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Numerical simulation of superplastic bulge forming test

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Abstract. Superplastic blow forming is a technology of shell parts production. The development of these processes requires computer simulation which cannot be realized without accurate parameters of the applied material. This characterization can be based on results of free bulging tests. Characterization techniques utilize the models of the dome growth during the bulging test. This study is devoted to the assessing of friction coefficient effect on the linear behavior of normalized thickness - normalized height relation.

1. Introduction

Superplasticity is a viscous behavior of polycrystalline materials which can be observed in a narrow range of temperatures and strain rates. Superplastic materials like aluminum and titanium alloys can sustain elongations up to 2000% pre failure [1,2] this ability makes them applicable in auto and aerospace industries [3].

The family of industrial processes that utilize superplastic materials is called superplastic forming. During these processes the sheet metal specimen is blowing by pressure into the die which has a cavity with the negative shape of the product. The accurate improvement of these processes is impossible without the computer simulation. These simulations are usually made by commercial CAE software such as ABAQUS CAE, MSC.Marc, Deform3d, etc. Accuracy of finite element simulations is strongly affected by the accuracy of material characteristics. Thus, the problem of accurate material characterization is in the focus of many studies [2-8]. The ideal superplastic material model is established by Backofen [9] equation defining the relation the equivalent flow stress σ_e and equivalent strain rate as:

$$\sigma_e = K \dot{\varepsilon}_e^m \quad (1)$$

where m – strain rate sensitivity index, K – strength coefficient.

Another idealized constitutive equation takes strain hardening into account. This modified equation was used in studies [10,11]:

$$\sigma_e = K \dot{\varepsilon}_e^m \varepsilon_e^n \quad (2)$$

where ε_e - equivalent strain, n – hardening index.

The most popular experimental technic which is generally applied for characterization of sheet materials subjected to superplastic forming are tensile test and bulge forming test. The tensile test procedure is standardized by ASTM standard [12]. Nevertheless, a nonuniform flow of the material in a gauge region of the specimen leads to inaccuracies in material characterization. The effect of specimen geometry on the material behavior both experimentally and numerically [13-16]. It is also worth to notice that the exploitation of materials characteristics from tensile test processing for real SPF process simulation can leads to inaccuracies because during superplastic forming processes biaxial tension is observed while tensile tests reproduces uniaxial tension [17].



The test that reproduce biaxial tension is superplastic bulge test standardized by ASTM standard [18]. During the test the sheet specimen is blown into cylindrical female die by pressure regime. The scheme of free bulging process presented on figure 1. The preference of superplastic bulge test usage for material characterization was discussed in many studies [7,8,17,19,20].

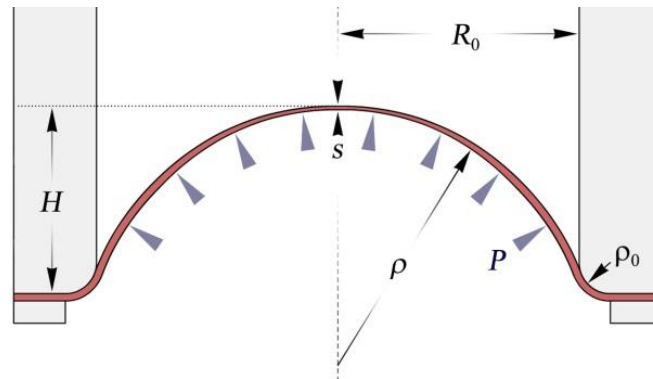


Fig. 1. Scheme of the free bulging test.

All approaches to superplastic materials characterization based on the free bulging test results can be divided on two main parts. The approaches from the first one is based on the inverse analysis with finite element simulation for the direct task solving. This approach was used in [21]. All other methods utilize models of the dome growth during the free bulging test [2-8,10,11,22]. Thus, the normalized thickness at the pole – normalized dome height relation ($s(H)$ relation) plays the significant role during the characterization procedure.

