Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 46
ISSUE 1
May
2011

Research highligths of sheet metal testing by hydraulic bulging

B. Tomov, V. Gagov*, E. Yankov, R. Radev
Department of Materials Science and Technology, University of Rousse,
8 Studentska St., Rousse 7017, Bulgaria
* Corresponding author: E-mail address: gag@uni-ruse.bg

Received 15.03.2011; published in revised form 01.05.2011

Analysis and modelling

ABSTRACT

Purpose: The aim of this paper is to outline the mechanical conditions when sheet metals are tested by hydraulic bulging as a research background for analysis of the experimental results.
Design/methodology/approach: The methodology adopted for this investigation consists in application of the engineering plasticity to a general description of the sheet bulge deformation under lateral hydraulic pressure.
Findings: Governing differential equations of hydraulic sheet bulging are found and the current thickness over the bulged dome of the deformed diaphragm is expressed in terms of loading and geometric parameters.
Research limitations/implications: The mathematical treatment is limited here to the cases of axial symmetry which assumes that planar isottropic sheet metals are bulged into circular die apertures.
Practical implications: Experimental results and other computational models can be analysed in more details comparing them with the derived general mathematical expression.
Originality/value: The mechanical state of the sheet bulging is analysed in more general way without any restrictions to the loading rate and to the hydraulic pressure distribution.
Keywords: Sheet testing; Hydraulic bulging; Analytical description

Reference to this paper should be given in the following way:
B. Tomov, V. Gagov, E. Yankov, R. Radev, Research highligths of sheet metal testing by hydraulic bulging, Journal of Achievements in Materials and Manufacturing Engineering 46/1 (2011) 65-70.

1. Introduction

The sheet metal testing comprises a number of various experimental methods described in several books [1, 2] and handbooks [3, 4] in connection with the widespread sheet processing by cold forming. At the same time the deformation behaviour of sheet metals under processing involves not only the conventional mechanical properties and the work hardening but also such phenomena [2, 4] as normal and planar anisotropy, local or diffuse necking and later fracturing, possible appearance of buckling and wrinkling, undesirable shape distortions or surface quality changes, etc. In addition to these features the sheet metal forming operations are too different in type, mechanical state or extent and often are sensitive to the conditions of workpiece-tool interaction. Because of that no simple testing procedure could provide an accurate indication of the aptitude for forming of a material in all situations. However, on one hand, a quantitative estimation of the sheet metal properties made together with a careful analysis of the forming operations needed to manufacture a particular part are indispensable in process planning design for successful stampings production and in development of most efficient process. On the other hand, in view of current production control [1, 5] purposes, it is often enough only to qualify the sheet materials to be processed as good or bad. Recently, the extended use of the finite element method for sheet forming simulation also requires [6-8] correct materials data found by mechanical testing. Referring to [2, 3] the all wide variety of experimental methods for sheet metal testing can be classified into two basic groups as follows:

(i) intrinsic tests that measure the main characteristics of mechanical behaviour properties such as strength, ductility, strain hardening, anisotropy, etc. These evaluations should be made under different but well defined mechanical conditions and for that reason they are independent on any particular processing circumstances such as die design and geometry, blankholder force, lubrication, etc. The uniaxial tension is the most frequently used test state but other methods for biaxial stretch testing and shear testing are also often applied in practice;
(ii) simulative tests which subject a sheet metal to deformation close corresponding to this one that occurs in a particular type of forming operation. Usually these methods provide simple estimations of forming limit concerning the metal and operation being tested and in some cases additional information about sheet quality. The data obtained could not be transferred directly to other forming processes. There exist many cupping, stretching and bending test experiments in various modifications which fall into this group.

In addition to this basic classification some other groups of methods for sheet metal quality estimation could be distinguished [1] as follows:

(i) physical and chemical investigations, mainly experimental examinations of composition, structure and surface quality. The importance of these attributes is also pointed in [9] as a matter of fact but the methods used are typical not only of metal testing procedures;
(ii) statistical processing of experimental data as in [2] in order to get united criteria for sheet metal performance under deformation and to detect main relations of the forming limit with the mechanical properties;
(iii) computation of strain distribution by check trials of intricate shape parts production and comparison of data obtained with the forming limit of the sheet metal used. Such experiments in fact are common in sheet forming process development but usually they are not assigned to the metal testing procedures.

