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Overview on constitutive modeling for hydroforming with the existence of through-thickness normal stress

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ABSTRACT

The hydroforming process is used widely across many industrial fields. High applied pressure during hydroforming makes it necessary to consider the influence of the through-thickness normal stress, while traditional approaches based upon a plane-stress assumption are not appropriate in such cases. Reliable constitutive models that consider the through-thickness normal stress are summarized in this paper, which focuses on the state of the art in the following several aspects: determine the flow stress curve with proper experimental methods and choose the measurement and computational methods to minimize the error as much as possible; select the proper three-dimensional anisotropic yield criterion for the specific material; Define the forming limit model and construct corresponding experimental verification method. The review of existing work has revealed several gaps in current knowledge of the hydroforming process accounting for the through-thickness normal stress. Conclusions are drawn concerning some critical issues and potential future developments in hydroforming modeling.

1. Introduction

The hydroforming process, which applies fluid pressure replacing the solid punch or die to the blank (either sheet or tube) to form component, is a well-known long established process that has been developed before World War II. In recent years, hydroforming is applied widely across many industrial fields, especially in automotive industries due to the attainable advantages as follows (Ahmetoglu and Altan, 2000):

(1) tight dimensional tolerances and low springback;
(2) low tooling cost due to fewer parts;
(3) high material utilization;
(4) few secondary operations;
(5) improved structural strength and stiffness.

However, the main drawbacks of hydroforming are the high equipment cost, long cycle time and lack of theoretical knowledge for process and tool design.

So far, many researches on the hydroforming process have been carried out, and finite element simulation is routinely used to predict metal flow and optimize the hydroforming process. To obtain reliable FE results, accurate constitutive models must be used as input. These include flow stress model that defines the effective stress versus effective plastic strain, the yield criterion that describes the yield behavior, and the forming limit model that estimates when and where the instability happens. During FE simulations, most researches regard the hydroforming process as a plane stress state. However, when the applied pressure is at very high level such as 200–300 MPa, larger through-thickness normal stress may arise on one or both sides of the sheet metal (Smith et al., 2003a,b) which plays a significant role in formability, the plane stress assumption may not be practical, and the constitutive models that are used traditionally in sheet metal forming simulation should be updated correspondingly.

In this paper, an overview on reliable constitutive models for the hydroforming process, which accounts for the influence of the through-thickness normal stress such as flow stress curve, yield criterion and forming limit model, is made in order to accumulate the knowledge and make the process simulation more accurate.

2. Flow stress curve determination by proper experimental methods

During metal forming process, the mechanical properties of deforming materials greatly influence metal flow and product quality. Therefore, the flow stress curve reflecting material work hardening behavior is indispensable for FE forming simulation. To obtain reliable FE simulation results, an accurate flow stress curve

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must be captured within large strain scope. Thus, a reliable and discriminating test is needed (Yadav, 2008).

The uniaxial tensile test, which is used to determine tensile strength, yield strength, elastic modulus, uniform elongation and total elongation, is one of the commonly used experimental methods because it is simple and inexpensive to implement. However, this method has clear limitations. The flow stress–strain data collection is limited by local necking during tensile process. It is reported that (Gutscher et al., 2004) with the standard tensile test, the true strain level can hardly reach 0.3. However, the strain range of hydroforming exceeds that value before necking occurs. One remedy is to use Bridgman's correction (Hosford and Caddell, 2007), which allows effective stress–effective strain data to be collected at large strain scope. However, if a necking appears too sharply, voids generated at the necking region may decrease the loading cross section. This method has not been used these years. During the uniaxial tension test, the onset of necking renders conventional extensometers inadequate since strain fields become variegated, the optical measurement method-DIC can be used to capture the strain response after necking. Grytten et al. (2009) developed a novel methodology including 3D DIC with two cameras and stereovision to determine full-field displacements during the uniaxial tensile test. The local strains were measured and the corresponding local stresses were calculated form the total load and the current cross sectional area. By doing this, the large-strain tensile properties for the materials were measured. For generic uniaxial tensile test whose stress–strain data is obtained by classical mechanical methods, an extrapolation is required to predict stress response undergoing large strain for FE simulations, and flow stress model such as Hollomon model, Ludwik model, Voce model, Ghosh mode and Swift model should be used to extrapolate the stress data at large strain from the stress–strain data obtained by the uniaxial tensile test. This may cause significant errors in process simulations. So the best way to obtain the accurate flow stress curve is to get the flow stress data at as large strain as possible by experiments.

