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DETERMINATION OF FLOW STRESS BY THE HYDRAULIC BULGE TEST

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In sheet metal forming operations the mechanical properties of the sheet metal (stress-strain curve, flow stress) greatly influence metal flow and product quality. Accurate determination of the stress-strain relationship is important in process simulation by finite element method. In this paper the sheet thickness gradation in different points of the hemisphere formed in the bulge test is analysed, both theoretically and experimentally. A precise determination of sheet thickness at the pole is very important in the precise determination of stress-strain relationship. The use of the hydraulic bulge test for estimation of flow stress under biaxial stress-strain state is discussed.

Key words: hydraulic bulge test, flow stress, thickness distribution, DDQ steel sheet

Određivanje naprezanja tečenja hidrauličnim pokusom dubokog izvlačenja. U oblikovanju trake mehanička svojstva trake ($\sigma-\varepsilon$ dijagram, naprezanje tečenjem) značajno utječu na tečenje i kakvću proizvoda. Točno određivanje odnosa naprezanje-istezanje je važno u procesu simulacije metodom konačnih elemenata. Na pokusu dobijenim dubokim izvlačenjem analiziralo se i teoretski i eksperimentalno, po debljini trake i polukugli. Precizno određivanje po debljini trake je važno za odnos naprezanje-istezanje. Raspravljeno je rabljenje hidrauličkog pokusa dubokog izvlačenja za procjenu naprezanja tečenja za dvoosno stanje naprezanje-istezanje

Ključne riječi: hidraulički pokus dubokog izvlačenja, naprezanje tečenja, raspodjela debljina, DDQ čelična traka

INTRODUCTION

Uniaxial tension test is pure and simple; it introduces us to relevant material properties but bears little resemblance to an industrial sheet metal forming processes. In sheet forming operation biaxial as well as uniaxial stress state exists [1-2]. Thus, one must know and understand material hardening behaviour as a function of stress state.

Satisfactory modeling of sheet forming is dependent on availability of accurate data for plastic behaviour to the high strain level in such operations. Routine forecasts of formability could also benefit from this information. However, for some reasons, standard uniaxial tension tests cannot provide this data [3]:

- the range of stable uniform strain is restricted to less than half of that sustainable under biaxial stress,
- observable stress-strain relationships are, generally, imprecisely ascertained,
- variation of strain hardening behaviour is difficult to discern, but would obviously affect the probable extrapolation,
- biaxial strain deformation is sensitive to plastic anisotropy.

It is obviously desirable to generate the required data directly from biaxial strain test.

The hydraulic bulge test is widely used in determining the strain hardening properties of sheet materials in biaxial tension. In the bulge test, stress and strain can be determined up to failure of the specimen, while in the conventional uniaxial test only the uniform strain range can be utilized. Since the strains in press forming are normally larger then the uniform strain, the bulge test can better describe the plastic properties of a sheet metal at large strains. This is especially important in determining the stress-strain behaviour of sheets, which are in cold-rolled condition.

Hydraulic bulging has long been known as a convenient method for judging the ductility of sheet metal and it is an appropriate method for ascertaining biaxial stress-strain relationships because, provided that the die aperture is in order of a hundred times the sheet thickness, the only insurmountable drawback is some very

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slight bending; whereas other methods, employing cruciform of tubular specimen, induce local stress concentrations or necessitate prior deformation [4].

The aim of the present work was experimental and theoretical examination of sheet thickness distribution in hemisphere formed in hydraulic bulge test and to compare plastic behaviour of sheet material under uniaxial and biaxial tension.

HYDRAULIC BULGE TEST

Material data obtained from a uniaxial tensile test using sheet samples cannot be used for process development or simulation in hydroforming for the following reason: In the tensile test, the specimen is subjected to a uniaxial state of stress, which does not accurately reflect the state of deformation encountered in the deep drawing or the hydroforming processes (both tube and sheet), which subjects the material to a biaxial state of stress. For DDQ steel sheets, the flow stress determined using the hydraulic bulge test is much larger than the one determined by the tensile test Localized necking occurs for most materials in a tensile test at effective strains between 0,2 and 0,4. In bulge tests, localized necking occurs at effective strains between 0,5 and 0,8 (Figure 1).

To set the standards for material formability and expansion and to deliver reliable material data to the industry, the Department of Technologies and Materials at The Technical University of Košice has developed and implemented the biaxial bulge test. This test can be used to determine the formability of various materials, including aluminum alloys, stainless steels, carbon steels, brass, nickel alloys, etc.

