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Theoretical failure investigation for sheet metals under hybrid stretch-bending loadings

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The deformation limit of sheet metals predicted from forming simulations relies on the failure criteria employed. Localized necking and ductile fracture are two different failure mechanisms. They are applied to construct the Forming Limit Diagram (FLD) and Fracture Forming Limit Diagram (FFLD) in sheet metal forming processes. Recently, high strength steels and aluminum are extensively used as lightweight materials in road vehicle engineering to reduce fuel consumption. The deformation limit of those materials under stretch-bending condition shows significant bending radius dependent phenomenon. The bending process related to the stretch-bending loading of sheet metals is an out-of-plane effect, which has not been fully considered in traditional failure criteria. Most research efforts have been focused on the relationship between the localized necking phenomenon (ductile fracture) and the bending ratio (defined as the radius over the thickness). In this study, the different combinations of the tension and bending during the stretch-bending deformation referred as hybrid stretch-bending loading under the same bending ratio are investigated with proposed analytical models. The system instability and local material behavior are presented as two different failure mechanisms for forming limits and ductile fracture. Results from this study show that the localized necking failure is strongly affected by such loadings even under the same bending ratio. The final failure mode is a result of the competition between the localized necking and ductile fracture. It also suggested that the bending effect on forming limits is not just a function of the bending ratio but also a function of the specific hybrid stretch-bending loading applied on the sheet.

1. Introduction

The Forming Limit Diagram (FLD) is defined as the onset of localized necking as a system instability phenomenon to assess the formability of sheet metals in press forming operations. Ductile fracture phenomenon usually occurs after the localized necking in sheet metal stamping for mild steels. In order to increase energy efficiency, lightweight materials are increasingly adopted in forming structural components. A new challenge in fabrication of these lightweight materials such as high strength steel and aluminum is attributed to their low formability in forming processes especially under stretch-bending condition as reported by Xia et al. [1]. They found that the failure occurs abnormally for some levels of advanced high strength steels under small radius stretch-bending deformation. Furthermore, such phenomenon cannot be predicted by traditional FLD. Contrary, some experimental FLD results based on the so-called “mini” Nakajima tests [2–4] with small radius punch and small radius three-point stretch-bending tests suggested that necking limits have been enhanced by small bending radius. These special phenomena have attracted various research works aimed at explaining and understanding failure mechanisms of lightweight sheet metals especially for high strength steel and aluminum under different stretch-bending conditions.

The localized necking and ductile fracture are two distinct failure mechanisms for sheet metal deformation processes. In sheet metal forming applications, localized necking failure shows path-dependent [5,6], geometry-dependent [7] and texture-dependent properties [8]. FLD was originally developed by Keeler and Backofen [9], in which they conducted extensive forming limit tests and measurements for a wide variety of sheet metals and promoted the practical use of FLD on die tryout shop as the criterion for checking the potential splits. One theoretical model to predict formability of sheet metal was proposed by Hill [10],

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where it was assumed that the existence of a zero-extension direction is the necessary condition for localized necking to occur. Marciniak and Kuczynski [11] (M–K) introduced an initial band of imperfection into the sheet metal in the form of thickness reduction as a tool to trigger the deformation instability, which is often referred as M–K analysis. Under such non-homogeneous assumptions for sheet metal, localization occurs naturally as the sheet deforms under the entire range of biaxial loading. The theoretical imperfection in the M–K analysis is often treated as a numerical method to obtain the formability of the sheet metal. Moreover, Stören and Rice [12] introduced the vertex theory of plasticity into the instability analysis of sheet metal necking. Their study showed that the J_2-Deformation theory of plasticity is a simplified version of the vertex theory under certain assumptions. Furthermore, both Vertex-theory analysis and M–K model were extended by Hutchinson and Neale [13]. The M–K method is further developed by assuming the rotation of weak band in sheet metal when proportional loadings are applied. This development introduces physical-based minimum energy principle in the prediction of formability. These researches are focused on necking failure under in-plane tension deformation for sheet metals. In the past few years, localized necking is considered as the dominant failure mode for the loss of load capability of sheet metals.

In phenomenological method, ductile fracture is considered as a one point material damage accumulation process during forming deformation. From a microscopic point of view, ductile fracture of metals follows the procedure of nucleation, growth and coalescence of micro-voids or cracks. Dozens of fracture criteria are proposed in the past few years as coupled or uncoupled fracture criteria. For coupled fracture criteria, the damage evolution affects the material's plasticity since the defect propagation leads to weaker material. To achieve this assumption, void volume fraction is coupled with the constitutive equation to consider softening effect. The Gurson–Tvergaard–Needleman (GTN) ductile fracture criterion [14,15] is widely used. This criterion is further modified to describe fracture behavior at zero or low stress triaxiality with shear effect [16]. Coupled fracture criterion attempts to explain and understand the ductile fracture with micro-defect and its effect on material's plasticity, but the key parameter void volume fraction as a statistic value is inconvenience to determine with experiments.

