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FE simulations of gas blow forming and prediction of forming limit diagram of AZ31 magnesium sheet

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ABSTRACT

FE simulation of elliptical bulge forming of AZ31 automotive magnesium sheet has been carried out based on a recent experimental study where a new method of simultaneously bulging of two clamped blanks of different geometries was successfully employed to experimentally obtain tension–compression side of the FLD. The present study complements the earlier experimental study by providing insight into material plastic flow and strain localization for various ‘double blank’ configurations. In addition, FE simulation results are utilized to predict the FLD of AZ31 sheet at 300 °C based on a recently proposed strain localization criterion and other material model assumptions. Good agreement has been observed between the experimental and predicted FLDs.

1. Introduction

Performance of automotive sheet materials for stamping or other forming applications is often assessed by means of a forming limit diagram (or FLD). Complex sheet forming process such as drawing, plane strain deformation and biaxial stretching can be easily represented on a FLD which defines the onset of necking of sheet materials under various modes of deformation. FLD is essentially a locus of two principal strains (also referred to as major and minor strains) in the vicinity of a localized neck, The FLDs of sheet materials are commonly determined by hemispherical punch stretching (HPS) experiments by methods proposed by Nakazima et al. (1968) and Hacker (1975). In the work of Nakazima et al., several gridded blanks of different blank shapes are utilized to generate various biaxial strain paths. While the experimental study of Hecker is similar to the Nakazima method, a grid classification scheme was devised to demarcate the boundary between necked and un-necked grids. Gas blow forming (GBF) and superplastic forming (SPF) are similar processes where a sheet is clamped and deformed at high temperatures by pressurized gas into a die cavity. The SPF process and its industrial application has been reviewed in detail by Barnes (2001). GBF was employed by Luo et al. (2007) to study the effect of temperature on total elongation, dome height, final thickness distribution in a fine grained aluminum alloy AA5083. In addition, formability of AA5083 sheet was assessed by utilizing elliptical dies of different aspect ratios for biaxial tension side FLD determination. The method has certain advantages over the punch based method as it largely eliminates the effect of friction between punch and sheet and also minimizes the temperature gradient that may exist with the heated punch and dies. However, until recently, the elliptical bulge method could be applied to only obtain the biaxial tension side of the FLD. More recently, the method has been extended to cover the tension–compression side of FLD by Banabic et al. (2013) and the present authors, Mitukiewicz et al. (2014). In the work of Banabic et al., a new procedure was developed for the experimental determination of the FLCs and especially to obtain the tension–compression side of the FLD. The methodology is based on the hydraulic bulging of a ‘double-blank’ specimen where the upper blank has a pair of holes pierced in symmetric positions with respect to the center, while the lower blank acts both as a carrier and a deformable punch. By modifying the dimensions and reciprocal position of the holes, they were able to attain several different strain paths and generate the left side of the FLC. Mitukiewicz et al., followed a similar methodology to the work of Banabic et al. (2013) of deforming a double-blank specimen but, instead of a pair of holes, employed a pair of slits of different spacing in the upper blank. In addition, the concept of generating the tension–compression side of FLD was demonstrated for gas bulging at higher temperature (instead of a liquid bulging and room temperature deformation in Banabic et al.). Lastly, the double-blank concept was tested for

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AZ31 magnesium sheet where same material was used for upper and lower blanks. In contrast, Banabic et al. had utilized different sheet materials for their double blank specimen. In Mitukiewicz et al., the gas bulging experiments on AZ31 sheet were conducted at 300 °C and 400 °C where different aspect-ratio elliptical openings in the die were utilized for obtaining a range of biaxial tensile strain paths.

