DETERMINATION OF MATERIAL PARAMETERS OF SHEET METALS USING THE HYDRAULIC BULGE TEST

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Abstract

Hydraulic bulging experiments are performed in order to evaluate the mechanical parameters of cold rolled steel (DC04) and aluminium alloy (EN AW 6016-T4) sheet materials. The biaxial yield stresses, and the biaxial anisotropy coefficients are derived from the biaxial stress-strain curves and the ratio between the strains in the transverse and in the rolling direction, respectively. The mechanical parameters resulted from the bulge test in combination with the results from the tensile tests are used to determine the yield loci of the two materials. The effect of the number of input parameters on the capability of the BBC 2008 yield criterion to predict the yield locus is also discussed in the paper.

Keywords: hydraulic bulge test, mechanical properties, yield surface

1 Introduction

The most commonly used tests for the determination of the biaxial yield stress are the biaxial tensile test of cruciform specimens [1-4] and the hydraulic bulge test. A review of biaxial tensile tests using cruciform specimens is presented in the papers [5, 6]. The disadvantages of this method are the complicated geometry of specimens as well as the complexity and high cost of the equipment. An alternative to this test is the hydraulic test.

The most important advantage of the hydraulic bulge test is the absence of the contact (and therefore of the frictional interactions) between tools and specimen in the area of interest, which simplifies the analytical solutions for the calculation of stress and strain, but also ensures the repeatability of the test. The hydraulic bulge test is the subject of many scientific papers and has been investigated by other authors such as Hill [7], who developed analytical models for the calculation of polar thickness and curvature radius. He neglected the influence of the fillet radii of the die. The accuracy of the formulas proposed by Hill has been improved by Chakrabarty [8] by taking into account the hardening effects. Furthermore, Shang [9] extended the formulas proposed by Hill in order to take into account the fillet radius of the die insert. Atkinson [10] also tried to improve the accuracy of the analytical predictions referring to the polar thickness and dome radius. Kruglov [11] developed a formula for the calculation of the polar strains. Banabic [12] developed analytical models for the computation of the pressure-time relationship for the bulging of both strain hardening and superplastic materials trough elliptical dies and Vulcan [13] and Banabic [14] for superplastic forming of aluminium sheets for the cone-cup test. Lăzărescu [15-17] developed analytical models for the determination of stress-strain curves using dies with circular and elliptical apertures. Koç [18] performed experimental studies for the

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assessment of the accuracy of some analytical models for the calculation of polar thickness and dome radius.

As the hydraulic bulge test is not yet a standardised experimental method, the authors of some recently published papers [19-21] dealt with the development of procedures for the evaluation and validation of the biaxial stress-strain curves resulted from the bulge test in combination with optical measurement.

In this paper, the hydraulic bulge test is used to determine the biaxial stress-strain curves and the variation of the principal strains. On the basis of the experimental results, the biaxial yield stress and the biaxial anisotropy coefficient are determined for a cold rolled DC04 steel and an EN AW 6016-T4 aluminium alloy. Finally, the material parameters obtained from the hydraulic bulge test in combination with parameters from the uniaxial tensile test are used to determine the experimental yield surface of the two materials.

2 Experimental materials and procedures

2.1 Materials

The tested materials in this paper are a cold rolled steel sheet of grade DC04 with the nominal thickness 0.85 mm and an aluminium alloy EN AW 6016-T4 with the nominal thickness 1 mm. **Table 1** and **Table 2** show the chemical composition of these materials.

Table 1 Chemical composition of DC04 steel [wt. %]

Material	C	Mn	P	S
DC04	0.08	0.4	0.03	0.03

Table 2 Chemical composition of EN AW 6016-T4 aluminium alloy [wt. %]

Material	Mn	Si	Fe	Cu	Mg	Cr	Zn
EN AW 6016-T4	0.2	1-1.5	0.5	0.2	0.25-0.6	0.1	0.2

2.2 Hydraulic bulge test

In the hydraulic bulge test, the flat specimen is firmly clamped on its contour between a blank holder and a die, **Fig. 1** (left side).

