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Determination of the flow stress of five AHSS sheet materials (DP 600, DP 780, DP 780-CR, DP 780-HY and TRIP 780) using the uniaxial tensile and the biaxial Viscous Pressure Bulge (VPB) tests

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ABSTRACT

Room temperature uniaxial tensile and biaxial Viscous Pressure Bulge (VPB) tests were conducted for five Advanced High Strength Steels (AHSS) sheet materials, and the resulting flow stress curves were compared. Strain ratios (*R*-values) were also determined in the tensile test and used to correct the biaxial flow stress curves for anisotropy. The pressure vs. dome height raw data in the VPB test was extrapolated to the burst pressure to obtain the flow stress curve until fracture. Results of this work show that the flow stress data can be obtained to higher strain values under biaxial state of stress. Moreover, it was observed that some materials behave differently if subjected to different state of stress. These two conclusions, and the fact that the state of stress in actual stamping processes is almost always biaxial, suggest that the bulge test is a more suitable test for obtaining the flow stress of AHSS sheet materials for use as an input to Finite Element (FE) simulation models.

1. Introduction

This study is concerned about two types of AHSS; Dual Phase (DP) steels and Transformation-Induced Plasticity (TRIP) steels. The microstructure of DP steels is composed of ferrite and martensite, while the microstructure of TRIP steels is a matrix of ferrite, in which martensite and/or bainite, and more than 5% retained austenite exist. The increased formability of AHSS is the main advantage over conventional HSS. DP steels, for example, have high initial strain hardening and a high tensile-to-yield strength ratio, which accounts for the relatively high ductility, compared to conventional HSS. This issue was pointed out (a) by ASTM (2007) which discusses the standard test methods for obtaining the tensile strain hardening components and (b) by ASTM (2006) that explains the test methods used for measuring the plastic strain ratio 'r' for sheet metals. Nevertheless, compared to Draw Quality Steels (DQS), AHSS steels have relatively low ductility. In the stamping industry, running Finite Element (FE) simulations is an important step in the process/tool design. A critical input to FE models is the mechanical properties (flow stress curve) of the sheet material used. Usually, flow stress curves are obtained using the uniaxial tensile test. Although accurate and convenient, two main limitations exist for this test. First, values of strain attained in this test are generally less than the values observed in stamping processes. As a result, data obtained in a tensile test, is usually extrapolated in conducting FE simulations. Second, the state of stress in actual stamping is usually biaxial, which raises questions on the suitability of using flow stress data obtained under a uniaxial loading condition. Based on these considerations, the biaxial bulge test was used extensively in the Engineering Research Center for Net Shape Manufacturing (ERC/NSM), for obtaining flow stress input to FE models. The ERC/NSM bulge test uses viscous material as the pressurizing medium. Therefore, it is called the "Viscous Pressure Bulge (VPB)" test. This test was originally developed by Gutscher and Altan (2004) and further developed to include anisotropy by Palaniswamy and Altan (2007).

2. Background on the VPB test

Fig. 1 is a schematic of the tooling used in the VPB test. The upper die is connected to the slide and the cushion pins support the lower die (the blank holder) to provide the required clamping force. The

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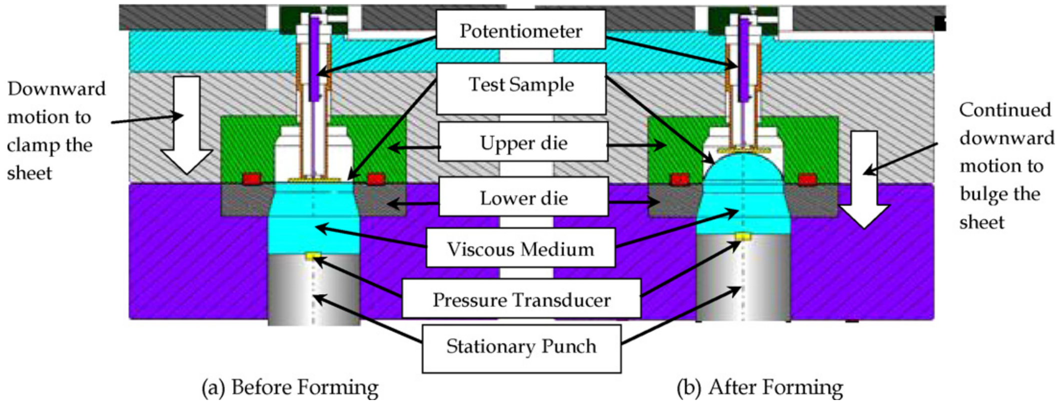

