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Experimental and analytical evaluation of the stress-strain curves of AA5754-T4 and AA6061-T6 by hydraulic bulge test

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Abstract

The hydraulic bulge test can be used as a means to achieve large uniform plastic strains under biaxial stress conditions, applied to hardening curve determination of sheet metal materials. The larger information on hardening behaviour is the reason why a mechanical characterization system has been developed to determine stress-strain curve by reading bulge test variables: bulge pressure (p), radius of curvature (ρ) and pole thickness (t). The determination of stress-strain curve may be based on continuous data acquisition from bulge test results (p, ρ, t) or from the use of analytical equations relating these variables with dome height. In this paper it is presented a study comparing different methodologies to obtain stress-strain curve by means of analytical methodologies relating "dome height with pole thickness" evolution. It is shown that these existent methodologies to determine pole thickness don't apply when compared with experimental values and they show an evident dispersion among them. Therefore a better analytical methodology is proposed and tested. The study and corresponding material characterization is applied to two aluminium alloys, AA5754-T4 and AA6061-T6, currently used in automotive industry.

Keywords: Aluminium alloy; sheet metal characterization; bulge test; thickness evolution.

1. Introduction

1.1. Background

Nowadays sheet metal forming processes are strongly dependent on design and optimization by finite element analysis (FEA) and this topic is a key factor on improving quality, as well as reducing development time and costs. Besides the challenges of using new materials and dealing with corresponding non-traditional material behaviours there is a need for higher accuracy on results. The accuracy and reliability of numerical results depend, on other hand, on mechanical modelling of the material, on selected material model and the accuracy of corresponding parameters, being tuned with appropriated experimental data.

Commonly, the stress-strain curves of sheet metal materials are obtained using the uniaxial tensile test, which is a widely accepted method. However, this test has some limitations, such as lower values of uniform strain range, when compared to formability limits of the material achieved in sheet metal forming processes.

Since the mechanical characterization of the material behaviour is a critical input on numerical models, the accuracy of material models get restricted by the limited amount of experimental strain data of tensile test.

An alternative and complementary method to obtain additional information on material behaviour for higher plastic strain levels is using the hydraulic bulge test [1]. This experimental test is known for its ability

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to plastically deform the material to higher strain levels, mainly due to the presented state of biaxial stress and the absence of friction between the material and the tools.

To obtain the stress-strain curve of hydraulic bulge test, a continuous measurement of some bulge variables is needed, such as bulge pressure, the sample curvature and also the thickness at the pole. The experimental system gives directly the bulge pressure, but the curvature and the thickness of the sample can be obtained by indirect methods based on analytical expressions, which are presented and studied in this paper, or by direct methods. Also, there are two possible approaches that can be used in direct methods: mechanical and optical measurements.

In this work a comparison of analytical methodologies and its evaluation with experiments is presented, which gives the basis for a proposal of a new methodology and new equation for thickness evolution, in order to extend bulge continuous data up to fracture.

1.2. Theory for stress and strain measurement

The determination of the biaxial stress-strain behaviour using the experimental data acquired by hydraulic bulge test takes into account the membrane theory [2]. The ratio between bulge diameter and sheet thickness must be higher than 50 [3], so that it remains in the applicability domain of the membrane theory and therefore bending effects may be neglected. Through thickness stress at the pole on the force equilibrium is also neglected and thus it is possible to establish a relationship between stresses, hydraulic pressure, sample geometry and thickness by the following expression [4]:

$$\frac{\sigma_1}{\rho_1}+\frac{\sigma_2}{\rho_2}=\frac{p}{t} \qquad (1)$$

in which σ_1 and σ_2 are the principal stresses in the sheet plane and ρ_1 and ρ_2 the corresponding radius of curvature. The variable p relates to hydraulic bulge pressure and t to sheet metal thickness.