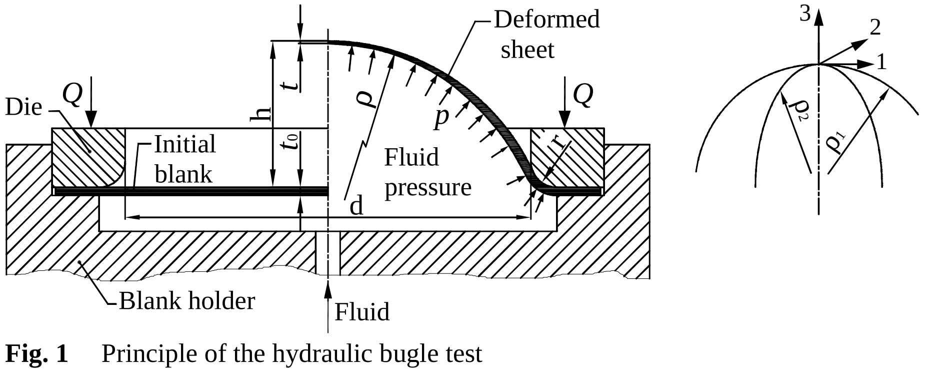

Fig. 1 Principle of the hydraulic bugle test

When the fluid, under uniform increasing pressure, gets into the hydraulic chamber, the blank is deformed through a die heaving a circular aperture with the diameter, d, **Fig. 1** (right side). The blank holder force (Q) should be high enough to avoid the radial slipping of the specimen during the test. The fracture occurs in the polar region of the specimen when the material strain exceeds its forming limit.

Fig. 2 shows a general view on the equipment used to perform the hydraulic bulge tests. This consists in a hydraulic device for the pressure development; a bulging device containing the die and a 3D optical measurement system ARAMIS. A die with an aperture diameter (d) of 80 mm and a fillet radius (r) of 5 mm was used to perform the bulge experiments. The hydraulic bulge tests were carried out with strain rate as 0.007 s^{-1} for the DC04 steel and 0.004 s^{-1} for the EN AW 6016-T4 aluminum alloy.

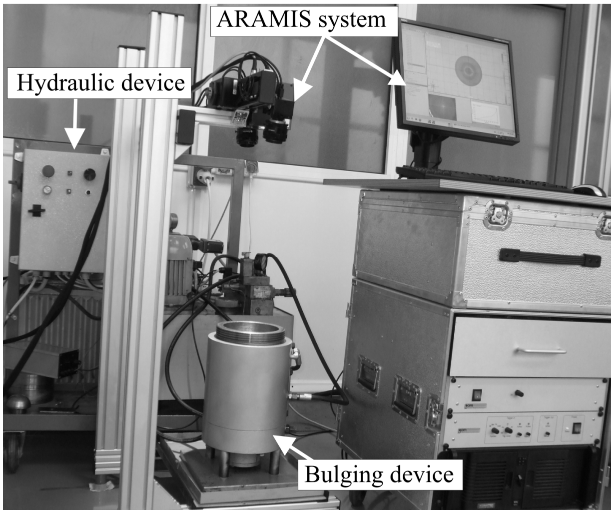

Fig. 2 Equipment for the hydraulic bugle test

The relationship used for the calculation of the polar stress is based on Laplace's equation from the membrane theory. For an axially symmetric element, under the action of uniform pressure (p) the equilibrium equation can be written as

$$\frac{\sigma_1}{\rho_1}+\frac{\sigma_2}{\rho_2}=\frac{p}{t}, \tag{1.}$$

where: σ_1, σ_2 [MPa] - principal surface stresses
ρ_1, ρ_2 [mm] - radii of curvature of the bulge in the two meridian sections (**Fig. 1**)
p [MPa] - hydraulic pressure
t [mm] - actual polar thickness of the specimen.

On the basis of the assumption that the material is isotropic and the shape of the deformed specimen is spherical, the bulge radius is the same in any meridian section $\rho_1 \cong \rho_2 = \rho$ and the polar stresses are also balanced $\sigma_1 \cong \sigma_2 = \sigma$ [22].

