INFLUENCE OF MATERIAL RHEOLOGICAL CHARACTERISTICS ON THE DOME THICKNESS DURING FREE BULGING TEST

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Received 05 September 2016
Accepted 11 May 2017

ABSTRACT

Free bulging process is an experimental technique which can be used to characterize a sheet material under conditions of biaxial tension during hot forming. Analytical and semi-analytical models of this process are usually based on the hypothesis offering certain relations between the geometrical characteristics of a bulge during forming. The paper presents an original relation between a specimen thickness at the dome pole and the dome height which is used by the semi-analytical method for simulation of free bulging process. The finite-element computer simulation results are generalized to obtain this relation. The influence of the material constants on the geometrical parameters of the bulge is studied. It is shown that the sheet thickness corresponding to a specific dome height is dictated by the strain rate sensitivity index of the material. The equation describing the influence of the strain rate sensitivity index on the dome apex thickness is presented.

Keywords: *mathematical simulation, gas forming, superplasticity, free bulging test, finite element method, mechanical properties.*

INTRODUCTION

Hot gas forming is a material processing technology for production of shell type parts for aerospace industry. Utilization of superplasticity effect allows one to obtain more uniform thickness distribution and to increase the product geometry complexity. This effect occurs in ultra fine grained materials while forming in a specific temperature and strain rate range. To provide superplasticity of the material during gas forming the pressure should be controlled to maintain the maximum local strain rate in the specimen volume at a constant value. Pressure regimes that provide the best forming conditions are unique to the concrete product and are calculated using computer simulation [1]. Accurate calculation of such regimes requires information about the material rheological behavior.

The most common approach to describe the rheological behavior of superplastic materials is represented by Bakofen equation:

$$\sigma_\epsilon = K\dot{\varepsilon}_\epsilon^m \tag{1}$$

where K and m are constants characterizing the material flow behavior.

Uniaxial tensile test is typically used to determine the mechanical properties of superplastic materials. In this case, the coefficients of Eq. (1) are calculated approximating the experimental stress values obtained for different constant strain rates. However, refs. [2 - 5] show that the material characteristics obtained under uniaxial tension conditions cannot be always acceptable to describe the material behavior in biaxial tension stress state. The latter is closer to the one realized in industrial forming. From this point of view, free bulging tests are more preferable than tensile ones. The differences of the material properties obtained by tensile and free bulging testing are reported in refs. [3 - 6]. Several techniques are developed to obtain the material characteristics based on the results of free bulging tests [7 - 10]. A method for direct calculation of the rheological constants K and m

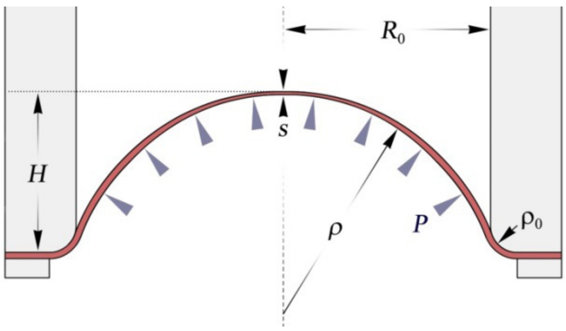

Fig. 1. Schematic presentation of the free bulging test.

is proposed in ref. [7]. This method was later extended [8] in order to take the strain hardening into consideration. Inverse analysis techniques for characterization of superplastic material are presented in refs. [9, 10]. The direct task can be solved by FEM [10], or by semi-analytical method proposed in ref. [9].

Free bulging test scheme is presented in Fig. 1. A metal sheet of an initial thickness is formed by pressure in a cylindrical die with an aperture radius and an entry radius . At an instant moment , the free part of the dome is assumed to be a spherical surface with a radius . is the height of the dome and is the current thickness at the dome apex.

The interpretation of the free bulging test results requires the construction of a mathematical model of the dome forming. Such models are usually based on a hypothesis assuming certain form of the relation between the dome height and the sheet thickness at the apex [11 - 14].

A relationship proposed in ref. [11] is based on the hypothesis of a uniform workpiece thickness distribution in the dome:

$$s = \frac{s_0 R_0^2}{R_0^2 + H^2} \tag{2}$$

The assumption that the stress mode at every specimen point is a balanced biaxial tension leads to the following relation proposed in ref. [12]:

$$s = \frac{s_0 R_0^4}{(R_0^2 + H^2)^2} \tag{3}$$

A suggestion about uniform meridian elongation [13] leads to the relation:

$$s = s_0 \left(\frac{sin(\alpha)}{\alpha} \right)^2 \tag{4}$$

where $\alpha(h) = arcsin\left(\frac{2HR_0}{R_0^2+H^2}\right)$.