For many years the bulge test is used flow curves and forming limit diagrams of various sheet metals to be found and the related anisotropic models to be verified. This investigation deals with a general analysis of the mechanical state at sheet bulging under hydrostatic and hydrodynamic loading. Some own experimental results are also indicated as a start point for further investigations on the bulge shape examination and strain hardening evaluation.

2. Description of the bulge testing

2.1. Brief overview

The sheet metals under biaxial tension 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 [3] but does not determine exactly the acting stresses. The cross tensile test allows both balanced and unbalanced in-plane biaxial stretching [10] but an optimised cruciform specimen is required and it should

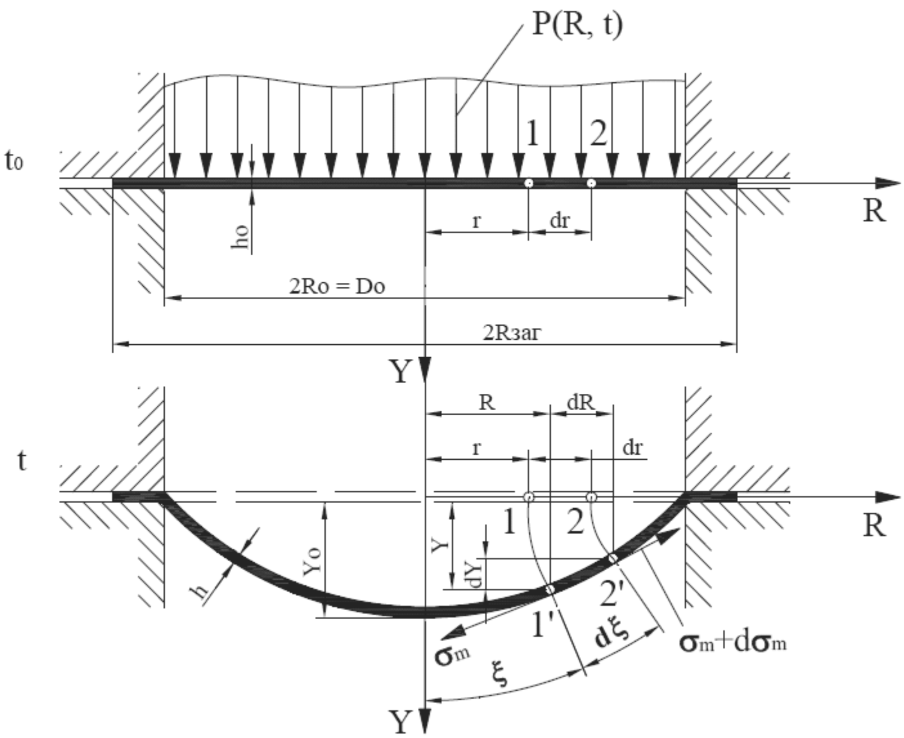

Fig. 1. Meridional section of a clamped sheet before (time t_0) and during (time t) bulging

be loaded by special equipment. In the hydraulic bulge test the sheet specimen is deformed [1, 2] by lateral pressure into dome under out-of-plane biaxial tension and both the stresses and the strains can be defined in a fairly simple way at least around the bulge top. The bulge testing of sheets is often carried out using elliptical die apertures [11] to involve a greater variety of the strain ratios or applying viscous pressure carrying medium [8] to simplify the test setup. Furthermore, the bulge test is applicable to deformation behaviour investigation of metallic foils [12] as well as at the elevated temperatures [13] of superplastic forming.

During the years many authors, for example [7, 8, 11, 14-27] among others, have presented various computational models and experimental results concerning the hydraulic bulge testing of sheet metals. Until now, however, definite conclusions from the comparisons [28-31] between the analytical expressions, the numerical solutions and the test evaluation data are not drawn yet. Some questions are still open for discussion about, for instance, the accuracy of the strain hardening determination using bulge testing or the correlation of the data from this test and from other methods for sheet metal testing.

2.2. Analytical background

The hydraulic bulge testing consists in clamping of a sheet specimen against a die with a circular or elliptical aperture and subjecting the opposite side of the fixed specimen to an increasing hydraulic pressure. In such a way the bulge dome into the die is formed (i) only from the inner clamped part of the specimen at the expense of the unequal thinning over the dome and (ii) without contact friction. In fact these deformation preconditions contradict the common manufacturing practice of hydrofoming but are very important for the further analytical treatment.