The principal stresses, σ_1, σ_2, can be assumed equivalent under isotropic assumptions defining equibiaxial stress state at the pole ($\sigma_1 = \sigma_2 = \sigma_b$). The same applies to radius of curvature where $\rho_1 = \rho_2 = \rho$. Therefore, Eq. 1 can be simplified and flow stress can be determined by:

$$\sigma_b=\frac{p\cdot\rho}{2\cdot t} \qquad (2)$$

For the acquisition of radius of curvature and thickness at the pole a mechanical system is used as shown in Fig. 1, thus allowing the determination of these variables during the test. The calculation of radius of curvature makes use of a simple geometric construction given by:

$$\rho=\frac{\left(D_{cv}/2\right)^2+h^2}{2\cdot h}-\frac{t}{2} \qquad (3)$$

where D_{cv} is the diameter defined by spherometer and h is the difference between the spherometer support and displacement transducer as presented in Fig. 1; a correction is performed for half thickness of sheet, since the calculation is done for external surface of the cap. The current thickness (t) of the sample can be obtained through Eq. 4, knowing the initial thickness (t_0) and the current thickness strain ε_t.

$$t=t_0\cdot\exp(-\varepsilon_t) \qquad (4)$$

Considering incompressibility of the material, the thickness strain can be obtained as follows:

$$\varepsilon_t=-(\varepsilon_1+\varepsilon_2) \qquad (5)$$

As for stresses and radius of curvature, the strains at the plane are also considered the same and therefore the strain in thickness direction is given by:

$$\varepsilon_t=-2\cdot\varepsilon \qquad (6)$$

where ε is the membrane strain.

The determination of membrane strain is performed by measuring the expansion of a circle with an initial diameter of D_{st0}. This measurement is performed by an extensometer, which follows the deformation of sheet metal sample during the bulge test. Since the diameter of the circle increases to a diameter D_{st}, the current thickness strain can be obtained by:

$$\varepsilon_t=-2\cdot\ln\left(\frac{D_{st}}{D_{st0}}\right) \qquad (7)$$

2. Experimental Methodology

The developed mechanical characterization system consists of 4 different components (Fig. 1) in order to obtain test data from bulge test [6]:

- pressure transducer;
- spherometer;
- extensometer;
- displacement transducer.

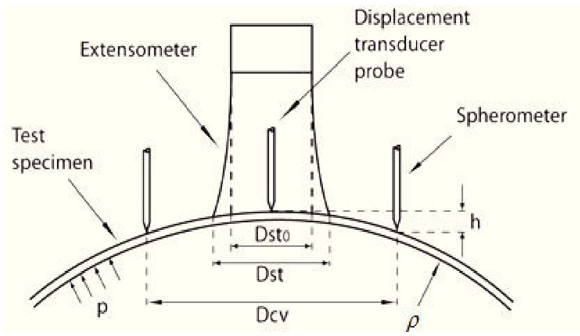

Fig. 1. Variables used for evaluation of stress and strain.

Due to extensometer characteristics and uncertainty of its robustness, the strain acquisition isn't performed until the rupture of the sample, due to the oil "explosion" at the time of sample fracture. The experimental tests run in two steps:

- performing a first experiment to burst the sample, thus obtaining the burst pressure, the total height sample, the radius of curvature and measuring the final thickness at the pole of the sample; only extensometer is not used and other components have enough robustness to oil burst. Final thickness at the pole is measured by using a micrometre;
- performing a second test until pressure reaches values between 90 and 95% of the burst pressure and obtaining values of pressure, the total height, the radius of curvature and thickness evolution (strain).

In this methodology, the remaining 10% until the rupture of the sample represents around 30% of thickness evolution and strain information. In order to complete the remaining information analytical methodologies are used to obtain the thickness evolution at the pole of the sample.

3. Analytical Methodology

3.1. Analysed methodologies

The determination of thickness evolution at the pole can be done using the analytical expressions which relate the evolution of thickness (t) with increasing total height (h_t) of the sample. The equation proposed by Hill for evolution of the thickness assumes that the deformation on the sheet surface is the same in all directions [7,9]:

$$t = t_0 \left(\frac{1}{1 + \left(2 \cdot h_t / d_m\right)^2} \right)^2 \qquad (8)$$

Previous equation suggested by Hill was improved by Chakrabarty and Alexander introducing into the equation the material hardening coefficient, n (n being obtained from tensile test data):

$$t = t_0 \left(\frac{1}{1 + \left(2 \cdot h_t / d_m\right)^2} \right)^{2-n} \qquad (9)$$

Panknin [10] investigated the influence of strain hardening coefficient. The results showed a significant influence on thickness evolution with total height of the pole, i.e., the higher the strain hardening coefficient the smaller is the thickness reduction to the same total height of the pole. Later, Kruglov proposed an analytical expression based on the same principle of Hill but the evolution of the thickness being dependent on the geometry of the bulge die diameter (d_m) and radius (r_c) [8,11]:

$$t = t_0 \left(\frac{\sin \alpha}{\alpha} \right)^2 \qquad (10)$$

where α :

$$\alpha = \arcsin \left(\frac{r_c + d_m/2}{h_t/2 + \frac{1}{2 \cdot h_t}\left(r_c + d_m/2\right)^2} \right) \qquad (11)$$