Relatively, the high costs involved in developing the required equipment, such as an advanced pressurization and sealing system to pressurize the tube, a data acquisition system to monitor the experimental results, and a computer program to obtain the flow stress from the tests. The Department has developed cost-effective techniques that can determine material formability from biaxial tests for sheet. The basic system consists of a hard tooling set (Figure 2), hydraulic pressurization system, and data acquisition equipment. Because this system was intended for use by industrial and research institutions, simplicity was emphasized throughout the design process.

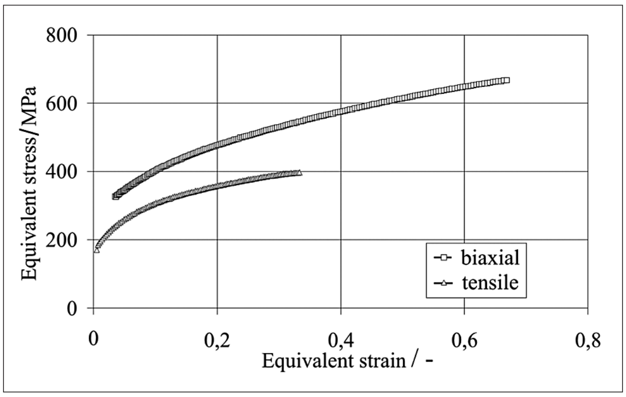

Figure 1. Uniaxial tensile and biaxial stress-strain curves of the DDQ steel sheet

Figure 2. Equipment for hydraulic bulge test

EXPERIMENTAL PROCEDURE

The bulge test consists of the following steps:

1. Expand the sheet metal with internal pressure while the edge of the sheet is held firmly to prevent axial movement.
2. Measure the internal pressure and bulge height continually during expansion.
3. Convert the data into true stress-strain data using analytical equations.
4. Use the least-squares method to fit the data into known and widely used equation forms to obtain a flow stress curve that is easy to use. The bulge tooling also can be used as a quality control tool. This test, which can determine the formability of sheet material quickly, is suitable for use on the shop floor for evaluating the quality of incoming material before it is released to production.

DATA COLLECTION AND ANALYSIS

The internal pressure (*Pi*) and bulge height (*hi*) of the sheet are measured continuously using a pressure sensor and linear potentiometer, respectively (Figure 2). The pressure sensor is located on one end of the rod holding the hydraulic cylinder, and the linear potentiometer is fixed on the upper die. The pressure and bulge height values are collected during the experiment with the help of HYDROTEST, a computer data acquisition system. The data is exported into SIGMALAB, the software developed at the Department of Technologies and Materials at The Technical University of Košice to analyze the measured data. This program calculates the true stress and true strain values, which then are curve-fitted into widely used forms of the flow stress curve shown in Equation 1. By using SIGMALAB, it is possible to determine the flow stress (true stress versus true strain) of the material accurately in the following forms:

$$\sigma = K.\varepsilon^{n} \quad (1)$$

Table 1. **Relationships for determining of thickness distribu-tion at the pole of bulge**

Model	Actual thickness calculation
Atkinson [3]	$s = \dfrac{R - \sqrt{R^2 - \dfrac{s_0 \cdot (C_0)^2}{2h}}}{2}$
Enikeev- Kruglov [5]	$s = s_0 \left(\dfrac{\sin\alpha}{\alpha} \right)^2$
Hill [6,7]	$s = s_0 \cdot e^{-\varepsilon_e}$
Marciniak [6,7]	$s = s_0 \left(\dfrac{x^2}{x^2 + h^2} \right)^2$
Isachenkov [6,7]	$s = \dfrac{s_0}{(1+\varepsilon_1)(1+K.\varepsilon_1)}$
Constancy volume law [7]	$s = \dfrac{x^2.s_0}{x^2+h^2}$
Jovane [7]	$s = \dfrac{x^2.s_0}{x^2+h^2}$

When the object of hydraulic bulging is to evaluate plastic properties of the sheet material, the strain distribution may not be ascertained by any method that requires presupposition of those properties.

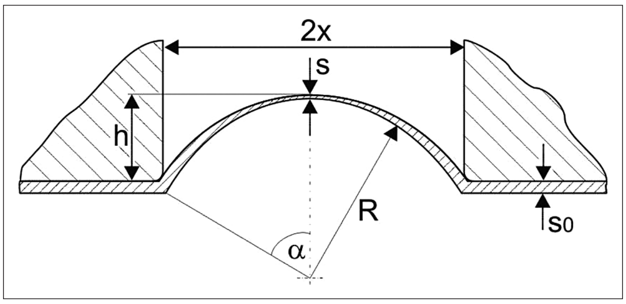

Figure 3. Geometric parameters of hydraulic bulge test study

Joint resolution of both bulging strains and material properties together is feasible, but it would require complex instrumentation to provide enough information for the computation. Therefore detailed geometric analysis of the measured central dome (Figure 3) appears to be most practicable method for calculating the local strain gradients of curvature.

