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A new method of determining forming limit diagram for sheet materials by gas blow forming

G. Mitukiewicz[a], K. Anantheshwara[a], G. Zhou[a], R.K. Mishra[b], M.K. Jain[a,*]

[a] Department of Mechanical Engineering, McMaster University, Hamilton, Ontario, Canada
[b] General Motors Research and Development Center, Warren, MI 48090-9055, USA

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ABSTRACT

A new methodology is proposed to obtain forming limit diagrams (FLDs) of sheet materials using gas blow forming process at elevated temperatures. Tension–tension side of the forming FLD is achieved by using circular as well as elliptical dies of different aspect ratios. To achieve tension–compression side of FLD un-bonded bi-layer specimen with slots are utilized. The widths between the slots are varied to achieve different strain paths. A correlation is established between the hemispherical punch-based tests and GBF tests of samples with slots to achieve different strain paths. FLDs for automotive AZ31 magnesium sheet at 300 °C and 400 °C in two different orientations are determined. Increase in forming limits of AZ31 with increase in temperature is observed.

1. Introduction

Gas bulge (or blow) forming (GBF) of sheet materials has been extensively used in the past in the aerospace industry for superplastic forming (SPF) of complex components from aluminum and titanium alloys. Starke and Staley (1996) have reviewed various aerospace aluminum alloys for their SPF behavior where optimum forming conditions have been identified. Boyer (1996) has reviewed various candidate Ti–Al–V alloys for SPF of specific aerospace components emphasizing the need for specialized processing for controlling microstructure in these alloys. More recently, the process has been successfully used to assess elevated temperature formability of automotive aluminum alloy AA5083 at a range of temperatures (425–500 °C) and strain rates (10^{-3} to 10^{-1} s^{-1}) for warm forming applications (Taleff et al., 2009). Different experimental techniques have been developed to determine the FLDs of sheet materials. Marciniak and Kuczynski (1967) developed a technique to determine limit strains by using a double sheet specimen configuration and a flat bottomed cylindrical punch for sheet stretching. By choosing different specimen shapes for the double sheet specimen, they were able to attain a range of strain paths up to the onset of necking. Nakazima et al. (1968) developed a technique to evaluate formability of sheet materials by hemispherical punch stretching experiments. Hecker (1975) further refined the Nakazima method for FLD determination by using samples of different widths. The major and minor strains in the neck and its vicinity are used to obtain FLD. GBF technique has been used to determine formability at higher temperatures under biaxial stretching conditions in the past. More recently, elliptical dies of different aspects ratios with the GBF technique and circle grid strain analysis were utilized to obtain the right side of FLDs of AZ31 magnesium sheet (Abu-Farha et al., 2012). The GBF method for FLD determination offers some advantages over the punch-based methods, such as by Nakazima, since undesirable effect of friction between the punch and the sheet on strain path variability is eliminated. In addition, the GBF method is much easier to implement for higher temperature FLD determination as the need for a heated punch is avoided and the temperature uniformity over the specimen surface during the test is easier to attain due to convective heat transfer to the test specimen with the heated gas than with the heated punch. However, a major limitation of the GBF process in the past has been its inability to provide the tension–compression and plane strain limit strain points on FLD (Fig. 1).

Hecht et al. (2005) developed a hydraulic bulging process for AZ31 sheet at elevated temperature. It is to be noted that the focus of this paper is on obtaining biaxial stress strain curves and limit strains on the biaxial tension side of FLD rather than on the tension–compression side of FLD. Merklein and Beccari (2006) compared the formability of aluminum and magnesium alloys at temperatures between 100 and 300° C by generating forming limit curves with the help of Nakazima tests and cup drawing tests. Banabic et al. (2013) developed a new procedure for the

* Corresponding author. Tel.: +1 905 525 9140x27841; fax: +1 9055727944.
E-mail address: jainmk@mcmaster.ca (M.K. Jain).

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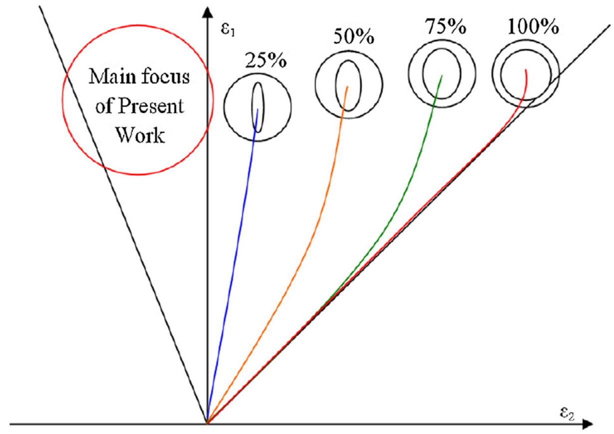

Fig. 1. A schematic representation of different biaxial tensile strain paths in the FLD space that can be achieved using different shapes of dies in case of GBF. The inner closed shape represents the elliptical die opening of different aspect ratios. The outer circle represents the outer dimension of the elliptical die used in gas bulging. The left side of FLD marked with a larger red circle is the main focus of the present work. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 bi-layer specimen, similar to the proposed method. 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.

