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Strain hardening evaluation by bulge testing of sheet metals*

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The sheet metals under biaxial tension can withstand much higher strain levels without local necking or fracture than in the tensile testing. Various techniques are known for testing in this state. In the hydraulic bulge test a flat sheet specimen is deformed into dome under out-of-plane biaxial stretching and both the strains and the stresses can be defined. This test is used both flow curves and forming limit diagrams to be found, but only a part of specimen around the pole is usualy employed. The paper represents work hardening curves evaluation using data for specimen areas out of pole by means of coordinate grid method for strain determination.

1. INTRODUCTION

The sheet metals under biaxial tension conditions can withstand much higher strain levels without local necking or fracture than in the tensile testing. Moreover, the biaxial stretching is a common strain state in many sheet forming operations. Three main techniques are known for testing in this state. The Marciniak's double blank draw test subjects the specimen to in-plane biaxial tension [1, 2] but does not determine the stresses and it is used for forming limit and sheet quality estimation. The cross tensile test [3-5] allows both balanced and unbalanced in-plane biaxial stretching but an optimised cruciform specimen is required and it should be loaded by special equipment. By now this technique has been applied mainly for the yield surfaces evaluation. In the hydraulic bulge test [6, 7] the specimen is deformed into dome under out-of-plane biaxial tension and both the stresses and the strains can be defined. This test is used both flow curves and forming limit diagrams to be found but only a part of specimen around the pole is usualy employed using not only circular but also elliptical [8, 9] die apertures to involve a greater variety of the principal strain ratios. This paper represents analytical solution and some preliminary experimental results for strain hardening curves evaluation using data for specimen areas out of pole. Circular bulge testing of isotropic sheet metals is under consideration here. The coordinate grid method has been applied for strain determination over the dome.

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2. ANALYTICAL BACKGROUND

In the case of isotropic sheet metals and circular dies the pole of the dome is in balanced biaxial stretching (fig. 1) when the principal stresses are $\sigma_1 = \sigma_2$ and the principal strains are $\varphi_1 = \varphi_2 = -\varphi_3/2$. For thin specimens with ratio $r/t_0 > 10$ (die aperture radius to initial thickness) the bending stresses can be neglected as $\sigma_3 \cong 0$ and, therefore, the true equivalent stress σ_i and the true equivalent strain φ_i can be readily calculated as

$$\sigma_i = \left(\sqrt{2}/2\right)\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} = \sigma_1 = PR/(2t_{min}) \tag{1}$$

$$\varepsilon_i = \left(\sqrt{2}/3\right)\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2} = |\varepsilon_3| = \ln|(t_{min}/t_0)| \tag{2}$$

where the pressure P and the current values of the radius of curvature R and of the thickness in the pole of the dome t_{min} should be measured.

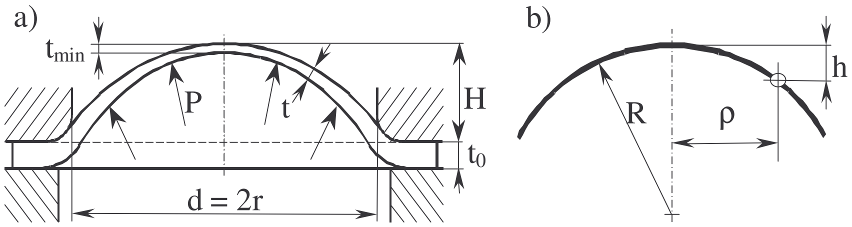


Fig. 1. Outline of (a) hydraulic bulge test and (b) dome geometry

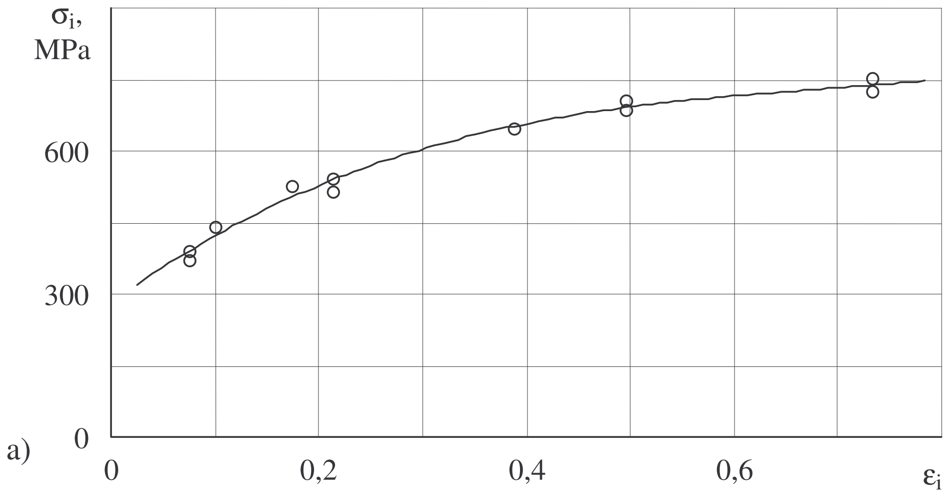
For all the points out of the pole $\varphi_1 \neq \varphi_2$ and $\sigma_1 \neq \sigma_2$ but the stresses and the strains are subjected to the following set of relations:

$$\left.\begin{array}{l} \sigma_1/R_1 + \sigma_2/R_2 = P/t \\ \alpha = \sigma_2/\sigma_1 = (2\varphi_2 + \varphi_1)/(2\varphi_1 + \varphi_2) = \text{const} \\ \beta = \varphi_2/\varphi_1 = (2\alpha - 1)/(2 - \alpha) = \text{const} \end{array}\right| \tag{3}$$

where R_1 and R_2 are the main radii of curvature and $R_1 = R_2$ in the case of spherical dome. This leads to $\varepsilon_i = 2\sqrt{k}\varphi_1/\sqrt{3}$ and $\sigma_i = \sqrt{3}\sqrt{k}\sigma_1/(2 + \beta)$ by the substitution $k = 1 + \beta + \beta^2$. Then it would be possible to calculate the values of σ_i and φ_i for every point out of the pole if φ_1 and φ_2 are known. In the case of spherical shape of the deformed specimen such evaluation could be done by the coordinate grid method using the GRID computer code for data processing. This code [10-12] provides an optional procedure for recalculation of the distances between the nodepoints determined in the X-Y plane when the initial flat surface of the grid pattern proves to be changed during deformation to a spherical one with radius R being known or measured in addition. If the dome is not spherical then the same way could be used but the R_1 and R_2 values should be measured cell by cell over the deformed grid.

3. EXPERIMENTS AND RESULTS

Test experiments by hydraulic bulging have been performed recently [13]using circular dies 26 mm and 30 mm in diameter. The materials tested were 1,2 mm and 1,5 mm thick low carbon steel, 0,8 mm thick stainless steel 18/8 and commercial aluminium and 1 mm thick brass 70/30 being nearly isotropic. The examinations of the deformed contour showed that the specimen shapes proved to be nearly spherical all over the dome for steels and brass but not for aluminium. This allowed the united flow curves $\sigma_i = \sigma_i(\varphi_1)$ to be plotted for low carbon steel (fig. 2) and brass using test data obtained both in the pole and out of the pole of the dome as described above. It has been found that the strain hardening determination by biaxial bulge testing is in a good agreement with the flow curves obtained by uniaxial tensile test.



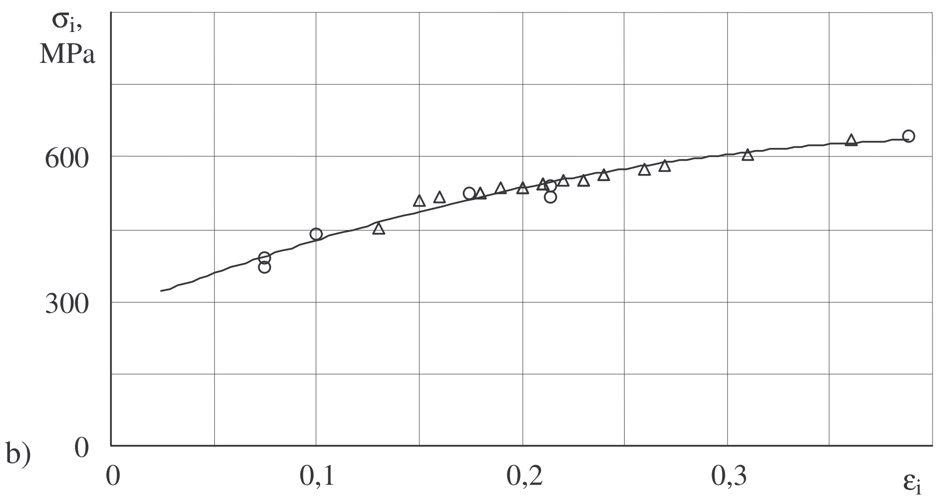


Fig. 2. Strain hardening evaluation for low carbon steel by data obtained from (a) the pole and (b) out of the pole of the dome

The spherical dome shape at hydraulic bulge testing has been discussed in more details in [14, 15]. In this field further investigations for other materials are needed about the influence of the sheet anisotropy [16-18] on the deformed dome shape and on the stress calculation out of the pole. Only a few [9, 13, 19] studies are carried out by now and additional analytical solutions, experimental tests and computer simulations should be combined in order to verify all the possible applications of the bulge testing for strain hardening determination of various sheet metals.

4. CONCLUDING REMARKS

Considering the presented results it could be concluded that the strain hardening curves of isotropic sheet metals may possibly be obtained by hydraulic bulge testing using data for specimen areas out of pole. In this way it is possible to get more experimental points and to improve the accuracy of the results at reduced number of tests. Further investigations are needed to validate the capability of the proposed approach in the cases of anisotropic sheet materials or non-spherical dome shape.

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