For uncoupled fracture criteria, it assumes that the damage accumulation has no effect on material's strength until the final failure. McClintock [17] investigated the growth of a cylindrical void and found that the stress state is critical in void evolution process. Rice and Tracey [18] studied void growth with a single spherical void shape in an infinite solid under remote loading. The results show that void growth was controlled by the stress triaxiality. Following their research work, many phenomenological ductile fracture criteria were developed and widely employed [19–22]. More recently, Bai and Wierzbicki [23] proposed that the lode parameter should be considered as one of the critical factor for ductile fracture. They reformulated the Mohr–Coulomb (MC) fracture model (Modified Mohr–Coulomb Criterion, MMC) and extended this limit to strain and stress mixed space for industry application. Lou et al. [24] proposed a new model with a changeable cut-off value for stress triaxiality based on the shear ductile fracture experimental results.

The localized necking failure is formulated under the in-plane tension deformation assumption. The out-of-plane stretch-bending loading effect is not included. In real sheet metal forming processes, the localized necking failure shows dependent phenomenon under different bending effects. In terms of experimental, Yoshida et al. [25] performed experiments based on the plane strain mode termed the three-point stretch bending test. The ratio between the initial thickness t_0 of sheet and the punch radius R are used as a non-dimensional bending index t_0/R. The limit wall stretch $L_{max}/L_{0,}$ which is defined as the ratio between maximum stretch length L_{max} and the initial length $L_{0,}$ is used to value the ability of the deformation limit of sheet metals. Their results show that an increased in the bending effect accelerates localized necking which can cause sheet metal to fail earlier. Tharrett and Stoughton [2] constructed a similar stretch-bending test to evaluate the forming limits of sheet metals of 1008 AK steel, 70/30 brass and 6010 aluminum under the influence of different bending radii. The enhanced limit strain is found with promoted bending index t_0/R. They also found that localized necking occurs under stretch-bending loading in plane strain mode when the strain in bottom surface of sheet metal material reaches FLD_0. The results suggest that bending effect gives positive impact on forming limits which benefits real stamping operations. For measuring localized necking phenomenon under different bending conditions, Kitting et al. [3] and Kitting et al. [4] proposed the "mini" Nakajima test with different small radius punches designed to stretch and bend sheet metals until necking occurs. The limit strain result suggests that bending effect enhances localized necking resistance capability of sheet metals. Martinez Lopez and Boogaard [26] then performed DP600 sheet metals with 20 mm radius punch in Nakajima test. Since enhanced forming limits are detected, they concluded that the effect of bending should be considered as one of the critical factors in formability. Shih and Shi [27] and Shih et al. [28] performed stretch-bending tests with a Stretch Forming Simulator (SFS) on various AHSS strips. During a SFS test, the strip is first clamped on both sides, the upper die then moves down and stretches the blank into the die cavity, while both the tension level within the strip and the bending angle increase. As proposed by Luo and Wierzbicki [29], in a SFS test, the R/t_0 ratio can be altered by replacing different lower dies, and the tension level on the strip is controlled by adjusting the clamping distance. Three failure locations of the strips can be achieved:

(1) the "shear fracture" within lower die radius;

(2) the final failure on the tangent point between lower die radius and sidewall;

(3) the localized necking failure in the sidewall between upper and lower dies.

To further understand shear fracture failure phenomenon, Zeng et al. [30] constructed FE simulation models and compare the experimental force value evolution with simulated results. They found that the maximum tension force will drop early under small bending radius loading, which is different with sheet metals under the normal necking failure modes. Then the critical bending radius over thickness (R/t_0) value has been proposed to divide different failure phenomenon. Luo and Wierzbicki [29] calibrated the newly proposed Modified Mohr–Coulomb (MMC) fracture model with DP780 experimental tests. They found that the early failure phenomenon can be successfully predicted by the MMC model. Based on this conclusion, they suggest that the early failure of DP780 sheet metal under stretch-bending loading is one fracture phenomenon but not localized necking defined in FLD. It means that fracture may occur before localized necking under certain bending radius condition, and that the FLD may not be sufficient for failure prediction in sheet metal forming simulation even the fracture forming limit curve is still higher than forming limit curve in strain space under plane strain condition as reported. Kim et al. [31] constructed stretch-bending test experiments with several levels high strength steels. With temperature measurement equipment, they found that local material area near small bending radius shows elevated temperature during stretch-bending deformation. This suggests that the high temperature is due to severe plastic deformation of stretch-bending processes. After heating up the local material, the thermal effect softs metal which makes deformation concentrated near small radius area. Localized necking followed by this thermal effect is found to cause early failure. Sung