A lot of $s(H)$ relations were presented. Relationship proposed by Jovane [2] is based on a uniform workpiece thickness distribution hypothesis. Hill in [5] proposed an equation based on the suggestion that the stress mode at every point of the specimen is a balanced biaxial tension. The assumption about uniform meridian elongation leads to the dependency proposed by Enikeev in [6]. The main problem of the relations proposed in [2,5,6] is the fact the all relations are invariant to material properties.

On the basis of the computer simulation of free bulge test results Carrino [22] proposed a linear model of normalized thickness at the pole – normalized dome height relation for concrete geometry of the mold. The slope of this linear dependency depends on strain rate sensitivity index.

By applying the same approach in [23] it was found that normalized thickness - normalized height relation strongly depends on strain rate sensitivity index as well as on dimensionless geometrical parameters of the equipment. The comparison of the $s(H)$ relations obtained in [2,5,6] and the [23] presented in [23] but relations from [22] and [23] need to be compared. The relation from [22] labeled as “model (1)” and from [23] labeled as “model (2)” will be compared in section 2 of this study.

All mentioned models of the dome growth during the free bulging test [2, 5, 6, 22,23] neglects the effect of friction influence which is significant during the actual SPF process.

This study is devoted to the assessing of friction coefficient effect on the linear behavior of normalized thickness - normalized height relation. The assessing was made according analysis of computer simulations results. The simulations were carried out with different strain rate sensitivity indexes and different friction coefficients.

2. Dome apex thinning models

2.1. Model (1).

Carrino et al. [22] developed the model for predicting dome height and thickness during the free bulging test and characterize PbSn60 alloy. In the study [22] it was noticed that the value of thickness varies linearly with $1/(1 + (H/R)^2)$ H – current height, R – aperture radius:

$$\frac{s}{s_0} = \frac{\alpha}{1+H_g^2} - \beta \quad (3)$$

where s and s_0 are current and initial thickness at the dome apex, $H_g = \frac{H}{R}$, parameters α_g, β_g depends on the values of m : $\alpha = \frac{0.1512}{m} + 0.9752$, $\beta = \frac{0.1456}{m} - 0.0178$. Equation (1) was used in [22] as constitutive equation.

This model was developed for specific geometry: $R = 30$, $\rho_0 = 2$. Equation (2) was used as constitutive equation. The modification of this method was presented in [11] it was shown that parameters α, β also depends on hardening index n

2.2. Model (2).

Model of dome apex evolution during the free bulging test presented by author in [23] is also linear:

$$\frac{s}{s_0} = 1 - B \frac{2H^2}{H^2 + (R + \rho_0)^2} \quad (4)$$

where ρ_0 – entry radius, parameter B depends on the values m and $\frac{\rho_0}{R}$:

$$B = 0.5 + \frac{1}{\alpha'(1+m)^{\beta'}} \quad (5)$$

where $\alpha' = -2.34 \frac{\rho_0}{R} + 2.1$, $\beta' = 1.79 \frac{\rho_0}{R} + 2.54$.

Material characterization technic based on this approach was used to determine superplastic parameters of OT4-1 titanium alloy at 840°C in [8]. Equation (1) was used as constitutive equation

2.3. Comparison

Both models show the linear dependency between normalized thickness at the dome apex and normalized height during the free bulging test. In order to compare model (1) and model (2) it makes sense to calculate the slope of the line for both methods. The calculation of the slope of the $s(H)$ from the model (1) can be reformulated in terms of model (2) through the following procedure:

It is necessary to fix the height of the dome equal to the aperture radius and makes entry radius equal zero for both methods:

$$\frac{s}{s_0} = \frac{\alpha}{1+H_g^2} - \beta = \frac{\alpha}{2} - \beta \quad (6)$$

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

Substituting (6) in (7) it is possible to obtain slope of the $s(H)$ dependency from the model (1) in terms of the model (2):

$$B_{(1)} = 1 - \frac{\alpha}{2} + \beta \quad (8)$$

Comparison of the models was made by formulas (5) and (8) for different material parameters. The results of comparison for materials with different strain rate sensitivity indexes as well as deviation between presented on figure 2.