Lazarescu and Banabic also studied the equation proposed by Kruglov and concluded that it could be improved taking into account the non-uniformity deformation along the sample meridian. Thus, Lazarescu proposed a correction factor, C, which included the value of the final thickness and the total height of pole sample [11]:

$$C = \left(\ln \sqrt{\frac{t_0}{t_f}} - \ln \frac{\alpha_{max}}{\sin \alpha_{max}} \right) \Big/ \left(\alpha_{max} \ln \frac{\alpha_{max}}{\sin \alpha_{max}} \right) \qquad (12)$$

where t_f is the final thickness of the bulge sample which correspondent to α_{max}:

$$\alpha_{max} = \arcsin \left(\frac{r_c + d_m/2}{h_{t,max}/2 + \frac{1}{2 \cdot h_{t,max}}\left(r_c + d_m/2\right)^2} \right) \qquad (13)$$

where $h_{t,max}$ is the total height of the sample at the end of the test. The Eq. 10 by Kruglov, when applied with Lazarescu correction factor comes:

$$t = t_0 \left(\frac{\sin \alpha}{\alpha} \right)^{2\cdot(1+c\cdot\alpha)} \tag{14}$$

Eqs. 8 to 10 and 14 are shown in Fig. 2 and reflect the evolution of thickness with increasing of total height of the sample. This is applied to a steel, thus showing the possibility of improvements on existing methodologies for determination of thickness evolution. The proposed approach will use the available experimental data, thus being fully accurate (on such data) for any material and getting a closer approximation curve on interpolation to final available experimental point.

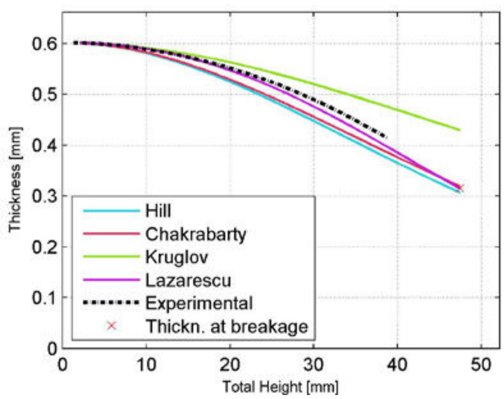

Fig. 2. Comparison of methodologies for determining the thickness for DP590.

By analysing these methodologies it is noticeable that improvements could be made in order to better predict the thickness evolution as function of total height.

3.2. Proposed methodology

The proposed methodology and equation to obtain the thickness evolution with pole height, until the sample breakage, is based on the experimental methodology, presented in section 2 of this article. The strain data from the extensometer provides values up to 90% of the burst pressure which is used to adjust a function defined by Eq. 15, in which all experimental data are considered, including the final thickness point.

$$t = a \cdot h_t^{\,b} + c \tag{15}$$

The corresponding results are presented in Fig. 3 and it is shown that a close adjustment of fitting and experimental curves is obtained.

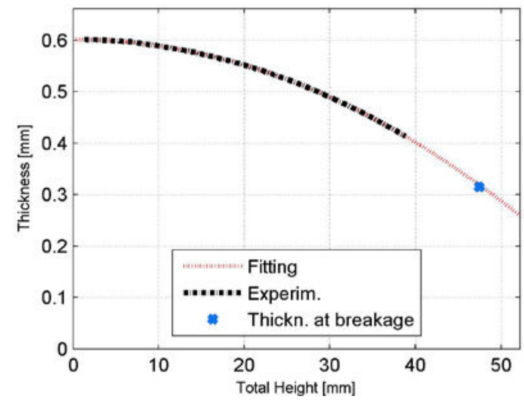

Fig. 3. Results from adjusting parameters from Eq. 15, for DP590.

4. Experimental Application

In this article two aluminium alloys - AA5754 and AA6061 were tested and the corresponding results for fundamental variables are presented in Table 1. These variables are then used to evaluate the methodologies presented on previous section.

Table 1. Data used in analytical equations for thickness evolution

Material	AA5754	AA6061
t_0 (mm)	0.991	1.041
t_f (mm)	0.657	0.747
n	0.21	0.15

As seen in Figs. 4 and 6, the proposed fitting curves describe properly the evolution of thickness for AA5754 and for AA6061.