Marciniak–Kuczynski (or M–K) method has been used for many decades to analytically predict FLDs of sheet materials. More recently, in the work of Evangelista et al. (2002), the M–K method has been employed within the finite element (FE) simulation to predict the FLD by incorporating tool geometry, material law (yield criterion and plastic constitutive equation), friction and a strain localization or damage criterion. Much effort has been made in the recent years to capture room temperature yielding behavior of magnesium in the form of a suitable yield criterion as it shows large anisotropy and tension compression asymmetry. Cazacu et al. (2006) introduced a macroscopic orthotropic yield criterion for HCP materials, which could describe the yield asymmetry between tension and compression and the anisotropy. Barlat yield criterion also has been adopted by Naka et al. (2008) for capturing the effect of strain rate, temperature and sheet thickness on yield locus of AZ31 magnesium sheet. From the microscopic aspect, polycrystal plasticity, by considering the deformation modes and grain orientation effect, provides another method to simulate the material deformation. Neil and Agnew (2009) predicted the forming limit of AZ31 based on crystal plasticity model combined with M–K approach at different temperatures. Serenelli et al. (2011) studied the limit strain of BCC and FCC sheet metal in a similar method and the results are in good agreement with the experiment data. All these predictions were employed in numerical calculation to analyze plastic deformation but without any real part geometry. It is to be noted that no crystal plasticity based FE simulations for AZ31 sheet that employ even simple forming tool based simulations, such as gas bulge forming in the present work, are not known to the authors. However, as discussed earlier, the anisotropy of AZ31 drops dramatically at 300 °C, so simple yield criteria, such as Mises and Hill quadratic, are likely to give a reasonable result. With regard to warm forming of sheet materials, plastic constitutive equation involving strain hardening, strain rate hardening and temperature is required. A large number of such equations are available in the literature in range their range of applicability and complexity depending upon the materials microstructure and dynamical metallurgical phenomena that occur during deformation and consequently the number of material parameters that need to be measured. Liang and Khan (2009) analyzed characteristics of four well-known strain rate and temperature dependent plastic constitutive laws for metallic material for large strain deformation processes such as sheet metal forming applications and identified limitations of each of them. Sung et al. (2010) also reviewed a large number of plastic constitutive equations for sheet forming applications and discussed their characteristics and limitations. Many of the available rate and temperature dependent plastic constitutive equations exhibit strain hardening at lower strains to stress saturation at large plastic strains. Since automotive magnesium sheet materials such as AZ31 typically exhibit strain hardening at very low strains and a long regime of strain softening up to large strains, utility of many of the proposed plastic constitutive equations for accurately capturing it flow behavior is limited. In the present work, strain rate and temperature dependent plastic constitutive equation for metal plasticity in Abaqus was modified to best represent the measured stress–strain data (or curves) at two different test temperatures for the purposes of predicting the FLDs via FE based M–K method (see Sections 3 and 4.2).

Pepelnjak et al. (2005) proposed a necking criterion based on strain-thickness analysis, and predicted the FLD with the FE approach. The maximum value of the second deviation of the thickness strain was chosen as the onset of the necking. However, this criterion has no clear physical meaning and the thickness strain is typically not directly measured in the experiment. Zadpoor et al. (2009) reviewed a number of continuum plasticity models and compared four different approaches for necking and fracture to predict the failure of 2024-T3. Martínez-Donaire et al. (2014) proposed two new approaches to detect the onset of necking based on the analysis of displacement and strain evolutions and compared the results with other criterions. We adopted a pseudo strain acceleration criterion developed by Situ et al. (2011) which has been already implied in FE simulation to predict the limit strains for 6111-T4. This work has shown good agreement results with experiment and has been referred to in the work of Martínez-Donaire et al. (2014). This criterion is discussed in some detail in Section 4.4.

In the present work, FE simulations of the earlier lab-based GBF experiments of Mitukiewicz et al. (2014) have been conducted to predict FLDs of AZ31 magnesium sheet at 300 °C by employing a strain localization criterion proposed by Situ et al. (2011). Based on the tensile tests and experimental gas bulging experimental conditions, FE models are set up using general purpose FE code, Abaqus dynamic implicit, to simulate the GBF process. The material flow and strain localization during the various elliptical bulging processes is analyzed. In addition, FLD of AZ31B magnesium sheet is predicted at 300 °C and compared with the experimental FLD.

Since the experimental details pertaining to material properties of AZ31 magnesium sheet, annealing, elliptical gas bulging test set-up, and post-test optical strain measurement procedure were covered earlier in Mitukiewicz et al. (2014), they are not repeated here. Instead, a brief summary of the experimental procedure is provided in Section 2.2 as a background for the present FE modeling work.

2. Experimental material data

2.1. Uniaxial tensile test

Uniaxial tensile tests were conducted using standard ASTM-E8 rectangular dog-bone specimens (see Fig. 1). The tests were performed using a computer-controlled servo-hydraulic mechanical test system of 250 kN capacity (MTS Model no. 312.31) fitted with a temperature-controlled environmental chamber (Instron Model no. 3119) as shown in Fig. 2. The tensile samples were prepared from the sheet at 0° (or RD), 45° and 90° (or TD) with respect to the rolling direction and the edges were lightly sanded to remove the burr. Tests were performed at three different temperatures, room temperature (RT) of about 20 °C, 200 °C and 300 °C. To characterize the strain rate sensitivity of the material, RD specimens were tested at three initial strain rates, $0.1\,\mathrm{s}^{-1}$, $0.01\,\mathrm{s}^{-1}$, and $0.001\,\mathrm{s}^{-1}$. The specimens were placed in the furnace and held for ten minutes to homogenize the temperature prior to testing.

In-situ full-field optical strain measurement system based on digital image correlation (or DIC) technique was utilized during uniaxial tensile tests to obtain strain maps, ARAMIS system from GOM mbH (2001a,b). The system consisted of a high resolution camera mounted on a tripod, a frame grabber, and a computer. Before the test, a stochastic (or speckle) pattern was applied to the specimen

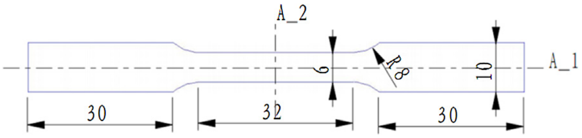

Fig. 1. A drawing of the ASTM-E8 sub-size AZ31 sheet specimen for uniaxial tensile tests. All dimensions are in mm.