The common drawback of all these relations refers to the fact that they do not depend on the material properties, which is not experimentally observed. It is known that the dome thickness variation corresponds to the strain rate sensitivity index: the higher value leads to more uniform thinning of the specimen and a greater workpiece thickness on the dome apex at the same height. This fact is used in ref. [14] to summarize the Eqs. (2) and (3) in order to show the dependence taking into account the material properties effect on the forming process:

$$s(H) = s_0 \left(\frac{R_0^2}{R_0^2 + H^2} \right)^{2-m} \tag{5}$$

A set of computer simulations is performed to verify the validity of Eqs. (2) - (5). The computer simulation of the free bulging tests using the finite element method is repeatedly carried out assuming different pressure values and rheological characteristics of the material. The simulation is performed for a die with the following parameters: mm; mm; . The Bakofen equation is used as a material constitutive equation. A 3D numerical model is created using the commercial FE code MSC.Patran/MSC.Nastran. The deformable part corresponding to the specimen is divided into 7200 four node shell elements. The die is considered perfectly rigid. The temperature and pressure values are considered stable.

An example of the thickness distribution in the dome obtained by the finite element method is presented in Fig. 2.

The computer simulation results confirm the dome thickness behavior taking into account the strain rate sensitivity index value. The simulation results are presented in Fig. 3. The signs in this figure refer to the relations described by Eqs.(2)-(5), while the curves are obtained by the finite element method for different values of the strain rate sensitivity index.

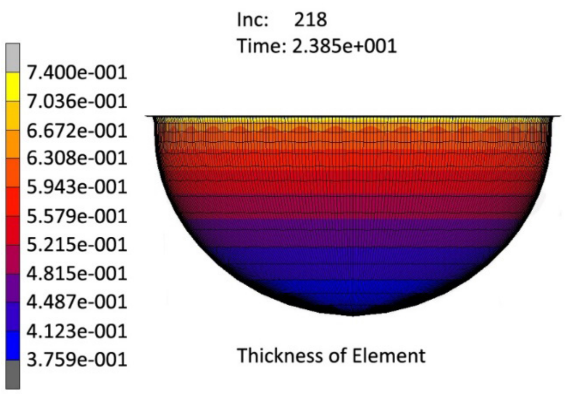

Fig. 2. Thickness distribution in the dome.

Fig. 3a illustrates the composition of the results obtained by finite element simulation to those obtained with the application of Eqs. (2) - (5). It can be seen that Eq. (2) is the worst in respect to consistency with FE modeling results, while Eq. (3) agrees well with the simulation results only for small values. At the same time Eq.(4) is applicable in case of high m values. Eq.(5) is the most universal, but the deviations between the numerical and the analytical data are significant. The dome pole thickness in reference to the dome height divided by the curvature radius is presented in Fig. 3b. This relation appears to be linear and it can be approximated by the following equation:

$$s/s_0 = 1 - B\frac{H}{\rho + \rho_0} \qquad (6)$$

where $\rho = \frac{H^2+(R+\rho_0)^2}{2H} - \rho_0$ is the radius of the dome curvature, while B is a constant depending on the material properties. The linear character of the relation s/s_0 vs. $H^2/(R^2+H^2)$ is reported in ref. [7]. But the effect of ρ_0 is neglected there.

The characteristics K, m and the pressure applied play a major role in metal forming during free bulging test. In order to evaluate the effect of these parameters on the $s(H)$ curve, finite element simulations are performed for different values of K ($K = 75$, $K = 150$, $K = 300$, $K = 600$) and applied pressure P ($P = 0.1$, $P = 0.4$, $P = 0.6$, $P = 0.7$). Calculations are performed with different equipment configurations: with a normalized entry radius $\tilde{\rho}_0 = \frac{\rho_0}{R}$, relations of $\rho_0 = 2$ $R = 20$; $\rho_0 = 3$ $R = 30$; $\rho_0 = 4$, $R = 40$; $\rho_0 = 5$, $R = 50$; $\rho_0 = 6$, $R = 60$, and with various values of the normalized entry radius ($\tilde{\rho}_0 = 0$; $\tilde{\rho}_0 = 0.05$; $\tilde{\rho}_0 = 0.1$; $\tilde{\rho}_0 = 0.15$; $\tilde{\rho}_0 = 0.2$; $\tilde{\rho}_0 = 0.25$; $\tilde{\rho}_0 = 0.3$). Some results of these simulations are illustrated in Fig. 4. One can see that coefficient K, the applied pressure and the proportional variation of the die dimensions do not affect the appearance of the $\frac{s}{s_0}\left(\frac{H}{\rho+\rho_0}\right)$ curve. However, the value of normalized entry radius $\tilde{\rho}_0$ affects the slope of the line which is denoted by coefficient B. If the specimen pole thickness s is available for a specific value of dome height