For a spherical membrane with a very small ratio between the radius of curvature and polar thickness it has been concluded that the meridian stress is much higher than the bending stress ($\sigma >> \sigma_i$), and therefore the effect of bending can be neglected [23].

In the membrane theory, the normal component of the stress is also neglected. Therefore the equivalent stress, also called biaxial stress (σ_b), can be calculated using the equation

$$\sigma_b = \frac{p\rho}{2t}\,. \tag{2.}$$

By assuming that the material is incompressible, and the shape of deformed specimen is spherical, the biaxial strain (ε_b) is equal to the true thickness strain in the polar region. Therefore the equation used for the calculation of biaxial strain is

$$\varepsilon_b = \ln(t / t_0)\,, \tag{3.}$$

where: t_0 [mm] - the original sheet thickness.

The biaxial stress in Eq. (2) can be calculated on the basis of three variables: the internal pressure, recorded during the experiment using a pressure gauge; the bulge radius and the average thickness determined using the ARAMIS system.

2.3 Tensile test

The tensile tests were performed using a Zwick Roell Z150 testing machine, which is equipped with an extensometer to measure the strains in two directions of the specimen. The stress-strain curves, the yield stress and the anisotropy coefficients were determined for specimen cuts from the sheet at 0°, 45° and 90° angles measured from the rolling direction. The uniaxial tension tests were carried out at strain rate of 0.001 s^{-1}. The data obtained from the tensile test will be used for the calculation of the biaxial yield stress and the yield loci, as it will be presented in the following paragraphs.

3 Results and discussion

3.1 Determination of the biaxial yield stress

In order to determine the biaxial yield stress from the hydraulic bulge test, the principle of the equivalent plastic work was used. The plastic work per unit volume is the area under the stress-strain curves in **Fig. 3** [24].

$$W_b = \int \sigma_b \cdot d\varepsilon_b \ \text{ and } \ W_u = \int \sigma_u \cdot d\varepsilon_u\,, \tag{4.}$$

where: W_b, W_u [mJ/mm^3] - the plastic work per unit volume for the biaxial and uniaxial tension cases, respectivelly
σ_b, σ_u [MPa] - the values of the biaxial and uniaxial stress, respectivelly
$d\varepsilon_b$, $d\varepsilon_u$ [-] - logarithmic plastic strain increment for the biaxial and uniaxial tension cases, respectivelly.

On the bases of the plastic work equivalence principle, the yield stresses of the same material, one from the biaxial test (YS_b) and the other from the uniaxial tensile test (YS_0), are identical only if the plastic work per unit volume are equal to each other ($W_b = W_u$), **Fig. 3** [25].

In order to obtain the biaxial yield stress, the biaxial stress - strain curves were compared to the curves obtained from the uniaxial tensile tests at 0° degrees from the rolling direction. The ratio (YS_b /YS_0), was determined for each specimen over a strain range, and the average ratio was computed.

For the DC04 material, 3 biaxial stress-strain curves from the hydraulic bulge test and 10 uniaxial stress-strain curves were used. Examples of stress-strain curves for the DC04 material are shown in **Fig. 4** from the hydraulic bulge test and in **Fig. 5** from the uniaxial tensile test.

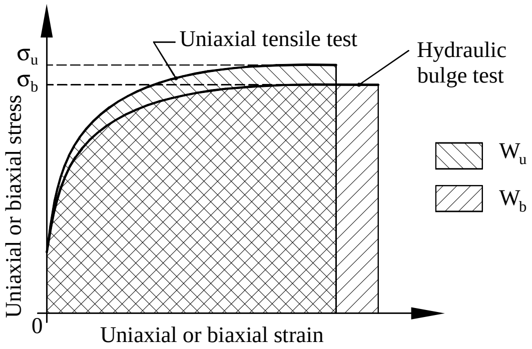

Fig. 3 Principle of the equivalent plastic work

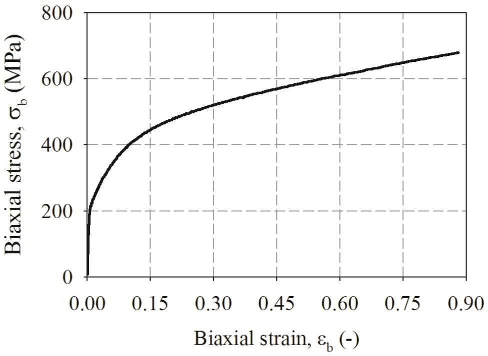

Fig. 4 Biaxial stress - strain curve obtained from the bulge test for the DC04 material