A sketch of sheet metal testing by hydraulic bulging is shown in Fig. 1, where a circular diaphragm with initial thickness h_0 and constant outer diameter $2R_{zag}$ is fixed to a circular die with hole diameter $D_0 = 2R_0$ and is loaded by variable hydraulic pressure $P = P(R,t)$. Assuming axial symmetry of the bulged dome, what applies for planar isotropic sheet metals, a cylindrical coordinate system is chosen. If thin specimens are tested, then the bending stresses over the dome are negligible and the membrane theory can be used for the equilibrium calculation.

Let consider an element $1'2'$ with initial coordinates $1(r,0)$, $2(r+dr,0)$ and current coordinates $1'(R,Y)$, $2'(R+dR, Y+dY)$ or $1'(\xi,\eta)$, $2'(\xi+d\xi, \eta-d\mu)$ in curvilinear coordinates. For thin sheets, plane stress state follows from the membrane theory with normal stress $\sigma_n = 0$ and principal stresses as meridional stress σ_m and circumferential stress σ_θ. In view of the continuum dynamics [32, 33] the differential equations of the motion are:

$$\frac{\partial \sigma_m}{\partial R} + \frac{\sigma_m}{h}\cdot\frac{\partial h}{\partial R} + \frac{\sigma_m + \sigma_\theta}{Y}\cdot\frac{\partial Y}{\partial R} + \\ + \rho\left(\frac{\partial^2 Y}{\partial t^2}\cdot\frac{\partial Y}{\partial R} + \frac{\partial^2 V}{\partial t^2}\right) = 0 \qquad (1)$$

$$\frac{\sigma_m \cdot \dfrac{\partial^2 Y}{\partial R^2}}{\left(1+\left(\dfrac{\partial Y}{\partial R}\right)^2\right)^{3/2}} - \frac{\sigma_\theta}{\left(1+\left(\dfrac{\partial Y}{\partial R}\right)^2\right)^{1/2}} - \frac{P}{h} + \\ + \rho\left(\frac{\partial^2 Y}{\partial t^2} - \frac{\partial Y}{\partial R}\cdot\frac{\partial^2 V}{\partial t^2}\right) = 0 \qquad (2)$$

where ρ is the sheet density and $V = R - r$. The principal strains may be expressed as follows:

$$\varphi_m = \ln\frac{d\xi}{dr} = \ln\frac{\sqrt{1+(\partial Y/\partial R)^2}}{1-\partial V/\partial R}, \quad \varphi_\theta = \ln\frac{R}{r} = \ln\frac{R}{R-V} \quad \text{and}$$

$$\varphi_n = \ln\frac{h}{h_0},$$

where h is the current thickness over the bulged dome at current time t. The plastic incompressibility condition $\varphi_m + \varphi_\theta + \varphi_n = 0$ in connection with the equations (1) and (2) yields the relation:

$$h = h_0\frac{(R-V)(1-\partial V/\partial R)}{R\left(1+(\partial Y/\partial R)^2\right)^{1/2}} \qquad (3)$$

which gives an overall description of the thickness distribution in the course of hydraulic bulging.

For a general solution of the differential equations (1) and (2), as usual, they should be combined with the following functions:

(i) an appropriate yield criterion for plane stress state such as well known Mises criterion $\sigma_m^2 + \sigma_\theta^2 - \sigma_m\sigma_\theta = \sigma_p^2$ or Tresca criterion $\sigma_m - \sigma_\theta = \sigma_p$, where σ_p stands for the current yield strength;

(ii) a strain hardening description $\sigma_p = \sigma_i(\varphi_1)$, where σ_i and φ_i are the equivalent stress and strains;

(iii) the flow rule $d\varphi_j = (3/2)(d\varphi_i/\sigma_i)S_j$, where $d\varphi_j$ are the principal strain increments, $d\varphi_i$ is the equivalent strain increment and S_j are the stress deviator components.

In more complicated cases of planar anisotropic sheet metals the above mentioned equations should be replaced by respectively extended equations to satisfy in full the testing conditions.

2.3. Bulge development

In the common cases of static or quasistatic hydraulic loading (Fig. 2) the pressure distribution on the tested specimen is uniform and the bulge is developed in a dome with nearly spherical shape with decreasing radii $R_1 > R_2 > R_k$. However, in the cases of impulsive loading (Fig. 3), stress waves may occur in the clamped specimen and just their propagation causes the bulge deformation. Because of that the bulge development differs under static and impulsive loading.