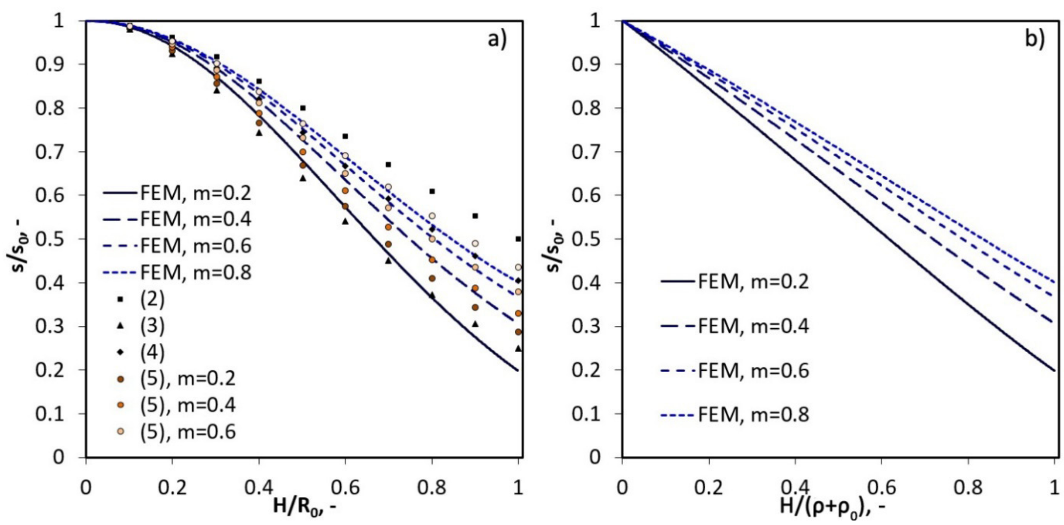

Fig. 3. Thickness of the dome apex obtained on the ground of the equations presented (signs) and the finite element

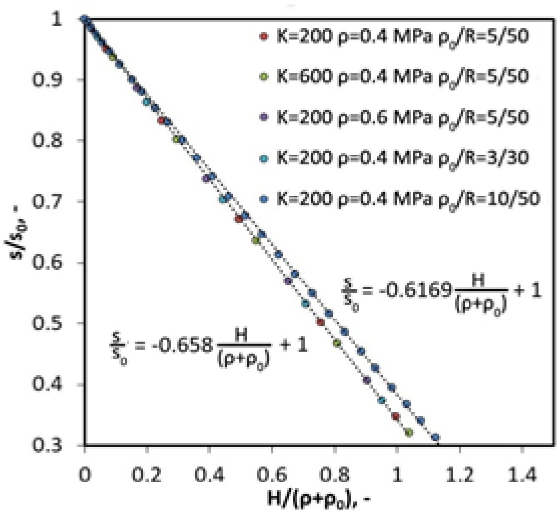

Fig. 4. Different parameters effect on s(H) dependency.

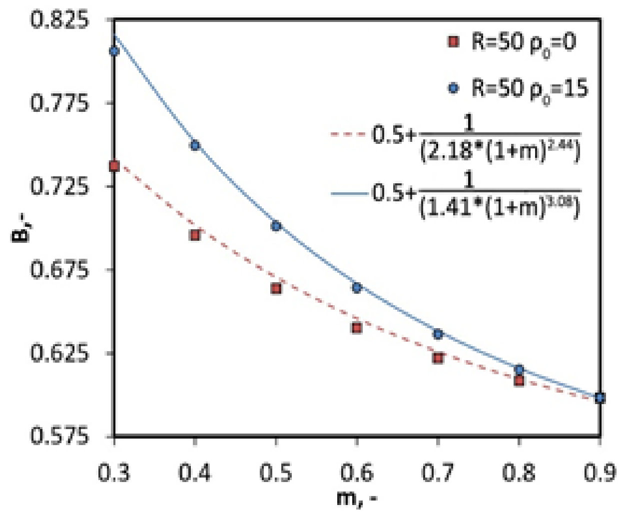

Fig. 5. Coefficient B variation with m for different $\tilde{\rho}_0$.