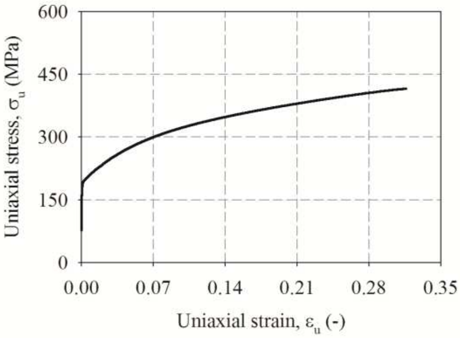

Fig. 5 Stress - strain curve obtained from the uniaxial tensile test for the DC04 material

By combining these curves, 30 ratios YS_b /YS_0 were obtained. **Fig. 6** shows an example of variation of YS_b /YS_0 - ratio with the increase of the uniaxial strain. The computed average value of the YS_b /YS_0 is 1.280. By multiplying this value with the value of uniaxial yield stress (YS_0) from **Table 3**, the biaxial yield stress was obtained (YS_b = 249.72 MPa).

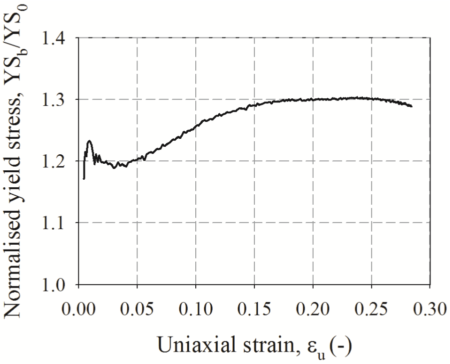

Fig. 6 Normalised yield stress for the DC04 material

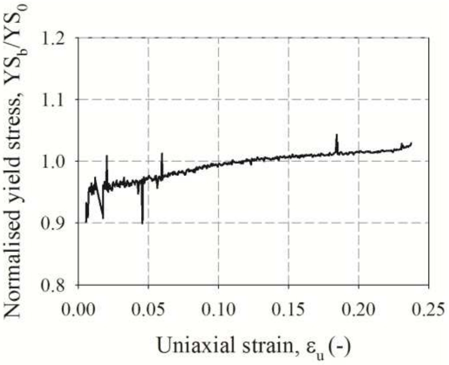

Fig. 7 Normalised yield stress for the EN AW 6016-T4 aluminum alloy

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For the EN AW 6016-T4 aluminium alloy, 7 biaxial stress-strain curves from the hydraulic bulge test and 7 uniaxial stress-strain curves were used. Examples of stress-strain curves for the EN AW 6016-T4 aluminium alloy are shown in **Fig. 8** from the hydraulic bulge test and in **Fig. 9** from the uniaxial tensile test. **Fig. 7** shows an example of variation of the normalised yield stress (YS_b /YS_0) for the EN AW 6016-T4 aluminium alloy. The computed average value of the YS_b /YS_0 - ratio is 1.012, and the biaxial yield stress is 140.76 MPa. The results are summarised in **Table 3**.

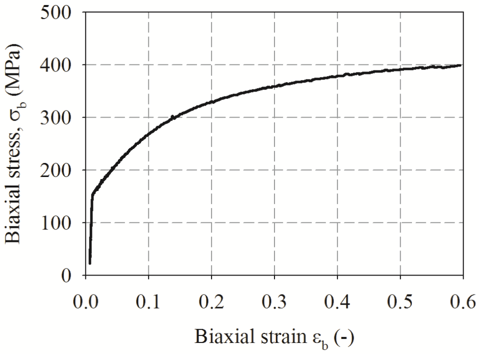

Fig. 8 Biaxial stress - biaxial strain curve obtained from the bulge test for the EN AW 6016-T4 aluminum alloy

