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An integrated finite element-based simulation framework: From hole piercing to hole expansion

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ABSTRACT

An integrated finite element-based modeling framework is developed to predict the hole expansion ratio (HER) of AA6111-T4 sheet by considering the piercing-induced damages around the hole edge. Using damage models and parameters calibrated from previously reported tensile stretchability studies, the predicted HER correlates well with experimentally measured HER values for different hole piercing clearances. The hole piercing model shows burrs are not generated on the sheared surface for clearances less than 20%, which corresponds well with the experimental data on pierced holes cross-sections. Finite-element-calculated HER also is not especially sensitive to piercing clearances less than this value. However, as clearances increase to 30% and further to 40%, the HER values are predicted to be considerably smaller, also consistent with experimental measurements. Upon validation, the integrated modeling framework is used to examine the effects of different hole piercing and hole expansion conditions on the critical HERs for AA6111-T4.

1. Introduction

In stamping operations of automotive body panels, steel and aluminum sheet metal workpieces are subject to blanking, trimming and piercing processes, including edge trimming, hole piercing, and window blanking, etc. In addition to geometric imperfections such as burrs, mechanically sheared or trimmed edges also contain excessive plastic deformation and local damage along the perimeter of the workpiece subjected to shearing operations. These shear-induced edge imperfections can lead to edge cracking in the subsequent stamping and forming operations, hence considerably compromise the formability of the materials.

Cracks stemming from previously sheared edges is a well-known problem for forming, and there are abundant experimental studies for steels [1–4] studying hole expansion of pierced holes. Still, predictive analyses on the influences of shearing processes/parameters on the subsequent formability are scarce due to the following difficulties: (1) accurately predicting the sheared edge geometry and damage and (2) effectively and accurately incorporating the above-predicted shearing-induced edge geometry and damage into the subsequent formability simulations.

Due to various global initiatives for improved fuel efficiency, aluminum sheets have received increasing attention in recent years as a practical replacement for steel sheets targeting vehicle weight reduction. Although there are numerous studies about shearing-induced defects in aluminum sheets, systematic and quantitative studies detailing the influences of the various shearing process parameters on the edge cracking during subsequent forming processes are quite limited.

Golovashchenko et al. studied edge cracking during tensile stretching of both aluminum [5] and steel [6,7] sheets trimmed along a straight line. Experimental observations after fracture of the trimmed part showed that tensile stretchability can decrease in excess of 50% depending primarily on the cutting clearances. It was reported that the planar failure mode varies from shear-type failure typical for small clearances to splitting-type failure where the cracking starts from the edge and propagates normal to the edge across the width of samples, usually observed in case of large cutting clearances. Hu et al. [8] developed an integrated finite element-based framework to study the tensile stretchability of previously trimmed AA6111-T4 aluminum sheets. The integrated framework includes a two-step finite element modeling analyses. First, a two-dimensional (2D) plane strain trimming model simulation is performed considering various trimming parameters such as clearance, punch radius and scrap support, etc. Next, the predicted edge geometry, plastic deformation and damage are carried over to the subsequent three-dimensional (3D) half dog-bone tensile model for stretchability predictions. The linkage between the two models is established with an ABAQUS/Python post- and pre-processing script, ABAQUS CAE and a user material subroutine

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(VUMAT). It has been demonstrated that the predicted stretchability results quantitatively compare well with experimental observations, including variation of tensile elongation, planar failure modes, and multiple edge cracking behaviors with varying cutting clearances.

Sartkulvanich et al. [9] used 2D axis-symmetric finite element models to simulate both the hole piercing and the subsequent hole expansion processes in DP590 steel. The burr geometry and strain and damage information from the blanking simulations are carried into the hole expansion process, and the calculated critical hole expansion ratios (HERs) defined by formula (1) were compared with experimental measurements for different blanking clearances.

$$HER = \frac{D_f - D_0}{D_0} \times 100\% \quad (1)$$

where *HER* is the percentage change in the diameter (D_f) of the expanded hole before a through-thickness edge crack can be detected in reference to the originally pierced hole (D_0).

Using the 2D axis-symmetric model to represent the hole blanking process is a well justified assumption. However, the 2D model is not sufficient to capture the edge cracking behavior during hole expansion test because the experimentally observed radial cracks along the edge cannot be represented in the 2D model where cracks may propagate in the direction deviating from the radial direction. Therefore, there is a lack of clear explanation on edge cracking in the finite element model, and the calculated HER for different hole piercing clearances may not be reliable. In the current work, the integrated framework developed by Hu et al. [8] is employed, and the 2D axis-symmetric hole piercing model with a rather fine mesh is selected to accurately account for the highly nonlinear contact geometry between the sharp-corner of the piercing tool and the sheet being processed. The 3D model is used for the subsequent hole expansion process with consideration of the sheared edge information predicted from the previous hole piercing model. The HER is calculated and examined for different cutting clearances and compared with experimental measurements.