H, the value of B can be found as:

$$B = \left(\frac{s}{s_0} - 1\right)\left(\frac{H^2 + (R+\rho_0)^2}{2H^2}\right) \tag{7}$$

For further investigation of the geometry influence on coefficient B an additional series of FE simulations are performed. They are carried out for different values of the normalized entry radius ($\tilde{\rho}_0 = 0$; $\tilde{\rho}_0 = 0.05$; $\tilde{\rho}_0 = 0.1$; $\tilde{\rho}_0 = 0.15$; $\tilde{\rho}_0 = 0.2$; $\tilde{\rho}_0 = 0.25$; $\tilde{\rho}_0 = 0.3$) and m ranging from 0.3 to 0.9. This range of strain rate sensitivity index corresponds to the superplastic and quasi superplastic materials [1]. The values of B are calculated using Eq. (7), while the the FEM simulations proceed till the dome height becomes equal to the die radius. For each $\tilde{\rho}_0$, the relation $B(m)$ is approximated in correspondence with:

$$B = 0.5 + \frac{1}{\alpha(1+m)^{\beta}} \tag{8}$$

where α and β are the parameters related to the value of $\tilde{\rho}_0$. Linear regression is used to approximate the values of α and β with respect to $\tilde{\rho}_0$. Fig. 4 shows the results of the calculations referring to several $\tilde{\rho}_0$ values. One can see that the value of coefficient B decreases with m and increases with $\tilde{\rho}_0$.

The signs in Fig. 5 correspond to the values of obtained by Eq. (7). The solid and dashed curves are constructed using Eq.(8). Different values of and matching different values are presented in Fig. 6 together with the lines fitting this data.

Finally the $s(H)$ relation can be described as:

$$s/s_0 = 1 - \left(0.5 + \frac{1}{\alpha(1+m)^{\beta}}\right)\left(\frac{2H^2}{H^2 + (R+\rho_0)^2}\right) \tag{9}$$

where $\alpha = -2.34\tilde{\rho}_0 + 2.1, \beta = 1.79\tilde{\rho}_0 + 2.54$

In order to verify Eq. (9) a new set of computer simulations is carried out. The latter are performed using the following geometrical parameters: $R_0 = 22$ mm; $s_0 = 1.2$ mm; $\rho_0 = 3$ for different values of m.

Fig. 7a shows the values of coefficient B obtained by Eq. (8) and the FE-simulation results obtained on the base of Eq. (7). Fig. 7b illustrates the maximum thickness estimated with the appliucaton of Eq. (9) deviating from the FE-simulation values.

It can be seen from Fig. 7 that Eq. (9) makes provides to obtain thickness values deviating by less than 1.6 % in respect to the FE prognosis.

The approximation (9) constructed to fit the s(H) data can be inversed in order to find the value of m:

$$m = \left(\frac{2H^2 s_0}{\alpha\left((s-s_0)(H^2+(R+\rho_0)^2) - H^2 s_0\right)}\right)^{\frac{1}{\beta}} \tag{10}$$

Eq. (10) provides the estimation of the value of the strain rate sensitivity index m, which is one of the key material rheological parameters. The estimation can be carried out using the values of s and H measured after a single experiment.