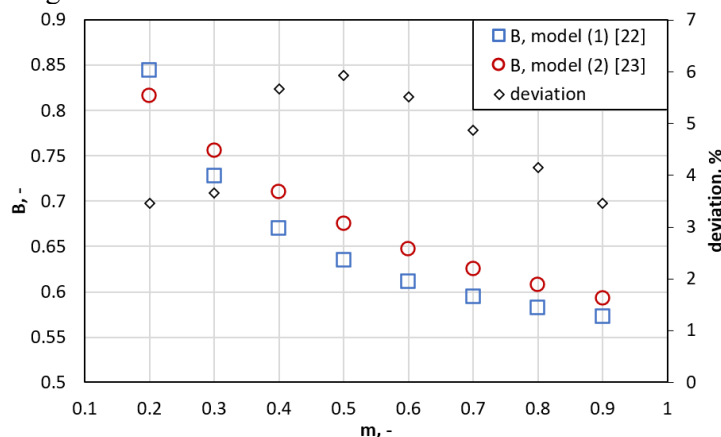


Fig. 2. Comparison between methods 1 and 2 for different strain rate sensitivity indexes.

The sets of boundary conditions are the same, the pressure regime was constant in both cases. The deviation is up to 6% can be caused by different friction coefficient used for FEM simulations.

3. Finite element simulation

Commercial software ABAQUS CAE was used for simulations. All simulations were made according ASTM standard [18] with follow geometry characteristics: aperture radius $R = 50$ mm, entry radius $\rho_0 = 5$ mm; initial thickness of the specimen $s_0 = 1$ mm. The die was considered rigid the pressure was constant. The specimen -deformable part was divided on 1500 volume 4 nodes elements in 5 layers. The view of the model with volume elements presented on figure 3.

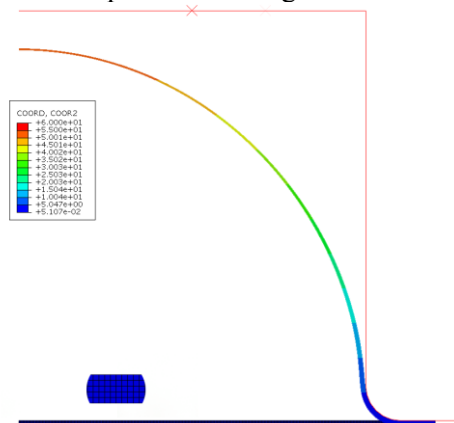


Fig. 3. Axisymmetric FE model

Figure 3 presents the view of the specimen both at the beginning of the free bulging test and at the moment when dome height is equal to the sum of aperture radius and entry radius ($H = R + \rho_0$). By colors different values of stress are shown.

4. Results and discussion

In this paper, the finite element simulation was applied to evaluate the effect of the friction coefficient as on the linear behaviour of $s(H)$ dependence. The simulations were carried out for different strain rate sensitivity indexes $m = 0.2 \div 0.9$ with a step 0.1 and different values of coulomb friction $fr = 0 \div 1$ with a step 0.2 . The influence of the friction on the $s(H)$ dependency is shown by the best way when strain rate sensitivity index is equal 0.9 . Normalized thickness at the pole – normalized dome height dependency obtained by FE simulation with $m = 0.9$ presented on figure 4.