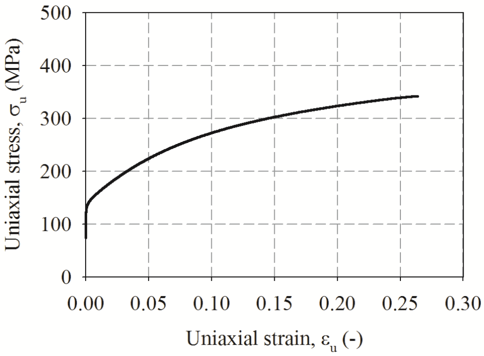

Fig. 9 Stress - strain curve obtained from the uniaxial tensile test for the EN AW 6016-T4 aluminum alloy

The high value of YS_b /YS_0 -ratio for the DC04 material, in **Table 3**, can be explained by the material anisotropy. As can be seen in **Table 4**, the DC04 steel shows much higher values of anisotropy coefficients than the unity.

Table 3 Yield stresses obtained from tensile tests and hydraulic bulge tests

Material	YS_0 [MPa]	YS_b/YS_0 - average	YS_b [MPa]
DC04	195	1.280	249.72
EN AW 6016-T4	139	1.012	140.76

3.2 Determination of biaxial anisotropy coefficients

The biaxial anisotropy coefficients are determined as an average value of the $\varepsilon_{TD}/\varepsilon_{RD}$ ratios obtained from a domain in which this ratio is as uniform as possible. This domain is usually after the initialization of straining, and before the necking of the specimen. The biaxial anisotropy coefficient (r_b) is defined by

$$r_b = \frac{\varepsilon_{TD}}{\varepsilon_{RD}}, \tag{5.}$$

where: ε_{RD} [-] - the logarithmic strain in the rolling direction

ε_{TD} [-] - the logarithmic strain transverse to the rolling direction.

In order to find the range on which the ratio between the ε_{TD} and ε_{RD} are uniform, this ratio was plotted as a function of the strain in the rolling direction (ε_{RD}) expressed in percents as shown in **Fig. 10** for the DC04 and in **Fig. 11** for the EN AW 6016-T4, for five and three experiments, respectively.

The uniform domains of $\varepsilon_{TD}/\varepsilon_{RD}$ ratios are between 10 and 40 % and between 10 and 30% from the strain in the rolling direction for the DC04 steel sheet and for the AA6016-T4 aluminum alloy sheet, respectively. The calculated average values are 0.957 and 1.050, respectively. These values are given in **Table 4**.

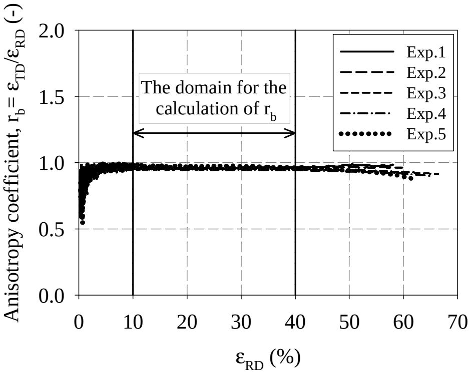

Fig. 10 Variation of r_b with the increase of ε_{RD} for the DC04 material

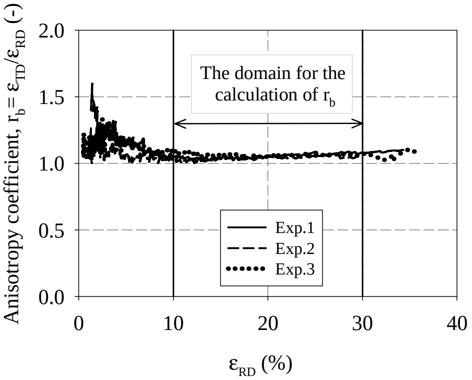

Fig. 11 Variation of r_b with the increase of ε_{RD} for the EN AW 6016-T4 aluminum alloy

3.3 Determination of the yield locus

In order to calculate the yield locus for the tested sheet materials, the BBC2008 yield criterion was used [26]. The material parameters used as input in the BBC2008 identification procedure are shown in **Table 4**. These parameters are:

- The ratio between the yield stress obtained from the uniaxial tensile tests along the directions defined by 0°, 45° and 90° degrees measured from the rolling direction and the yield stress at 0°. These ratios are denoted as YS_0, YS_{45} and YS_{90}.
- The ratio between the biaxial yield stress and uniaxial yield stress at 0° from the rolling direction. This ratio is noted as YS_b in **Table 4**.
- The anisotropy coefficients along the three directions (r_0, r_{45} and r_{90}) obtained from the uniaxial tensile tests.
- The biaxial anisotropy coefficient, r_b.

