BIAXIAL STRESS-STRAIN RELATIONSHIP OF SHEET METAL FROM HYDRAULIC BULGING TEST

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***Abstract**: The stress-strain relationship of the aluminium, brass and steel sheets was determined by uniaxial and equibiaxial (hydraulic bulging) tensile tests. Sheet thickness gradation in different points of hemisphere formed in bulge test was analysed, both experimentally and theoretically. The Hollomon equation was used to describe uniaxial and biaxial strain hardening curves, and differential (strain dependent) strain hardening exponent n_t was determined on the base of the results of uniaxial and biaxial testing.*

***Key words:** strain hardening, biaxial strain state, bulging test, sheet thickness distribution*

1. INTRODUCTION

The stress-strain relation and hardening behaviour of a material are very important in determining its resistance to plastic instability. In sheet forming operation biaxial as well as uniaxial stress state exists. 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 [1]:

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

Hydraulic bulging has long been known as a convenient method for judging the ductility of sheet metal and 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 slight bending; whereas other methods, employing cruciform of tubular specimen, induce local stress concentrations or necessitate prior deformation. When the object of hydraulic bulging is to evaluate plastic properties of a material, the strain distribution may not be ascertained by any method that requires presupposition of those properties. Joint resolution of both bulging strains and material properties together is feasible, but would require complex instrumentation to provide enough information for the computation.

2. MATERIAL AND MECHANICAL TESTING

The tests were carried out on the 1.0 mm thick half hard 63-37 brass sheet (M63), 0.8 mm thick DDQ (deep drawing quality) steel sheet and 0.8 mm thick AW1050 aluminium sheet in annealed state. The tensile specimens of 50 mm gauge length and 12.5 mm width were prepared from strips cut at 0^0, 45^0 and 90^0 according to the rolling direction of the sheet. The experiments were carried out using a special device, which recorded simultaneously the tensile load, the current length and width of specimen, using a microcomputer.

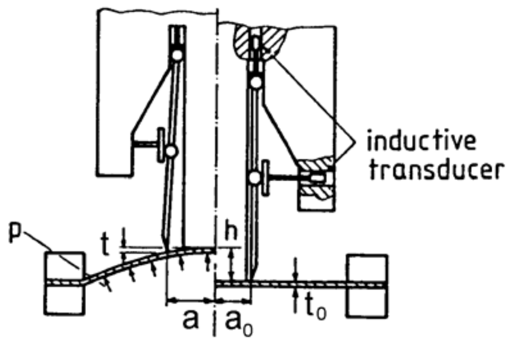

Fig. 1. Hydraulic bulge test apparatus

In order to determine the flow properties of a material in biaxial stretching, the bulge test was carried out, using hydraulic bulge apparatus (Fig. 1) with a circular die aperture of 80 mm diameter. The bulging pressure and the curvature of the pole were measured and recorded continuously up to specimen failure.

3. THICKNESS DISTRIBUTION

In bulging sheet metal through a die aperture by lateral fluid pressure, the expansion of surface area is only modest but the meridional strain gradient, from very little at the periphery to quite large at the pole, is severe. Let as consider free forming of a circular membrane. The current half arc length of any meridian passing trough the dome apex is equal to $R\alpha$ - where R is the dome radius and α is half the angle subtended by the dome surface at the center of curvature (Fig. 2). Since the initial half arc length of the meridian under consideration equals to the radius R_0, it is stretched $R\alpha/R_0 = \alpha/\sin\alpha$ times. Proceeding from symmetry, it follows that the principal positive strains are equal to each other and thickness at the dome apex equals

$$t_d = t_0(\sin\alpha/\alpha)^2 \tag{1}$$

Since the clamp does not deform during forming, the circumferential deformation along the periphery is negligible. On the other hand, meridian approaching the periphery is stretched by $\alpha/\sin\alpha$ times, and from this it follows that dome thickness at the periphery equals to

$$t_p = t_0(\sin\alpha/\alpha) \tag{2}$$

At some moment of deformation the point M transfer to point M', and point O to O' (Fig. 2). Let φ be the angle between the symmetry axis and the dome radius to the point M' under consideration. The latitude passing the point M' is stretched by ρ/ρ_0 times and the dome thickness at the point M' may be found as follow