Fig. 1. Viscous Pressure Bulge (VPB) test tooling.

punch in the lower die is fixed to the press table and therefore stationary. At the beginning, the tooling is open and the viscous material is filled into the area on the top of the punch. When the tooling closes, the sheet is totally clamped [Fig. 1(a)] between the upper and the lower dies using a lockbead to prevent any material draw-in in order to maintain the sheet in a pure stretching condition throughout the test. The clamping force (the selected press cushion force) depends on the material and thickness tested. The slide then moves down together with the upper die and blank holder. Consequently, the viscous medium is pressurized by the stationary punch and the sheet is bulged into the upper die. Since the tools are axisymmetric, the sheet is bulged under balanced biaxial stress. Continuously during the test, the dome height is measured using a potentiometer, and the bulging pressure is measured using a pressure transducer. Fig. 2 shows the details of the geometrical features of the VPB test tooling. All symbols used in this paper are summarized in the nomenclature, given at the end of the paper.

3. Inverse analysis methodology for determining the flow stress curve

3.1. Isotropic materials

The methodology used for determining the flow stress of the sheet assumes that the material follows the Hollomon power law (Eq. (1)).

$$\bar{\sigma} = K\bar{\varepsilon}^n \tag{1}$$

The effective stress and strain equations from the classical membrane plasticity theory are used (Eqs. (2) and (3)). These equations are derived under the assumptions that the bulge (dome) shape is spherical and that the sheet thickness is small compared to the surface area so that the bending stresses can be neglected as discussed by (Gutscher and Altan (2004) in detail.

$$\bar{\sigma} = \sigma_r = \frac{p}{2}\left[\frac{R_d}{t_d} + 1\right] \tag{2}$$

$$\bar{\varepsilon} = -\varepsilon_t = -\ln\frac{t_d}{t_o} \tag{3}$$

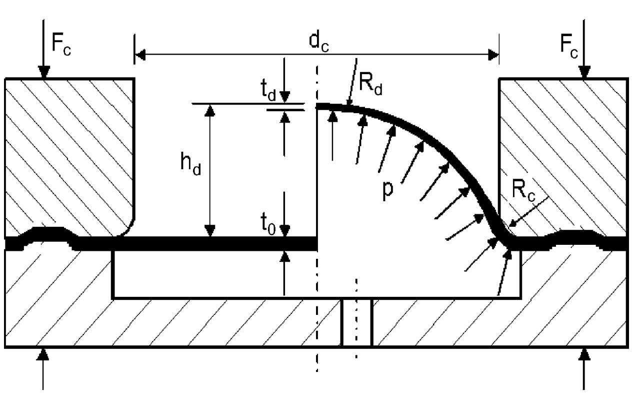

Fig. 2. Geometrical features of the VPB test.

In addition to the bulging pressure and dome height which can be easily measured in the test, Eqs. (2) and (3) above contain two other unknowns; the thickness and radius of curvature at the dome apex. To determine these unknowns, a series of FE simulations with different material properties (different n-value) were conducted using the commercial FE software PAMSTAMP to generate a database. This database shows how the thickness and radius of curvature at the dome apex change with the dome height. The Von-Mises yield criterion and the constitutive modeling of plasticity, outlined by (Hill, 1990) were used in the simulations.

An excel macro was then developed to iteratively determine the flow stress curve of the material using both the database and the experimental pressure vs. dome height curve. A flow chart describing the FE-based inverse analysis methodology is shown in Fig. 3. An initial guess of the n-value is made. Using the measured dome height and the database, the radius of curvature and thickness at the dome apex are calculated. Now that all the information needed are available, the membrane theory equations can be used to calculate the effective stress and strain. The power law is then used to represent the resulting curve. Another iteration is performed with a different n-value, and the process continues until the difference in the n-value between two subsequent iterations becomes less than or equal to 0.001. At this moment, the iterations are stopped, and the flow stress curve is extracted and reported.

3.2. Anisotropic materials

Since sheet materials are usually anisotropic (i.e. mechanical properties vary from one direction to another), the flow stress curve obtained in the bulge test may not be accurate if the material is assumed to be isotropic. Therefore in this study, the calculated flow stress curve using the methodology described in Section 3.1 was corrected for anisotropy. While Von-Mises yield criterion is used in the methodology described above, Hill (1990)'s anisotropic yield criteria is used in this section. Following is the correction factor used to correct for anisotropy:

$$\bar{\sigma}_{anis} = \sqrt{\frac{R_{90} + R_0}{R_{90}(R_0 + 1)}}\bar{\sigma}_{iso} \tag{4}$$