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Technical Paper

Formability prediction of aluminum sheet alloys under isothermal forming conditions

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ABSTRACT

The forming limit diagram (FLD) is a tool that is used by automotive engineers to assess and compare the formabilities of sheet metals. The FLD is experimentally determined by portraying the biaxial strain distribution in the plane of the sheet under proportional loading paths. However, experimental determination of the FLD is time consuming. With increasing interest in warm forming of aluminum sheets, the process for determining the forming limit diagram is further complicated and more cumbersome as the forming limits change with increasing temperatures. Accordingly, a process for predicting the FLD based on the material constitutive model is of interest. This paper presents a finite element based criterion for predicting the FLD under isothermal conditions. The paper provides experimental validation for the predicted results using select automotive 5xxx series aluminum alloys. The findings indicate that the developed criterion can adequately predict the forming limit for each strain path.

1. Introduction

The high strength-to-weight ratio of aluminum alloys, coupled with a good corrosion resistance, makes them attractive for use in automotive sheet metal applications. However, these alloys are known to have lower room temperature formabilities compared with the automotive steel alloys. Consequently, for applications that require high levels of ductility, forming of aluminum alloy sheets can be performed at elevated temperature. Though high temperature forming processes, such as superplastic forming, have been investigated and implemented in the manufacture of automotive sheet products, the high forming temperatures (above the recrystallization temperature of the alloy) and the low forming rates limit the use of these processes to low production levels. For high volume produced vehicles (<50,000 cars/year), faster production cycle times are needed. Therefore, warm forming has been proposed as a viable sheet forming process. Warm stamping of sheets is performed in matched die sets, as is the case of conventional room temperature stamping, with the difference being the elevated forming temperature.

The forming limit diagram (FLD) has been used by the sheet metal forming industry to assess the formability of sheet metals since it was introduced by Keeler [1] in 1965, followed by work by Goodwin [2]. The FLD is a two dimensional plot of the major (ordinate) and minor strains (abscissa) in the plane of the sheet. The forming limit curve (FLC) is a line that passes through the major and minor strain pair for each strain path representing the onset of localized necking. Strains below the FLC are considered safe and strains above the FLC are considered to cause failure due to either necking or fracture. Since its introduction, the FLD has been used as a tool to compare the formabilities of different alloys. Studies reported in the literature present empirical, analytical or numerical approaches for determining/predicting the forming limits and fitting the FLC.

An empirical approach for determining the FLC from experimental results was proposed by Strano and Colosimo [3]. Their approach, referred to as the logistic regression approach, focused on identifying the "separation area" between the safe strains and the failure strains by expressing the probability of failure as a function of the strains in the plane of the sheet. Such approaches provide the ability to improve the experimental accuracy in determining the forming limits, but still require a complete experimental investigation.

Continuum mechanics based techniques for determining the FLC have been developed, with each technique using a different combination of yield criteria and hardening rules [4]. One of the most widely used techniques for predicting the FLC is the Marciniak and Kuczynski (M–K) analysis [5]. This technique assumes the

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presence of an initial inhomogeniety (defect) in the sheet metal in the form of a groove that is machined across the width of the test specimen perpendicular to the loading direction. The presence of such defect causes strain localization leading to failure. While the M–K methods is a relatively easy test to perform, investigators [6–9] have shown that the results obtained through the test are affected by the shape and the depth of the groove as well as properties of the tested material; such as anisotropy and strain rate sensitivity. Therefore, researchers have focused on identifying methods for improving the forming limits predicted through the M–K method, by coupling the M–K method with yield criteria or empirical models. The work of Xu et al. [10], Ghazanfari and Assempour [11], Butuc et al. [12], and Knockaert et al. [13] present examples of such investigations validated using different alloys. Investigators have also reported that the shape of the predicted FLC could be influenced by the yield criterion applied in the predictive model, Wang and Lee [14], by the introduction of the effect of planar anisotropy and different hardening laws, Aghaie-Khafri and Mahmudi [15], and by the use of different necking criteria in predicting the forming limit curve, Zhang et al. [16]

Recent developments have focused on the use of numerical tools to predict the forming limits of sheet metal alloys. This is achieved by modeling the experimental biaxial formability tests representing the different strain paths through finite element models, without the introduction of an M–K type inhomogeniety. Examples of such approach the work of Takeda et al. [17] who coupled the predicted numerical results with a failure criterion to predict the forming limits under biaxial stretching; the work of Situ et al. [18] who used the second derivative of the numerically predicted major strain (referred to as the strain acceleration) for determining the formability limit; and the work of Li et al. [19] who predicted the formability limits as the strain in the elements just outside the necked area that had stopped deforming (i.e. adjacent elements to the necked element for which the change in the major and the minor strains approaches zero).

