of the void free area fraction along the maximum shear stress direction and the magnitude of the maximum shear stress as the flag for the onset of shear coalescence of voids to form a fracture surface. Although the GTN model and its modified forms takes account of all procedures of ductile fracture, Khan and Liu (2012) suggested that more than 10 material constants in GTN family forms are very difficult to calibrate due to the strong coupling among them. Moreover, some material constants have to be determined by stochastic methods. These limitations restrict extensive application of GTN family models to practical analysis of metal forming processes. Another famous coupled ductile fracture model is based on the continuum damage mechanics (CDM) (Lemaitre, 1985) which considers the mechanics of material damage and its mechanical effects within the framework of continuum mechanics. The CDM-based ductile fracture model introduces a continuous damage variable by establishing an additional damage evolution equation to represent the local distribution of microdefect. Saanouni (2006) fully coupled the CDM damage theory with anisotropic and anisothermal constitutive equations accounting for both combined isotropic and kinematic hardening and successfully applied the coupled CDM model to predict ductile fracture in various 2D and 3D applications, such as a three-stage forming of an axisymmetric wheel, the chevron-shaped cracks in a cold forward extrusion, the orthogonal cutting by chip formation including chip segmentation for an aluminum alloy and the 3D slitting of an anisotropic 1 mm thin sheet at room temperature.

Compared to the complicated coupled GTN family ductile fracture criteria and CDM-based models, simple uncoupled models are preferred for industrial applications because of their simplicity and less material constants to be calibrated using experimental data points. These simple models were developed based on experimental observations, analytical studies, numerical results or combination of them. Freudenthal (1950) postulated that the initiation and propagation of a crack was dominated by a critical value of the total plastic work per unit volume. Forty years later, Clift et al. (1990) experimentally proved that the Freudenthal fracture criterion predicted the fracture initiation site in all operations of simple upsetting tests, axisymmetric extrusion and strip compression and tension. Cockcroft and Latham (1968) proposed a model weighted by the maximum principal stress based on the observation that ductile fracture tends to take place in the region of the maximum tensile stress. Rice and Tracey (1969) approximated the growth of a single spherical void by an exponential function of the stress triaxiality. This approximation simplified the analytical results and made the Rice–Tracey model preferable to the complicated GTN family models for engineers. Brozzo et al. (1972) coupled the effect of the mean stress on ductile fracture into the Cockcroft–Latham criterion. Oh et al. (1979) normalized the largest principal stress in the Cockcroft–Latham criterion to provide accurate predictability in extrusion of Al 2024-T351 and in drawing of SAE 1144 cold-drawn steel. Oyane et al. (1980) derived a criterion for ductile fracture from the plastic theory for porous materials. Ko et al. (2007) combined the effect of both the maximum principal stress in the Cockcroft–Latham criterion and the stress triaxiality in the Oyane–Sato criterion to predict the hub-hole expanding ratio of SAPH440, CT440 and FB590. These uncoupled criteria, however, cannot predict the plastic fracture strain in a various stress state because there were no experimental results providing the shape of the fracture locus in different deformation conditions at the time of their proposal. Moreover, few material constants limit the flexibility of these ductile fracture criteria.

Bao and Wierzbicki (2004) carried out 15 type tests of Al 2024-T351 including uniaxial tension of notched specimens, dog-bone specimens, specimens with a central hole, shear specimens, tensile tube, cylindrical bars for compressive upsetting tests. These tests covered various stress states with the stress triaxiality ranging from −0.3 to 1.0, which first provided a clear shape of the fracture locus. Based on these experimental results, Bao and Wierzbicki (2004) proposed a pure empirical ductile fracture model with the dependence of the stress triaxiality to approximate the experimental data points with high accuracy. This empirical model, however, generated positive dependence of plastic fracture strain on the stress triaxiality, which conflicted with the generally accepted fact that high stress triaxiality accelerated void growth thereby reducing plastic fracture strain of metals. Xue (2007) noted that the plastic fracture strain in shear was smaller than that in the uniaxial tension for Al 2024-T351, which cannot be explained by ductile fracture criteria with negative sensitivity on the stress triaxiality such as the Rice–Tracey model. Ductile fracture criteria with negative sensitivity to the stress triaxiality predicted a higher plastic fracture strain in shear than that in the uniaxial tension due to lack of positive stress triaxiality for void growth in shear. They attributed the small plastic fracture strain in shear to the neglected effect of the Lode parameter in the modeling of ductile fracture. Two phenomenological functions were proposed to incorporate the effect of the Lode angle parameter on ductile fracture in their damage model using a heuristic way since there were no conclusive experimental results