Concerning the obtained stress-strain curves (Figs. 5 and 7), it can be seen that the extended data from fitting curves up to fracture still gives a very large amount of information (strain higher than vertical lines) on material characterization.

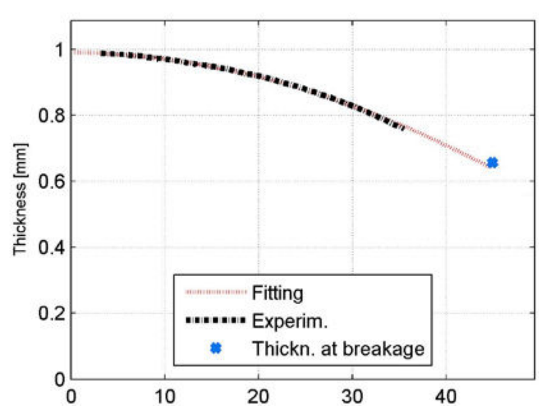

Fig. 4. Fitting equation for thickness evolution using proposed methodology, for AA5754.

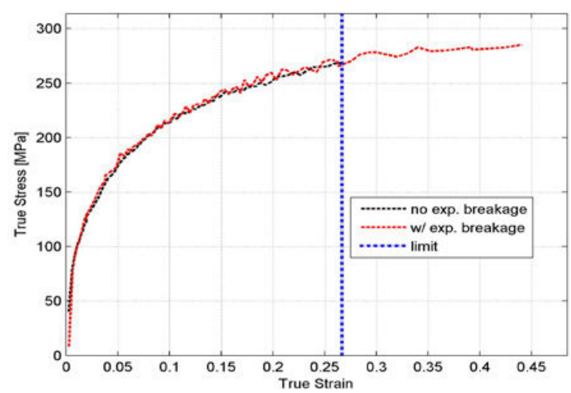

Fig. 5. Biaxial stress-strain determination for AA5754, using experimental strain data and proposed fitting equation.

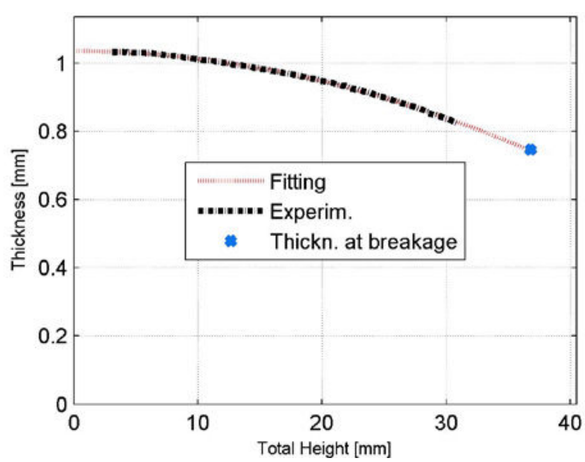

Fig. 6. Fitting equation for thickness evolution using proposed methodology, for AA6061.

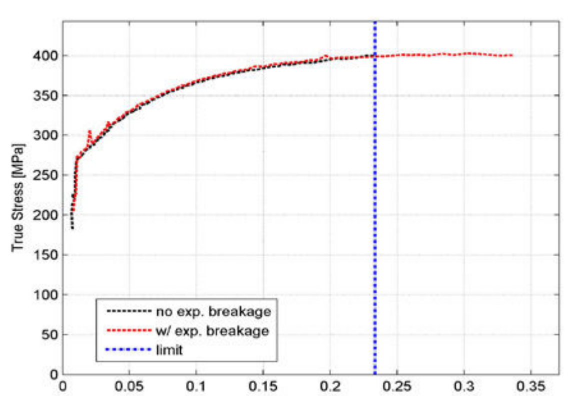

Fig. 7. Biaxial stress-strain determination for AA6061, using experimental strain data and proposed fitting equation.

5. Conclusions

The hydraulic bulge test represents an alternative and complement to the uniaxial tensile test for hardening curve determination of metallic materials, allowing higher strain values evaluation before necking. Evolution equations are studied and it is shown that current analytical equations to predict thickness evolution could be improved in order to give higher accuracy results. A proposal is presented which is coupled with a bulge test methodology for the evolution of thickness evolution which allows accurate extended results to characterize the material behaviour until the breakage of the sample. The current results are capable of being converted in effective stress-strain curve in order to improve the prediction of the material behaviour.

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