Sheet thickness distribution in radial section of the dome was determined at different stages of bulging.

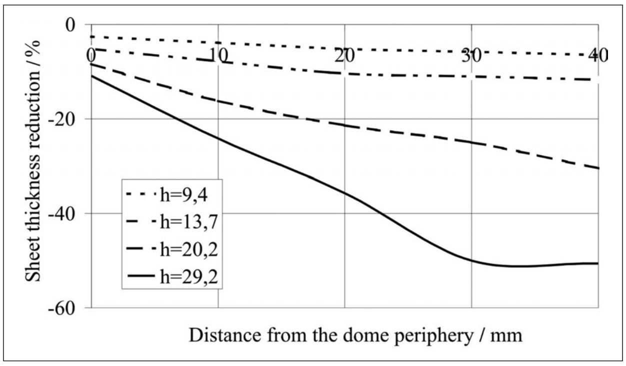

Figure 4. Sheet thickness distribution across radial section of bulged dome

Sheet thickness was measured in points marked on the sheet blank before testing. Difference in sheet thickness across the pole was observed from the beginning of bulging process (Figure 4) and it become more evident as bulging proceeds.

At first stage of hydraulic bulging sheet thickness at the pole decreases linearly with dome height increasing and this process starts to accelerate at the end of bulging, what is also the symptom of strain localization at the pole. In spite of different DDQ steel sheet initial thickness measured results of percentage thickness reduction are nearly the same. Measurements of sheet thickness in different points of the steel sheet hemisphere formed in bulging test (at the moment close to material failure) were compared with calculations using different models (see Table 1).

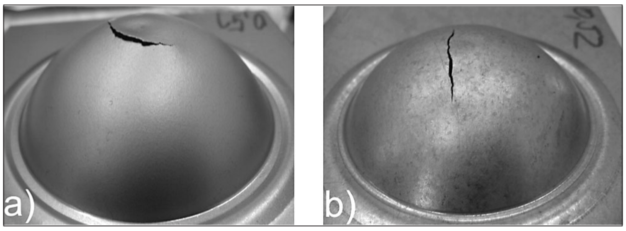

Figure 5. Bulge test samples of DDQ auto body steel sheet: a) isotropic, crack around the pole of bulge, b) anisotropic, crack in rolling direction

Figure 5 shows the tested samples of isotropic (IZ) and anisotropic steel sheets. Typical stress-strain curves of commonly used deep drawing quality auto body steel sheets with thicknesses from 0,8 - 0,83 mm are shown in Figures 7, 8 and 9, where: 1 – Marciniak model, 2 – Enikeev-Kruglov model, 3 – Isachenkov model, 4 – Hill model, 5 – Jovane model, 6 – model resulted from constant volume law (CVL) and 7 – Engineering curve.

As resulting from Figures 6, 7 and 8, none of compared analytical models is completely identical in full range of deformation with experimental results, but some of the models correspond with experiments, to a certain extent. Therefore, on the basis of experiments, the prediction of stress-strain curves was investigated by

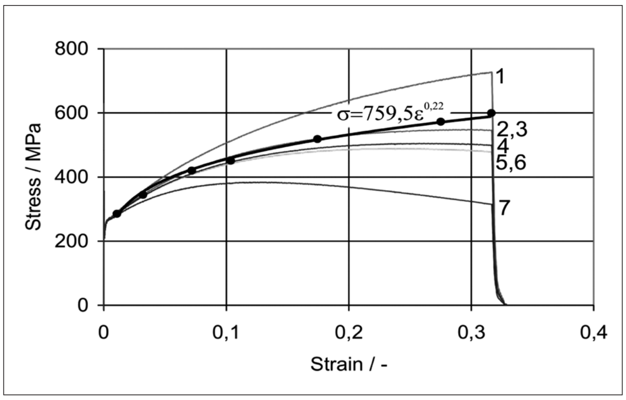

Figure 6. Comparison of experimental and calculated biaxial stress-strain relation of the DDQ autobody steel sheet, ZStE 220 IZ, 0,8 mm