In addition, during the hydroforming process, the material deforms under in-plane biaxial stretching condition. Under such condition, the true strain level may reach 0.7 or more. So it is better to determine the flow stress curve by experiments under biaxial tensile condition. In order to take into account the effect of the through-thickness normal stress, the hydraulic bulge test considering the normal pressure can be used to determine the flow stress curve accurately, and the effective stress model can be expressed as

$$\bar{\sigma}(\sigma_1, \sigma_2, \sigma_3) = f(\bar{\varepsilon}(\varepsilon_1, \varepsilon_2, \varepsilon_3)) \quad (1)$$

where $\bar{\sigma}$ is effective stress, σ_1, σ_2 and σ_3 are three principal stresses, $\bar{\varepsilon}$ is effective strain, ε_1, ε_2 and ε_3 are three principal strains.

2.1. Determination of flow stress curve for the sheet hydroforming process

For sheet hydroforming process, one of the best methods to determine the flow stress curve is viscous pressure bulge (VPB) test as shown in Fig. 1 (Gutscher et al., 2004), and the hydraulic medium is trapped between sheet and punch. When the punch moves upward, the medium is compressed to make the sheet deform.

According to the membrane theory (Rees, 1995) and Von Mises yield criterion, Gutscher et al. (2004) proposed effective stress and effective strain formulations that account for the through-thickness normal stress as follows:

$$\bar{\sigma} = \frac{p}{2}\left(\frac{R_d}{t_d} + 1\right) \quad (2)$$

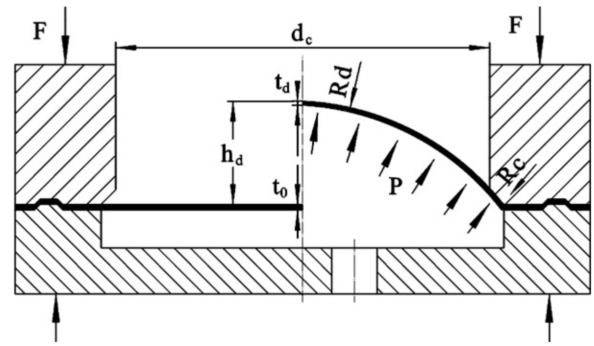

Fig. 1. Process parameters of viscous pressure bulge test (Gutscher et al., 2004).

$$\bar{\varepsilon} = \ln\frac{t_0}{t_d} \quad (3)$$

where R_d is the corresponding radius of the curved surface, p is hydraulic pressure, t_0 is initial thickness of the sheet or tube metal, and t_d is the thickness at the top of the dome.

These formulations considered the influence of the through-thickness normal stress on flow stress curve by defining the normal stress as the average pressure. By this means, Gutscher et al. (2004) investigated the VPB test experimentally, and the results showed that localized necking occurred at effective strains between 0.5 and 0.8, much larger than that in the uniaxial tensile test. However, the experimental data such as thickness and curvature were calculated by the geometric parameters approximately or measured directly by the classical mechanical methods (Santos et al., 2010). Using this method, even small variations of the measured height may lead to large variations in the radius. Keller et al. (2009) used the optical measuring system ARAMIS to measure the radius of curvature, thickness and strain at the dome apex and to calculate the corresponding effective strain and effective stress values. This method allows quick and accurate determination of the flow stress curve. Lazarescu et al. (2011) took into account the non-uniform distribution of the strains on the specimen surface and modified the computational formulations of effective stress and effective strain. In their study, the continuous pressure, bulge radius, polar thickness and flow stress curve measured by ARAMIS were used to validate the modified formulations. However, Koc et al. (2011) pointed out that the use of optical systems may not be accurate every time, especially at high temperatures due to the vapor and/or smoke issues.

Gutscher et al. (2004) did not consider the influence of anisotropy (R-value) on the hydroforming process, because Von Mises yield criterion is only suitable for describing isotropic plastic behavior, whereas the sheet metal generally exhibits significant anisotropy of mechanical properties due to the materials' crystallographic structure and the mechanism of the rolling process. So the effective stress–effective strain curve obtained above cannot properly express the mechanical properties of the anisotropic material unless the effect of R-value is considered.

Smith et al. (2009) proposed a new bulge formulation based on 2D Hill48 anisotropic yield criterion with a plane stress assumption. Compared with other methods in determining the flow stress curve, such as cruciform-biaxial, torsion, shear and moment-curvature, the bulge test is more reliable for diffuse necking regions. Nasser et al. (2010) suggested another bulge formulation based on Hill90 anisotropic yield criterion to obtain the flow stress curves of five advanced high-strength steel (AHSS) sheet materials.

However, the bulge formulations mentioned by Smith and Nasser did not take into account the effect of three-dimensional stress growing within the necked region. Therefore, in order to describe the flow stress behavior accurately for the case with high