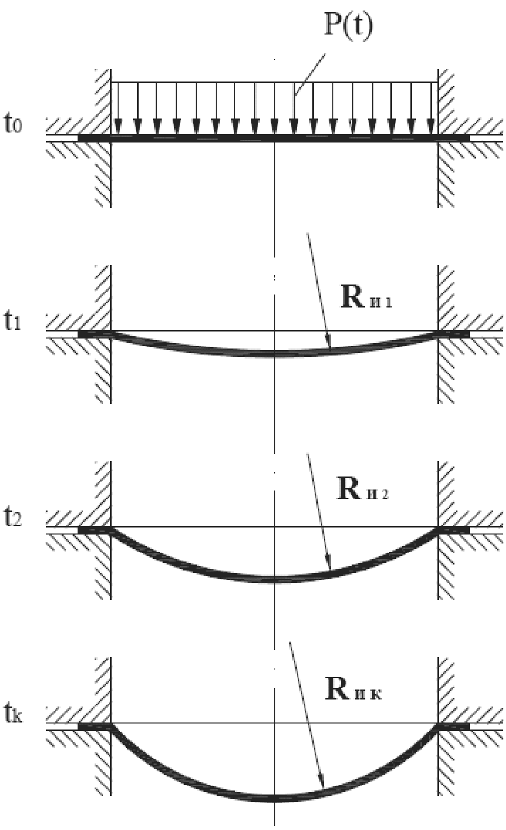

Fig. 2. Bulge development under static loading

Fig. 3a corresponds to the situation when the source of the hydraulic pressure impulse is close to the specimen. Then the pressure distribution $P = P(R, t)$ has a maximum at the specimen centre and at the time t_1 a plastic hinge is formed there. Fig. 3b shows the case when from a remote source of impulsive pressure a hydraulic wave reaches to the specimen with approximately uniform pressure $P = P(t)$ and at the time t_1 a plastic hinge is formed near the specimen periphery. Longitudinal and transverse plastic waves with their velocities $\lambda = \sqrt{(4/3\rho)(d\sigma_i/d\varphi_i)}$ and $a = \sqrt{(1/\rho)(\sigma_m/e^{\varphi m})}$ propagate in the respective specimen parts (AB and CD in Fig. 3a or BC in Fig. 3b) at the intermediate times t_2 until the final time t_k when the dome is completely formed. The end dome shape becomes nearly spherical like the case of static hydraulic loading.