$$t = t_0(\rho_0/\rho)(\sin\alpha/\alpha) \tag{3}$$

Taking into account that $\rho = R\sin\varphi$, $\rho_0 = \nu R_0$ and $\varphi = \nu\alpha$ the dome thickness at any point could be calculated from the following equation [2]:

$$t(\alpha,\beta) = t_0(\sin\alpha/\alpha)^2\varphi/\sin\varphi \tag{4}$$

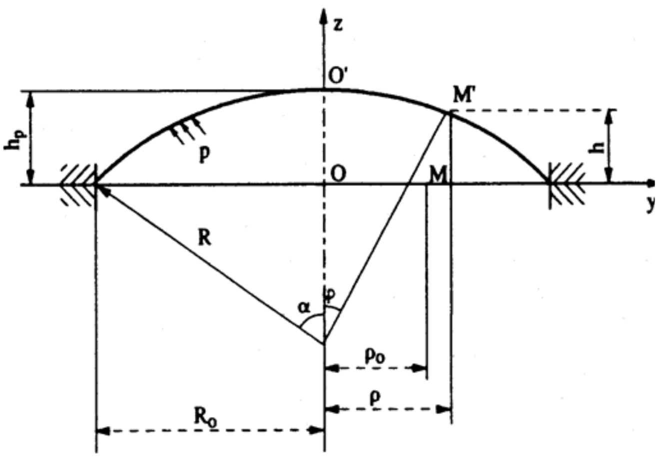

Fig. 2. Schematic of deformation modeling

Measurements of sheet thickness in different points of brass and aluminium hemisphere formed in bulging test were compared with calculations using eq. (4). From this presentation (Fig. 3) it is visible that thickness variation along the dome wall obtained in experiment is larger than determined theoretically. Because of this deviation, *in situ* measurement of the sheet thickness at the pole, e.g. with an ultrasonic probe, was suggested [4].

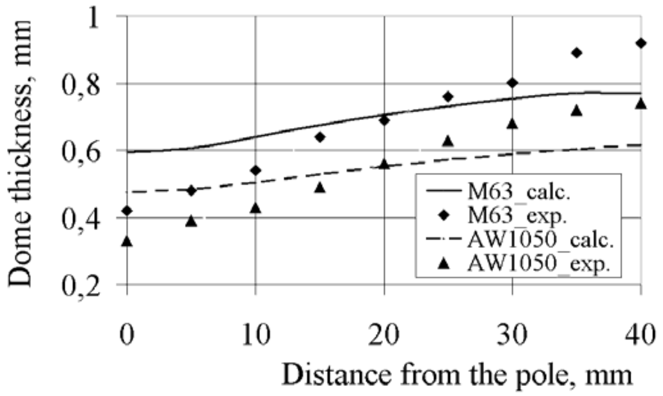

Fig. 3. Dependence of dome thickness on the distance from the dome apex of brass and aluminium sheet at the end of bulge test

4. STRESS-STRAIN RELATIONSHIP

In the bulge test a circular diaphragm, rigidly clamped at the periphery, is stretched by uniform lateral pressure. The sheet bends during deformation due to clamping. Provided that the sheet thickness/bulge diameter ratio is small, the effects of bending can be neglected in calculating membrane stresses. The average value of effective stress can be calculated on the basis of the force equilibrium of a small circular element at the center of a membrane from:

$$\sigma = \frac{pR}{2t} \tag{5}$$

where p is the bulging pressure, and R and t are the radius of curvature and the thickness of the element, respectively. The radius of curvature could be obtained from:

$$R = \frac{a^2 + h^2}{2h} \tag{6}$$

where *a* is measured width and *h* is measured height of the central part of membrane (Fig. 1).

On the base of measured width and height of the central part of membrane the effective strain (equals to the thickness strain) could be calculated as [5],

$$\varepsilon = 2\ln\left[1 + \left(\frac{h}{a}\right)^2\right] \tag{7}$$

Comparison of stress-strain relationships obtained in uniaxial tensile test and equibiaxial stretching (bulge test) have shown visibly differences (Fig. 4) – larger region of straining and higher stress value. The latest could be a result of different textural changes accompanying plastic deformation in these two tests. According to some works, uniaxial and equibiaxial stress-strain curves could be related using the following relationships:

$$\sigma = \left(\frac{1+r_{av}}{2}\right)^{1/2}\sigma_{av}, \qquad \varepsilon = \left(\frac{2}{1+r_{av}}\right)^{1/2}\varepsilon_{av} \tag{8}$$

where *r* is plastic anisotropy ratio and uniaxial material parameters are averaged as $x_{av} = (x_0 + 2x_{45} + x_{90})/4$.

