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Accurate characterization of biaxial stress-strain response of sheet metal from bulge testing

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ABSTRACT

A new method considering anisotropic deformation is developed to accurately calculate principal stresses and strains as well as the actual thickness at the specimen pole in circular bulge testing combined with digital image correlation techniques. The new method takes into account the elastic dilatancy and the bending effect when calculating the thickness at the specimen pole, the ratio of specimen thickness to the radius of curvature on the specimen outer surface and non-balanced biaxial curvatures in principal directions when calculating the effective stress at the specimen pole, which have been not considered in previous methods from literature including the ISO Standard (ISO 16808: 2014). The accuracy of the proposed calculation method is validated by circular hydraulic bulge testing for a 1.1 mm thick Al–Mg alloy and a 1.0 mm thick dual-phase steel. Accuracy is improved in comparison to previous methods described in the literature, which underestimate the thickness at the specimen pole and lead to an overestimation of stresses by up to 3% for the tested materials. In addition, attributed to the consideration of anisotropic deformation in the proposed method, the plastic strain ratio (also known as the r_b-value) in biaxial deformation is obtained as a function of equivalent plastic strain, which can be used to calibrate advanced anisotropic hardening models that allow for deformation-induced evolution of the yield surface shape.

1. Introduction

Satisfactory finite element (FE) simulation results depend on the accuracy of the input stress–strain curves. However, the maximum strains included in FE simulations often exceed the strain range of standard uniaxial tensile testing, in which accurate stress–strain measurement is restricted to the uniform deformation regime. These higher strains can arise from biaxial tension, tension–compression cycles, or in out-of-plane bending deformation that are common in metal stamping processes. Extrapolation of hardening behavior to extend the stress–strain curves beyond the limit of uniform strain introduces considerable uncertainty to the FE simulation results. Nevertheless, it has been acknowledged that the hydraulic (Hill, 1950; Young et al., 1981; Atkinson, 1997; Zhang et al., 2014; ISO 16808: 2014) or pneumatic (Siegert et al., 2003), viscous

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pressure (Gutscher et al., 2004) bulge testing is a convenient way to obtain stress–strain data over a larger strain range in biaxial deformation. Kuwabara and Sugawara (2013) used hydraulic tube expansion test to obtain stress vs. strain curves under biaxial tension. In a very recent report by Jeong et al. (2015), an elasto-viscoplastic self-consistent (EVPSC) analysis of X-ray diffraction measurements was first applied to Marciniak testing to characterize the biaxial flow stress during testing. Although there is no bending issue in Marciniak testing, the stress predicted by the EVPSC analysis of X-ray diffraction measurements still has significant deviation from that of hydraulic bulge testing.

The bulge test is also considered essential to calibrate advanced yield functions that require more than uniaxial tension measurements to fully define the model parameters and enable more realistic prediction of yield behavior under biaxial stress conditions. Some models that are able to account for anisotropic hardening require stress-strain data in both uniaxial and balanced biaxial conditions. In addition, the plastic strain ratio (e.g. the ratio of the plastic strain in transverse direction to that in rolling direction) can be obtained at the specific stress ratio or as a function of equivalent plastic strain in bulge testing, which is also critical to characterize the slope of the yield surface of sheet materials (Barlat et al., 2003; Yoon et al., 2004). Yet, with respect to the hardening behavior, it is an open question how to precisely obtain stress vs. strain data from bulge testing for sheet metals (Yoshida, 2013), especially for materials with significant anisotropy, since biaxial strain deformation is sensitive to planar anisotropy (Atkinson, 1997). In addition, there remains a limitation in bulge testing: the effect of bending at the specimen pole on the calculation of thickness and therefore the stress, cannot be avoided or ignored, and this effect becomes more pronounced as the dome height of the specimen increases.

In circular bulge testing, where the die cavity has axial symmetry, deformation is assumed to be balanced biaxial and bending curvature at the pole of the dome is assumed to be spherical in some early reports (Hill, 1950; Young et al., 1981; Atkinson, 1997). Then the biaxial stress, σ_b, is computed by Eq. (1) according to membrane theory (Hill, 1950; Young et al., 1981)

$$\sigma_b = \frac{p \cdot R^O}{2t} \tag{1}$$

where p is the internal pressure, R^O is the spherical radius on the outer surface, and t is the actual thickness at the specimen pole. p can be easily measured with a pressure gage. Therefore, there are two unknowns (i.e. R^O and t) in Eq. (1), and their measurement leaves two extremely critical issues to overcome for accurate characterization of the stress-strain behavior of sheet metals. Before the advent of digital image correlation (DIC) techniques, R^O was measured with a spherometer as illustrated in Fig. 1a (Young et al., 1981) and calculated by Eq. (2).

$$R^O = \frac{R_a^2 + h^2}{2h} \tag{2}$$

where R_a and h are the horizontal and vertical distances between the leg and displacement transducer of the spherometer, respectively. It is seen that the accuracy of R^O depends on the extent of deformation homogeneity within the range of $2R_a$ on the dome apex of the bulge specimen and the gage length of R_a (Yoshida, 2013). In regards to the sheet thickness, t, it is not simple to perform in-situ thickness measurement at the pole of the specimen during a bulge test, thus, several approximate methods were proposed to determine t. Yoshida (2013) combined an extensometer with a spherometer in order to measure strain on the outer surface of the bulge specimen in the direction perpendicular to the spherometer (Fig. 1b). Here, the biaxial strain (ε_b) is expressed by Eq. (3)

$$\varepsilon_b = \ln(L_\varepsilon / R_\varepsilon) \tag{3}$$

where R_ε is the gage length between the extensometer legs, and L_ε is expressed as

$$L_\varepsilon = R^O \cdot \arcsin \frac{R'_\varepsilon}{R^O} \tag{4}$$

where R'_ε is the length between the extensometer legs after deformation. Thickness at the pole, t, is then obtained from Eq. (5) by considering the incompressibility of plastic deformation and ignoring the elastic dilatancy,

$$t = t_0 \cdot \exp(\varepsilon_t) \tag{5}$$

where t_0 is the initial thickness of the specimen and the strain in thickness direction, ε_t, is $-2\varepsilon_b$ based on the assumption of balanced biaxial strain deformation. It should be noted that this equation only applies for in-plane stretching where the strain through the sheet thickness is uniform, but is only an approximation when the sheet is curved, as in the case of bulge testing.

Atkinson (1997) noted that the strain on the surface in the small area (e.g. $2R_\varepsilon$ in Fig. 1b) at the apex of a bulge specimen was not uniform, and that the actual thickness of the bulge specimen increased with an increase of distance between the