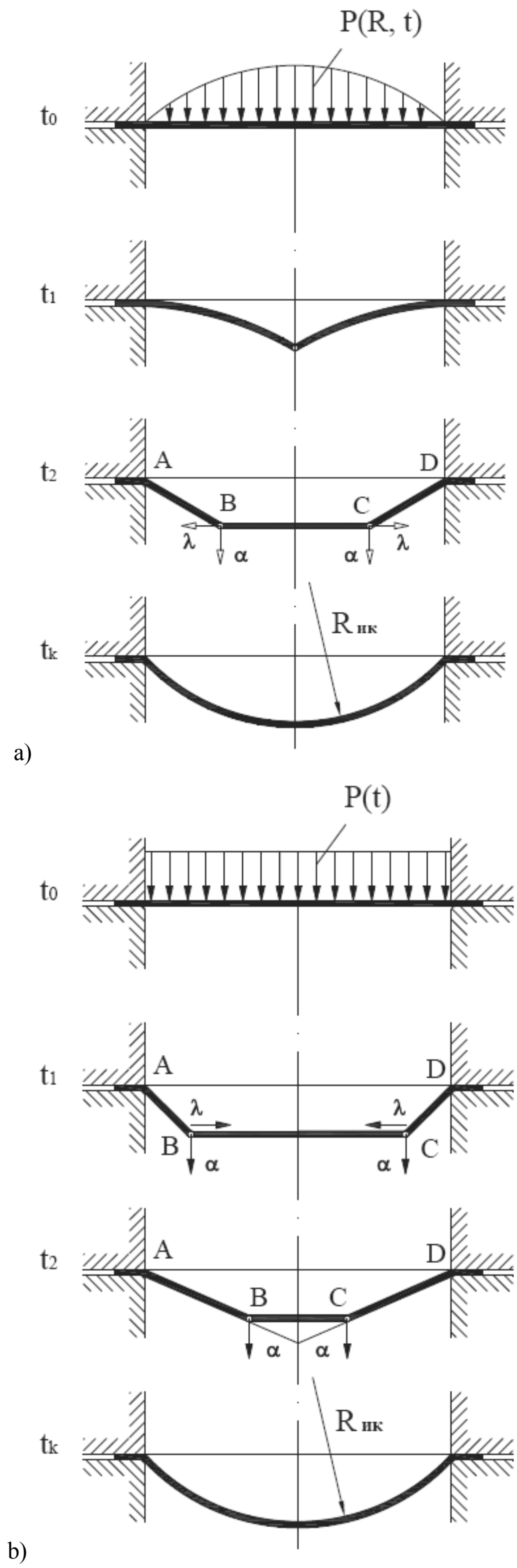

Fig. 3. Bulge development under impulsive loading with (a) concentrated and (b) uniform pressure

3. Complementary results

During the past years some new contributions have been proposed [19, 21, 26, 34] by the current authors regarding the sheet bulge testing in circular dies. The main experimental results and methodical findings are briefly stated here in addition to the general analysis above.

It was shown [19] that the coordinate grid method can be applied for experimental strain hardening determination of sheet metals taking into account data for strains in specimen areas out of the pole. In such a way it is possible to get more experimental points and to improve the accuracy of the results at reduced number of tests. We maintain the opinion that the experimental stress-strain relation should be invariable regardless of the test method and, therefore, the biaxial tension in hydraulic bulging only extends the measureable uniform deformation without appreciable effect on the rate of hardening.

a) b) c)

Fig. 4. Bulge shape as (a) real specimen, (b) smoothed surface model and (c) 3D solid model section

The influence of the loading state on the tensile properties of some sheet metals (brass, aluminium, low carbon steel, stainless steel) was studied [26] using strain rates about 0.05 s^{-1} for testing by uniaxial tension and hydrostatic bulging and about 1 s^{-1} for hydrodynamic bulging. The comparison between the ultimate tensile strength at the uniaxial tension and the tensile strength under static and dynamic biaxial tension showed, as could be expected, that the tensile strength increases when changing the mechanical state from uniaxial to biaxial tension and the rate of deformation from static to dynamic loading. Similarly, the strains before fracture increase at the transition from uniaxial to biaxial tension and decrease at higher deformation rate.

The shape of the bulged dome has been discussed by many authors [7, 14, 16, 20, 29, 31] during the years by using various mechanical or optical techniques to collect experimental data. In [26] the dome shape was examined by precise measuring the contours of the tested sheet specimens in two orthogonal cross sections after several deformation steps. The measurements were made after several consecutive deformation steps. For brass, low carbon steel and stainless steel the dome contours were found to be statistically indistinguishable from circles at confidence levels over 0.95 but it was not the case for aluminium.

Recently [34] it was proposed one more way for the purpose of spatial examination of the tested sheet specimens. It consists of three-dimensional scanning along both the outer and the inner surfaces of the dome after a step of hydraulic bulging to some extent without fracture. 3D laser scanner of the brand NextEngine was applied to accomplish such measurements with a resolution of 0.01 mm. An example of 18/8 stainless steel bulging is shown in Fig. 4. The surface models were smoothed by spline functions and then the outside and the inside of each scanned bulge were centered together using SolidWorks to build a solid model of the dome. It is easy to handle such a model in any further numerical investigations of the dome shape and the thickness distribution in horizontal or vertical sections.

4. Conclusions

It is outlined the mechanical state when sheet metals are tested by hydraulic bulging as a research background for analysis of the experimental results. The methodology adopted for this investigation consists in application of the engineering plasticity to a general description of the sheet bulge deformation under lateral hydraulic pressure. Governing differential equations of hydraulic sheet bulging are found and the current thickness over the bulged dome is expressed in terms of loading and geometric parameters. The mechanical state of the sheet bulging is analysed in more general way without any restrictions to the loading rate and to the hydraulic pressure distribution. The mathematical treatment is limited here to the common cases of axial symmetry. Experimental results and other computational models can be analysed in more details comparing them with the derived general mathematical expression. Some own test results are indicated as a start point for further detailed investigations concerning the bulge shape examination and strain hardening evaluation.

Acknowledgements

This paper is partly supported by National Science Fund at Ministry of Education, Youth and Science of the Republic of Bulgaria under grant D002-158/2008.

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