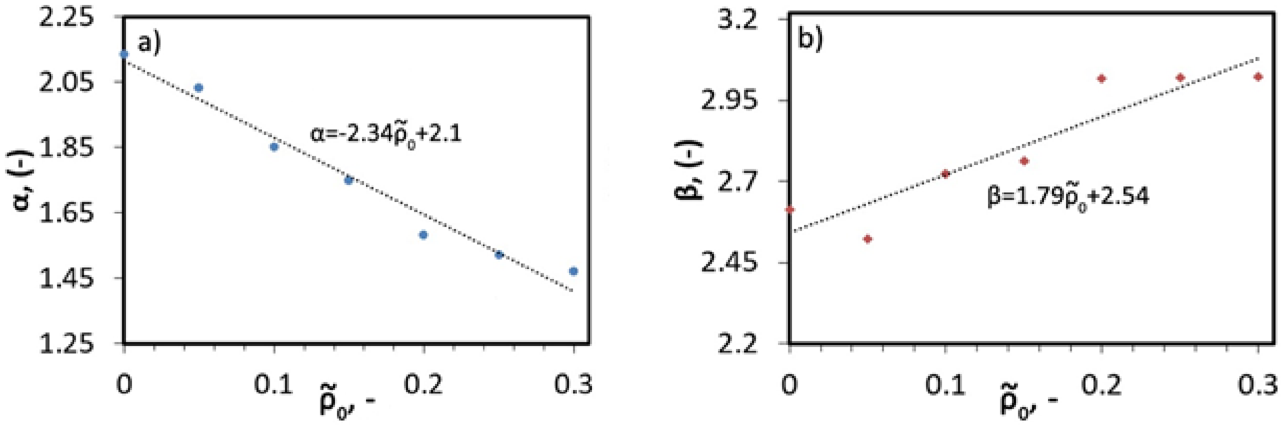

Fig. 6. Approximations of α and β.

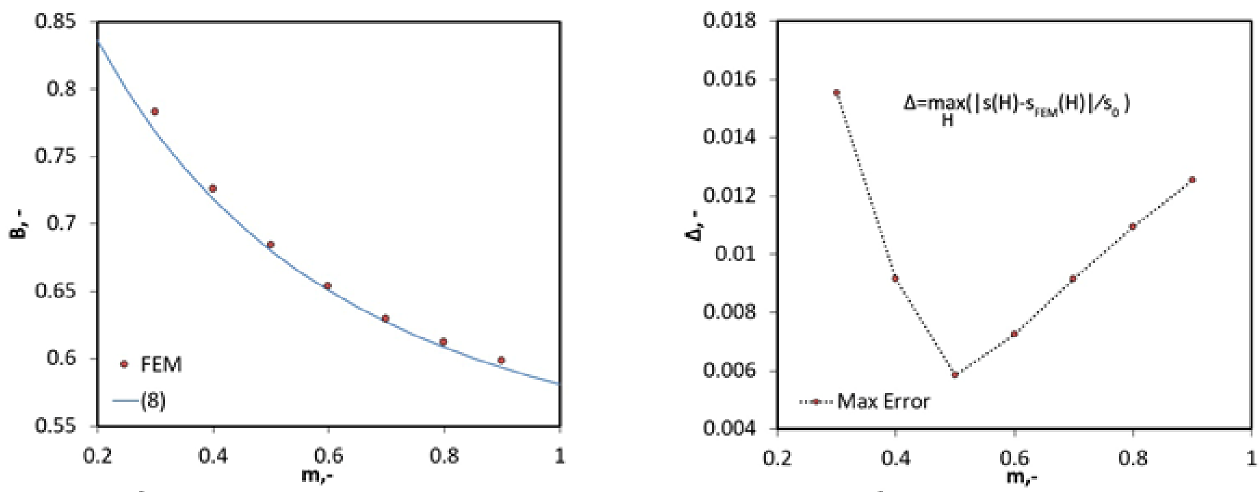

Fig. 7. (a) Values of B for different values of m obtained by FEM and Eq. (8); (b) deviations between the values of thickness calculated by Eq. (8) and FE simulations.

CONCLUSIONS

This work reports a study of the free bulging process by FE simulation. The results generalization shows that the dome pole thickness appears to be linearly related to $H/(\rho - \rho_0)$. The slope of this relation denoted as B does not depend on the applied pressure, the initial thickness of the specimen and K coefficient of the Bakofen equation. In the absence of strain hardening, the strain rate sensitivity index affects the slope of the line and as a result the specimen pole thickness. The B coefficient depends also on the die geometry expressed through the value of the normalized entry radius. The approximation advanced on the ground of the computer simulation results provides the estimation of the specimen pole thickness at a specific dome height. This relation is applicable to materials of a strain rate sensitivity index in the range of 0.3-0.9 to be used as a die with the entry normalized radius less than 0.3. The inversion of approximation pointed above makes it possible to estimate the value of the strain rate sensitivity index on the ground of the results of a single free bulging test.

Acknowledgements

The study was implemented in the framework of the Basic Research Program at the National Research University Higher School of Economics (HSE) in 2016.

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