In **Table 4**, k = 3 for CVC materials and k = 4 for CFC materials.

The calculated BBC 2008 yield loci are shown in **Fig. 12** for the DC04 material and in **Fig. 13** for the EN AW 6016-T4 aluminum alloy. Discrete experimental points are also plotted on these diagrams.

Two identification cases of the BBC 2008 yield criterion were superimposed on the graphical representation of the yield loci, namely, with 8 and 6 material parameters. In the second case, the biaxial plasticity characteristics were not used for identification. As shown on the diagrams, the absence of these parameters negatively affects the quality of predictions provided by the BBC 2008 yield criterion. Both for the DC04 steel and the EN AW 6016-T4 aluminum alloy, the surface obtained with only 6 parameters underestimates the strength in the biaxial area. The deviations are quite large for the DC04 steel. The use of an inaccurate description of yield surface in the numerical simulation of a forming process will provide results affected by errors.

From these diagrams, it can be concluded that the material parameters obtained from the hydraulic bulge test are very important for an accurate prediction of the yield locus.

Table 4 Material parameters used as input in the BBC 2008 yield criterion for the calculation of yield locus

Material	YS_0	YS_{45}	YS_{90}	YS_b	r_0	r_{45}	r_{90}	r_b	k
DC04	1	1.067	1.048	1.280	1.955	1.299	2.192	0.957	3
EN AW 6016-T4	1	0.985	0.979	1.012	0.648	0.530	0.640	1.050	4

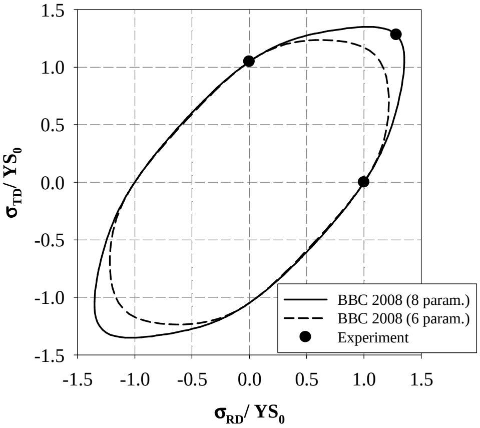

Fig. 12 Normalized yield locus predicted by the BBC2008 model for the DC04 material

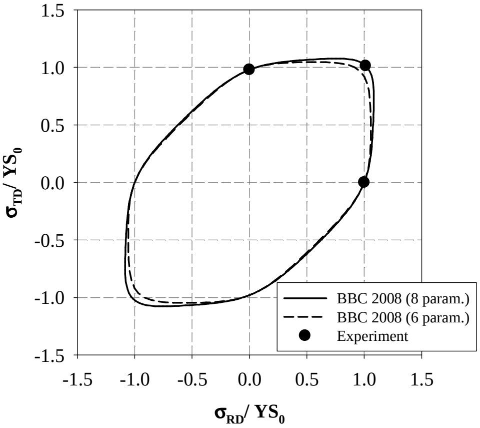

Fig. 13 Normalized yield locus predicted by the BBC2008 model for an EN AW 6016-T4 aluminum alloy

4 Conclusions

From the obtained results it can be concluded that the material parameters provided by the hydraulic bulge test are very important for an accurate prediction of the yield surface.

Both for the DC04 steel and the EN AW 6016-T4 aluminum alloy, the prediction of the yield surface obtained in the absence of the biaxial plasticity characteristics (identification with only 6 parameters) underestimates the strength stress in the biaxial area, and the deviation is higher in the case of the DC04 material.

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