2. Methodology

2.1. The hole piercing model

For accurate predictions of edge stretchability during hole expansion, i. e., the critical HER, of previously hole-pierced sheets, an accurate calculation of edge conditions resulted from piercing, such as damage and plastic deformation, is essential. Fig. 1 show the 3D models of both the hole piercing and hole expansion tools. Fig. 2 shows the finite element model setup for the hole piercing process of a 0.9-mm-thick (t) sheet to produce a ⌀10 mm hole. The model uses 2D axis-symmetric elements with reduced integration and hourglass control (CAX4R) to model the sheet material. The clamp, punch dies are assumed to be rigid bodies. Typically in industry, tool corners are very sharp, although they can evolve with time due to tool wear. Here, the die corner radii are assumed be 20 μm to represent fresh die conditions. In the model, the sheet material being pierced is an AA6111-T4 aluminum alloy and assumed to be an elasto-plastic deformable body. Because damage and fracture near the cutting edge will be emphasized, commercial finite element package ABAQUS/Explicit [10] is used. For accurate modeling of tool/sheet contact, a rather fine mesh size ($6 \times 10\ \mu m^2$) is used in the shear zone. To reduce the problem of mesh distortion at large deformation and prevent tool/sheet penetration, arbitrary Lagrangian–Eulerian (ALE) adaptive meshing and adaptive contact algorithms are used [11]. The tool/sheet contacts are assumed to obey a simple Coulomb's law with a constant friction coefficient of 0.1.

2.2. The material elastic and plastic properties

The sheet material is assumed to be isotropic, while the elastic constants, i. e., Young's modulus and Poisson's ratio, are assumed to be 70 GPa and 0.33, respectively, which is typical of aluminum alloys. An isotropic J2 flow rule is used for plasticity. In our previous work, the work-hardening behavior was represented by a three-section Ludwik power law fitting [11] for the experimental uniaxial tension test:

$$\sigma = \sigma_0^i + k_i \epsilon^{n_i}, \quad i = 1 - N \quad (2)$$

It must be noted that the plastic flow curve obtained from the tensile test for AA6111-T4 is valid only for the portion up to the limit strain of uniform deformation before the ensuing diffuse and localized necking behaviors. This limit strain is about 0.18, quite low compared with the local strain at necking and deformation in the shear zone during trimming of AA6111-T4 sheets. Detailed fracture surface observation of the grain shape at or near the sheared surface indicates that deformation strain can reach as much as 2, sometime even higher. The flow curve at large strains used in the finite element model essentially is an extrapolation of the last section of the Ludwik power law fitting.

Recently, Golovashchenko et al. [12] performed accumulated rolling and subsequent tensile tests to determine the flow stress at large strains of the AA6111-T4 sheet used in the current studies.

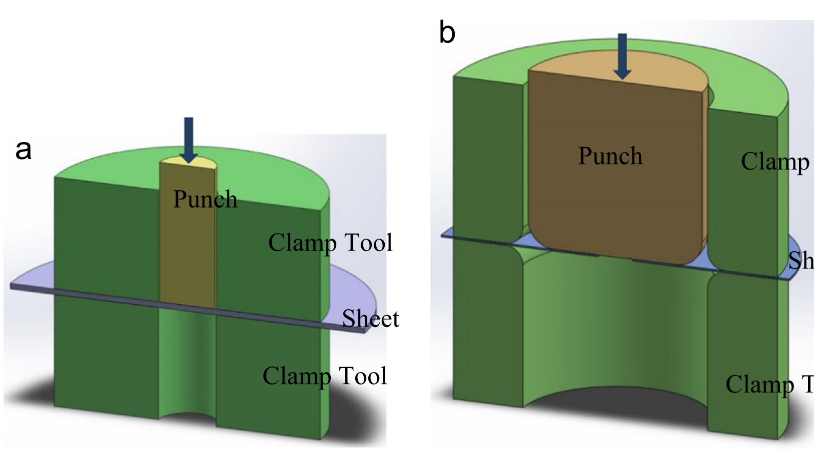

Fig. 1. The 3D models of the (a) hole piercing and (b) hole expansion tools, where the green parts are the clamp dies and the brown part is the punch die. The light blue part is the sheet to be pierced or expanded. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)