It is apparent that substantial progress has been made toward better understanding of the formability of sheet materials. Numerical approaches for predicting the formability limits have been reported in the literature. However, there are several presented approaches offering a range of complexities and computational efficiencies. This paper presents a simplified methodology to numerically predict the forming limit curve for aluminum alloys under isothermal forming conditions. The paper will demonstrate that by understanding the numerically predicted strain distribution in the sheet material, the FLC can be predicted at an acceptable level of accuracy without the need for extensive experimentation and without the need for a predefined imperfection. The paper presents experimental validation of the predicted room temperature FLC for AA5182-O and provides a comparison with the FLC predicted using the ISO 12004 FLC standard. The paper will also demonstrate the applicability of the developed approach in predicting the elevated temperature FLC for the investigated alloy.

2. Numerical tools for developing the forming limit

This study is performed using finite element modeling of the Nakajima formability testing tool shown in Fig. 1. Different strain paths are generated by varying the width of the modeled sheet. Following is a detailed description of the numerical modeling approach and the criterion used for determining the forming limit for each strain path. It should be noted that the hemispherical punch diameter was 100 mm.

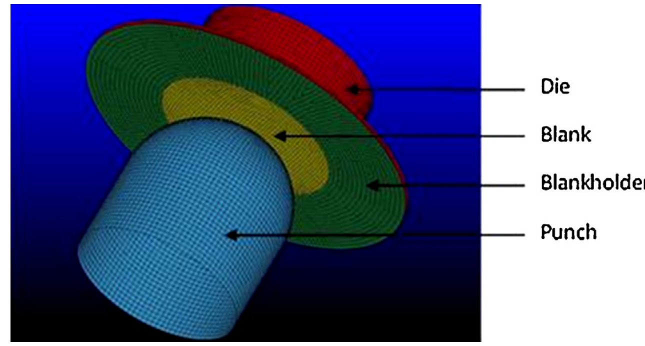

Fig. 1. Meshed schematic of the Nakajima testing tool used in the study. The figure also shows the blank.

2.1. Finite element modeling

The numerical analyses performed in this study were carried out using LS-DYNA. A solid model of the Nakajima formability testing tool set was modeled. The tooling set: punch, die, and blankholder, was considered to be made of a rigid material and represented by rigid shells. The tooling was assumed to be made of steel. The tested sheet was modeled as an elasto-plastic material and was meshed using Belytschko–Tsay shell elements, with an average element size of 2 mm × 2 mm as shown in Fig. 1.

Contact between the sheet and the tooling is modeled using the master-slave contact approach with surface to surface contact option in LS-DYNA (*one way surface-to-surface contact*). The non-deforming rigid surfaces of the tooling (punch, blankholder and die) are considered to be master surfaces while the sheet surfaces are considered to be the slave surfaces. The coefficients of friction used in the study were determined using an iterative process in which an experimental load–displacement curve is matched to the experimentally determined curve. A coefficient of friction of 0.2 was used in the contact model between all three pairs of interacting surfaces; i.e. blank–punch, blank–die, blank–blankholder.

In order to decrease the computation time, the mass scaling or velocity scaling may be used. In this study, the mass scaling approach was adopted since it does not affect the performance and accuracy of the simulation process. This is achieved by increasing the density of the material by several orders of magnitude. This study used a mass scaling factor of 1000. The velocity scaling technique can also be used; this approach involves increasing the forming speed (i.e. the punch speed) by several orders of magnitude. This approach only works for non-strain rate sensitive materials. While aluminum is not strain rate sensitive at room temperature, this study aims at determining the formability limit under warm forming conditions, where aluminum is strain rate sensitive. The Hocket–Sherby material model was used in the numerical analysis to represent the material flow behavior at room temperature (Eq. (1)):

$$\sigma = a - b \times \exp(-C\varepsilon^n) \quad (1)$$

The model considers the stress, σ, to be related to the strain, ε, using an exponential function. The parameters a, b, c and n are material constants at the investigated temperature; these parameters were determined by fitting the Hocket–Sherby model to the experimental stress–strain data. The Hocket–Sherby parameters determined at room temperature for the material used in the development of the numerical forming limit criterion (AA 5182-O) are given in Table 1.

LS-DYNA has an option to calculate stress and strain values for particular elements in an efficient manner. The option, called ELOUT, allows the user to create an ASCII file containing element history at a user specified time increment for a set of specified