Present work extends the capability of the GBF process for determining FLD at elevated temperature by enabling it to obtain a complete FLD of sheet materials. A new methodology for determining the tension–compression and plane strain limit strain points has been developed. Since warm forming of lightweight magnesium sheet is being actively pursued in the automotive industry, proposed new GBF methodology has been verified by determining complete FLDs of AZ31 magnesium sheet at two typical AZ31 warm forming temperatures.

2. Experimental procedure

2.1. Test set up and die design

The test set-up for gas bulge forming (or GBF) system consisted of a test frame on which the dies were mounted (Fig. 2). The dies were housed inside an environmental chamber that was also mounted on the test frame. GBF test tooling consisted of a die (shown here with a circular cavity) mounted on a square clamp plate with four posts. The clamping fixture above the die comprised of two circular rings separated from each other with a set of springs and a cylindrical core (Fig. 3). Clamping was achieved with a hydraulic cylinder located at the top of the test frame.

To achieve other biaxial tensile strain paths (i.e., right side of FLD), three additional elliptical dies of increasing aspects ratios (major versus minor axes dimensions of 4:3, 4:2 and 4:1) were designed and machined (Fig. 4). Outer radii of all die inserts were 170 mm. Different aspect ratios of the bulge specimen were achieved by keeping length along major axis constant (100 mm) and by varying the minor axis length to 25 mm, 50 mm and 75 mm. A die profile radius of 5 mm was selected to minimize failure in the bead region. Four grooves at the outer edge of the die were also added to the die for alignment purpose. These groves along with the markers (on the tooling) also helped to avoid any slippage of sample during the experiments.

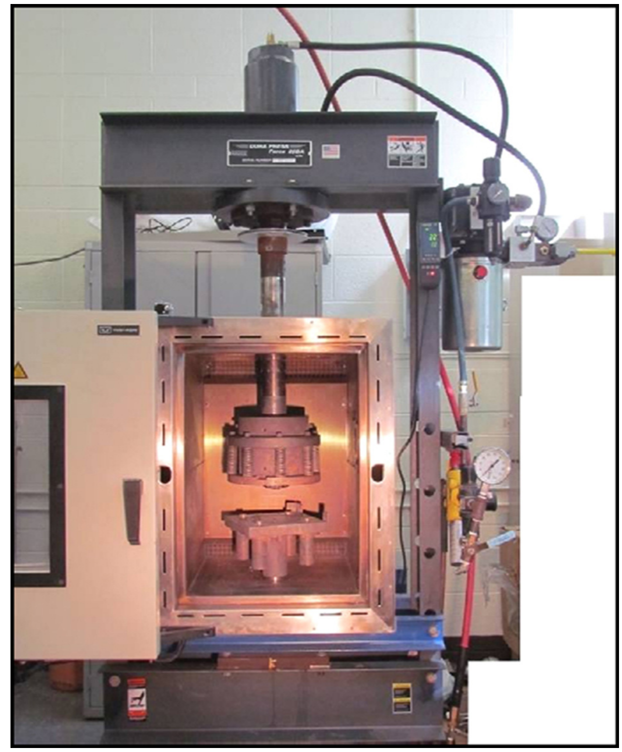

Fig. 2. Photograph of gas blow forming test rig as housed inside a furnace. Furnace allows carrying out experiments at a range of temperatures and under constant temperature conditions.

Fig. 5 shows schematic diagrams of the GBF test process. Sample was inserted between the die (indicated in fluorescent green) and a bottom plate mounted on four posts. A clamping force of 178 kN was applied via a spring-loaded clamping fixture (gray) from the top while keeping the bottom assembly, holding the die and the specimen, fixed. A circular die cavity was utilized to attain equi-biaxial stress–strain path whereas elliptical dies were used

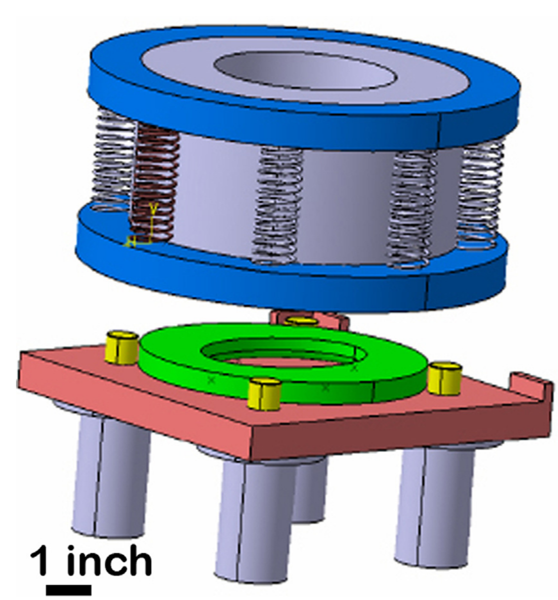

Fig. 3. A drawing of the high temperature bulge test tooling. The die plate with cylindrical cavity in green will be replaced with various elliptical openings to carry out elliptical bulge tests.