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Forming limit criterion for ductile anisotropic sheets as a material property and its deformation path insensitivity. Part I: Deformation path insensitive formula based on theoretical models

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ABSTRACT

In the common industrial thin sheet metal forming process at room temperature, in which in-homogenous deformation under the plane stress condition is typically the case, sheets are so ductile that sheet forming more often fails after abruptly severe strain localization, especially in the thinning mode. In such a case, measuring the fracture property might be impractical and an alternative criterion to measure sheet proneness to abruptly severe strain localization according to deformation modes, often dubbed as the forming limit criterion, replaces the fracture criterion to account for formability of the sheet, assuming that the criterion is applicable as a material property. However, severe strain localization is a mathematical consequence (of the boundary value problem) of the principle of linear momentum and the constitutive law; therefore not a part of material properties in principle, regardless of its sensitivity to deformation path. Nonetheless, the assumed applicability of the forming limit criterion as a material property in approximation for room temperature forming under the plane stress condition was partially validated in Part II in view of regular and modified hemispherical dome stretching and circular cup drawing tests, while its deformation path insensitive formulae were theoretically justified in Part I by examining the isotropic hardening formulation of rigid-plasticity and also theoretical forming limit models including the Considère (1885), Dorn and Thomsen (1947) and Hill (1952) models as well as the M–K (1967) model.

1. Introduction

Sheet metal forming is mainly driven by stretching, while bulk forming is by compression, and thin sheet forming fails most commonly by local sheet split incurred under stretching modes. Typical thin sheet forming is more or less under the plane stress mode, with such exceptions of hole-expansion and processes involving sharp bending like flanging, for which the 3-D analysis is proper. The sheet capacity to withstand fracture (or split), the fracture criterion, is considered a part of material properties in the continuum scale analysis along with potentials to describe yielding, hardening behavior (including the rate sensitivity) and the normality rule.

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Apart from the subject commonly known as fracture mechanics, which addresses crack propagation triggered by the spontaneous growth of existing (macroscopic) voids under the critical external stress, fracture of materials particularly regarding macroscopic voids formation has been an important research topic because of its significance in scientific value as well as engineering applications. While brittle fracture near initial yielding is important for product design to avoid the breakage of products during their usage, ductile fracture is important for process design to avoid pre-mature forming failure such as during sheet forming.

Numerous studies have been conducted on ductile fracture of common metals such as steel and aluminum alloys over the last several decades. Earlier efforts have been focused on the effect of high stress-triaxiality (the ratio of the hydrostatic stress to the effective stress) on ductile fracture associated with nucleation, growth and coalescence of micro-voids. Their experiments and theoretical modeling have confirmed that fracture tolerance when measured with the effective plastic strain decreases monotonically as triaxiality increases (Garrison and Moody, 1987; Hancock and Mackenzie, 1976; Johnson and Cook, 1985; Le Roy et al., 1981; McClintock, 1968; Rice and Tracey, 1969; Van Stone et al., 1985). Similar works covering the shear-induced fracture under low or even negative triaxiality condition have been presented by many researchers including McClintock (1972) and Johnson and Cook (1985), who have validated that the effective fracture strain decreases as triaxiality becomes smaller below the simple tension case as well. Fracture incurred by voids growth has been also found strongly dependent on the Lode angle through theoretical modeling (Gao and Kim, 2006; Kim et al., 2004; Zhang et al., 2001) as well as experimental works (Barsoum and Faleskog, 2007).

Constitutive laws involving ductile fracture have been proposed by Gurson (1977) considering yield criteria under the framework of compressible plasticity for porous materials, in which softening of hardening behavior (hardening deterioration) resulted from micro-void nucleation, growth and coalescence has been accounted for. Tvergaard and Needleman (1984) have extended the Gurson model in their GTN model. The GTN model has been even further extended to incorporate the void shearing mechanism of damage, which depends on the third stress invariant (Nahshon and Hutchinson, 2008; Xue, 2008). Adopting a damage parameter instead of a void parameter in a phenomenological way, Lemaitre (1992) has proposed a ductile damage model, in which material degradation leads to the decrease of material stiffness, strength and remaining ductility. In the GTN and Lemaitre models, softening of hardening behavior and the onset of ductile fracture have been coupled each other. However, their fracture criteria have been not explicit in their dependency on the stress-triaxiality and the Lode angle.

The fracture criterion, which is explicit in its dependency on the stress-triaxiality and the Lode angle, has been developed by Bai and Wierzbicki (2008, 2010) based on the modified Mohr–Coloumb stress-based fracture criterion. The model, however, does not account for the softening of hardening behavior, which has been addressed in the GTN model. Chung et al. (2011b) have developed an inverse calibration method to experimentally characterize the softening of hardening behavior and the triaxiality-dependent fracture criterion, which have been applied to evaluate the formability of the TWIP (twinning induced plasticity) steel sheet in hole-expansion under the high triaxiality condition.

Fracture behavior has been considered as a deformation path-dependent material property. To address its deformation path dependence, numerous empirical fracture criteria have been also proposed (Brozzo et al., 1972; Clift et al., 1990; Cockcroft and Latham, 1968; Oyane et al., 1980). Recently, more advanced empirical fracture criteria have been proposed by many researchers (Khan and Liu, 2012a,b; Lou et al., 2014).

To predict forming failure in an effort to optimize the forming process, characterizing a fracture criterion is a requisite as a part of material properties. However, in typical industrial thin sheet metal forming processes at room temperature, forming is driven by stretching under the plane stress condition (including the case of draw forming for which sheet draw-in is constrained enough) and fracture occurs either with or without abruptly severe strain localization as shown in Fig. 1. In the thickening mode, wrinkling is dominant, while, in the thinning mode, fracture accompanying abruptly severe strain localization is most common for highly ductile sheets, even though fracture without severe strain localization is occasionally

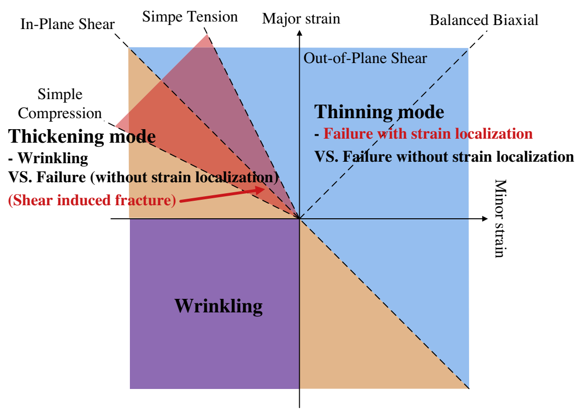

Fig. 1. Typical sheet formability under the plane stress condition.