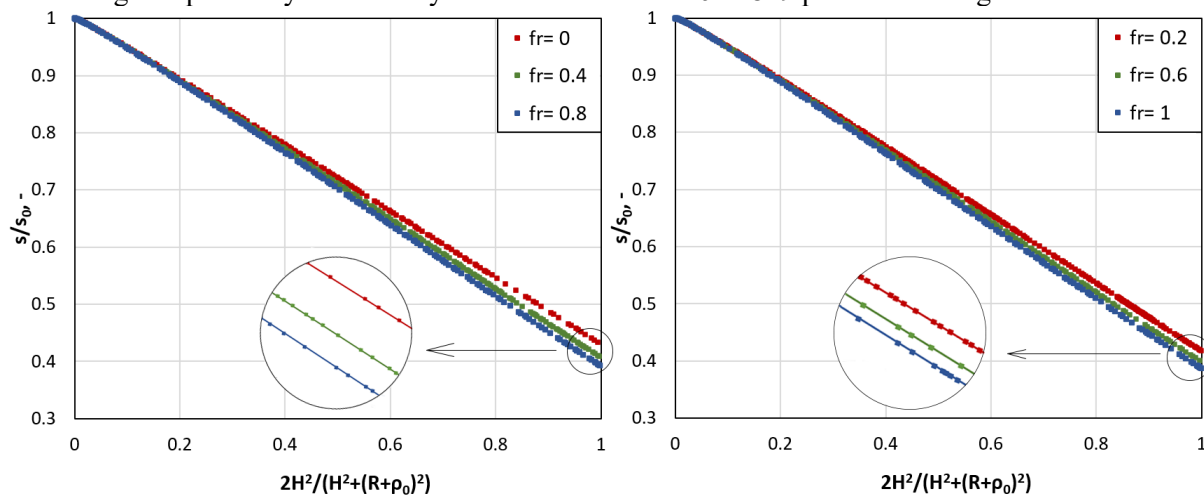


Fig. 4. Thickness at the dome apex for different friction coefficients.

Different colors correspond different friction coefficient the lowest lines correspond to the simulations with largest value of friction coefficient. It can be noticed that all presented dependencies for different friction coefficient are linear.

The results of all simulations with different strain rate sensitivity indexes m and values of friction were processed in order to obtain the values of the slope B . The coefficient B was calculated by inverting equation (4). Coefficient B was found for the moment of time when height of the dome is equal to the $R + \rho_0$. The values of B coefficient are illustrated on figure 5.

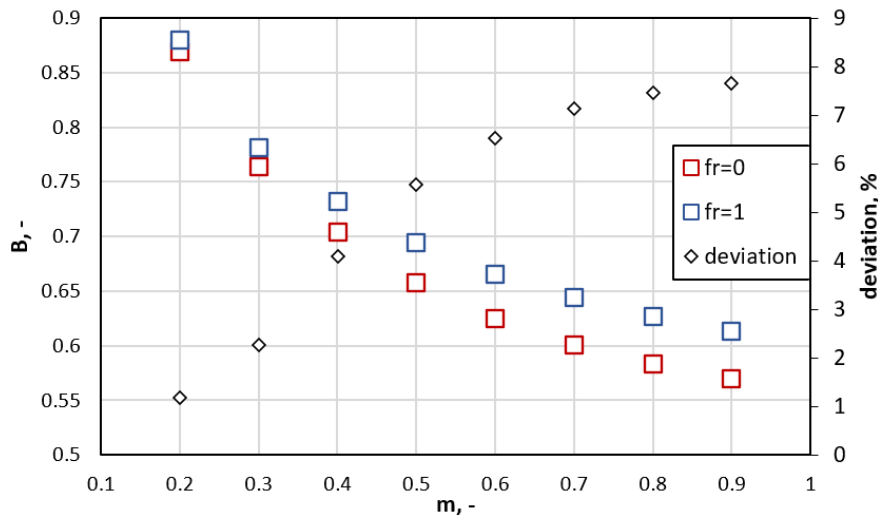


Fig. 5. Values of B for different strain rate sensitivity indexes and friction coefficient.

Red quadric markers correspond to the values of B obtained from simulations without effect of friction the blue ones correspond to the results of forming when friction coefficient was equal to 1. The deviations between parameters B is growing with the growth of the strain rate sensitivity index values which matches the physical essence of the process.

5. Conclusion

In this paper the normalized thickness at the pole – normalized dome height dependency during free bulging test is studied numerically. Two models of dome growth are compared the deviation between them is up to 6%.

By processing a series of numerical simulations of free bulging test with different material characteristics and friction coefficients it was found that when the effect of friction is taken into account the normalized thickness at the pole – normalized dome height dependence is linear. The difference in slopes of these dependencies is up to 8%.

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