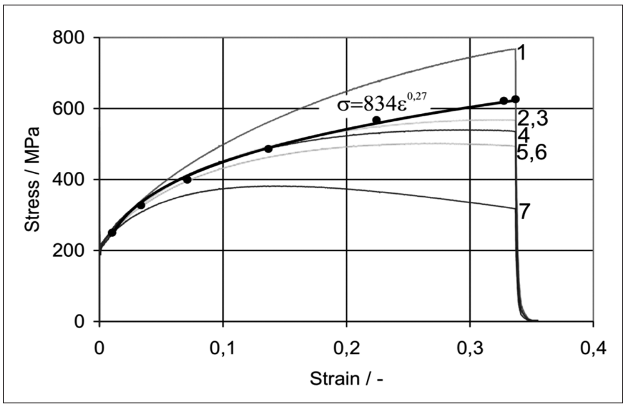

Figure 7. Comparison of experimental and calculated biaxial stress-strain relation of the EDDQ steel sheet, DC 05, 0,83 mm.

linear regression analysis. Accuracy of prediction was for the set of investigation auto body steel sheets very good, the *r* coefficients were in range from 0,96 to 0,99.

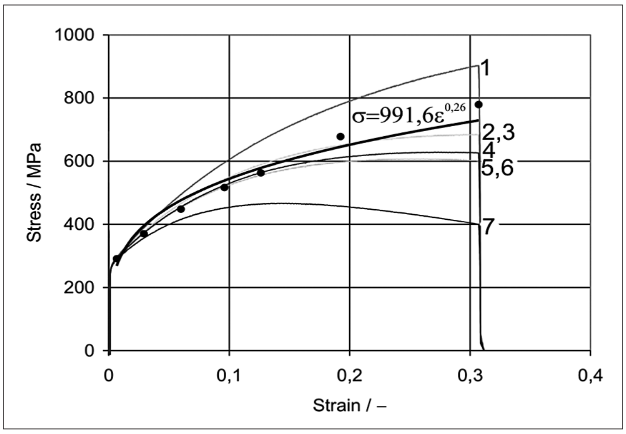

Figure 8. Comparison of experimental and calculated biaxial stress-strain relation of the DDQ autobody steel sheet, ZStE 220P, 0,8 mm

CAPABILITIES AND LIMITATIONS OF THE BULGE TOOLING

The tooling is set up for use with sheet metal of the following dimensions:

– Width: 130 mm

– Thickness range: up to 1.00 mm.

The data acquisition system comprises a pressure sensor and a computer data acquisition system. Internal pressure is recorded 30 times per second to measure the pressure precisely, which is used in the analytical equations.

The relevant specifications of the testing are:

Hydraulic pump: 25 MPa

Pressure sensor: 0-100 bar

Height sensor: incremental, range: 0-50 mm, precision 0,001 mm.

With analytical equations, flow stress data can be calculated simply by measuring the bulge height and internal pressure. The material data obtained from the bulge test is more accurate than the conventional uniaxial tensile test data and should be used for process simulation. The hydraulic bulge test also can be used in tube fabrication shops as a quality control tool for incoming material.

CONCLUSIONS

Sheet thickness distribution across radial section of bulged hemisphere is uniform. Precise determination of sheet thickness at the pole is very important in precise determination of stress-strain relationship, and it could be achieved using equations in Table 1. The analytical prediction models for determination of stress-strain curve were verified by experimentally measured values.

Since none of compared analytical models were completely identical in full range of deformation with experimental results, the experimental stress-strain curves were investigated by linear regression analysis with very good accuracy.

Equi-biaxial bulging was found to be very useful method for determining the strain hardening behaviour of the material at very large strains. The quasistable plastic flow range in the case of biaxial testing was twice larger than those under uniaxial tensile.

Calculation of biaxial stress-strain curve on the base of the results of uniaxial test was not satisfied, when both stress and strain level is concerned.

Because of visible difference in plastic flow under bulge test and uniaxial tensile, both of these two tests should be perform due to obtain material parameters needed for satisfactory modelling of sheet forming processes.

FUTURE WORK

– Hydraulic bulge test should be developed to be a “standard test” for determining the properties from different materials.

– Anisotropy effect needs to be studied and incorporated into the analytical method.

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Notation

σ – true stress / MPa
K – strength coefficient / MPa
n – strain-hardening exponent / -
ε – true strain / -
s – actual thickness / mm
s_0 – *initial thickness / mm*
h – height of sample dome / mm
x – half of die aperture (C_0=2x) / mm
R – radius of curvature / mm
α – half the angle subtended by a dome surfa - ce at its center of curvature / °

Note: Author is responsible as language lecture for English language