In present work calculation of equibiaxial stress-strain curve of the DDQ steel sheet, on the base of uniaxial stress-strain curve, resulted in poor agreement with experimental curve obtained from the bulge test (Fig. 4).

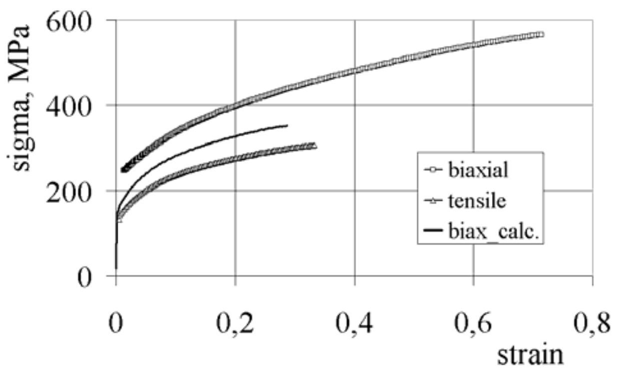

Fig. 4. Uniaxial tensile test and biaxial (bulge) test stress-strain curves of DDQ steel sheet

To describe the plastic behaviour of polycrystalline metals and alloys the Hollomon law in the form of:

$$\sigma = K\varepsilon^n \tag{9}$$

has been used the most frequently. The parameters involved in this laws, particularly *n*-value has been correlated to changes in the microstructure of a material and in some way represents processes which occur during deformation. They have also been used extensively to characterize the formability of sheet material. In the case of all the material tested the value of biaxial strain hardening exponent was larger than that of uniaxial one.

The *n*-value is strain dependent what resulted from the changes in the crystallographic texture [3]. Because of this the mean *n*-value (which describe the strain hardening of the whole strain range) and differential n_t-value were determined on the base of the results of uniaxial and biaxial testing. Taking the derivative from equation (9) yields

$$\frac{d\sigma}{d\varepsilon} = Kn\varepsilon^{n-1} = \frac{\sigma}{\varepsilon}n \tag{10}$$

what results in

$$n_t = \frac{d\sigma}{d\varepsilon}\frac{\varepsilon}{\sigma} \tag{11}$$

The results presented in Fig. 5 show clearly that there is no unique constant *n*-value, which may characterize hardening process in both uniaxial and biaxial deformation of brass sheets. The differential n_t-value varies continuously with strain - increases rapidly at small strains and at higher strains falls again somewhat less rapidly. It was established that at large strains (above 0.10) stress is controlled by the cell size. This observation suggested that there is a change in the accommodation process from the grain level at low strains to the cell level at large strains - what resulted in a change in the strain hardening process.

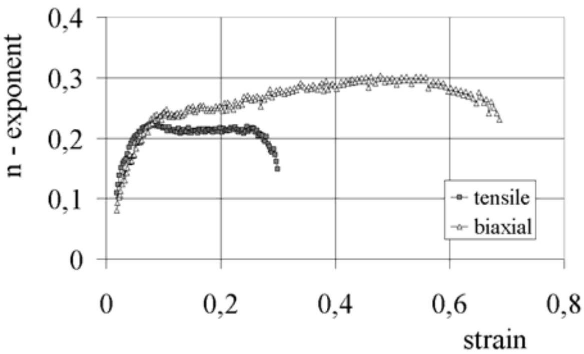

Fig. 5. Differential strain hardening exponent of uniaxial tensile test and biaxial (bulge test) of brass sheet

5. CONCLUSION

Calculation of biaxial stress-strain curve on the base of the results of uniaxial test was not satisfied. Because of visible difference in plastic flow under bulge test and uniaxial tensile, both of these two test should be perform due to obtain material parameters needed for satisfactory modeling of sheet forming processes.

6. REFERENCES

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