Superplasticity in Advanced Materials - ICSAM 2015

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Selected, peer reviewed papers from the
12th International Conference on
Superplasticity in Advanced Materials
(ICSAM 2015),
September 7-11, 2015, Tokyo, Japan

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Trans Tech Publications Ltd
Churerstrasse 20
CH-8808 Pfaffikon
Switzerland
http://www.ttp.net

Volumes 838-839 of
Materials Science Forum
ISSN print 0255-5476
ISSN cd 1662-9760
ISSN web 1662-9752

Full text available online at *http://www.scientific.net*

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e-mail: sales-usa@ttp.net

Materials Science Forum Vols. 838-839 (2016) pp 552-556
© (2016) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/MSF.838-839.552

Submitted: 2015-04-30
Revised: 2015-06-17
Accepted: 2015-06-25

Characterization of superplastic materials by results of free bulging tests

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Keywords: superplastic forming; free bulging; biaxial tension; material characterization.

Abstract. Determination of material constants describing its behavior during superplastic gas forming is the main subject of this study. The main feature of free bulging tests is the stress-strain conditions which are very similar to ones occurring in the most of gas forming processes. On the other hand, the interpretation of the results of such tests is a complicated procedure. The paper presents a simple technique for the characterization of materials superplasticity by free bulging tests, which is based on inverse analysis. The main idea of this technique is a semianalytical solution of the direct problem instead of finite element simulation which allows one to reduce the calculation time significantly. At the same time the results this simplified solution are accurate enough to obtain realistic material constants.

Introduction

The main goal of computer simulation of superplastic forming processes is optimization of pressure cycles providing optimal strain rate in critical parts of a formed product. Adequacy of the results of such simulations depends strongly on the accuracy of initial and boundary conditions and constitutive equations of the material.

Constitutive behavior of a material during isothermal hot forming is described as a relation between the equivalent stress σ_e, equivalent strain ε_e, and equivalent strain rate $\dot{\varepsilon}_e$:

$$\sigma_e = f(\dot{\varepsilon}_e, \varepsilon_e) \tag{1}$$

where $f(...)$ is a single-valued function which should be found experimentally. The mechanical behavior of superplastic materials can be approximated by the relation:

$$\sigma_e = \sigma_0 + K\dot{\varepsilon}_e^m \varepsilon_e^n \tag{2}$$

where σ_0, K, m and n are material constants. If the strain hardening and minimum stress are neglected so values of n and σ_0 are considered to be zero, the equation (2) is equal to the standard power relation proposed in [1] for describing of superplastic materials behavior. The most important characteristic in this power relation is the strain rate sensitivity m which is directly responsible for flow localization. Better plasticity is provided by higher values of m and superplastic materials have this value higher than 0.3 [2]. More complex constitutive equations can be used for description of material behavior in a wide strain rate range [2] while the equation (2) is more convenient for approximation of constitutive behavior when strain rate varies in a narrow range.

The most common way to obtain constitutive constants of a material is tensile testing. At the same time, complex experimental investigations [3, 4] shows that the material model based on uniaxial tensile tests may result in insufficient accuracy for describing of biaxial forming. Thus the determination of constitutive constants based upon constant pressure bulging tests is matter of scientific interest in many studies.

A method of determination of material constants on the basis of free bulging tests carried out to a predetermined dome height is proposed in [5]. A simple technique for determination of constants K, m and n is in the focus of [6]. Inverse method based on the finite element (FE) simulation is applied in [7].

Inverse analysis based on FE simulation appears to be the most universal way to determine the material constants. At the other hand FE calculations are very time consuming for using them for solving of direct problem during inverse analysis. In this regard using of simplified engineering models which provides the solution in analytical or semianalitical form could be more suitable. This approach was provided in [8, 9] for characterization of aluminum alloy by bulge testing using constitutive relations neglecting strain hardening.

In the given work the approach presented in [9] is improved so it needs less experimental data and takes the strain hardening into consideration. This approach was applied to processing of the experimental results of free bulging tests of aluminum alloy (AMg6) available in [9] and magnesium alloy (AZ31) available in [10].

Mathematical model and characterization technique

The characterization technique is based on inverse analysis using nonlinear simplex method [11] to find the material constants providing the minimum of objective function:

$$F = \sum_{i=1}^{N} \min_{t} \left(\sqrt{\left(\frac{H_i - H(t)}{H_i} \right)^2 + \left(\frac{t - t_i}{t_i} \right)^2} \right) \tag{3}$$

where N is a number of experiments, $H(t)$ – predicted dome height at current time t, t_i and H_i are the experimental values of time and dome height. $H(t)$ is obtained by simplified analytical model described below.

Consider the scheme of a free bulging process illustrated at Fig. 1. A metal sheet of initial thickness s_0 is formed by pressure P in a cylindrical die of an aperture radius R_0 and entry radius ρ_0. Free part of the dome is assumed to be a spherical surface with radius ρ. H is the height of the dome and s is the current thickness at the dome apex.

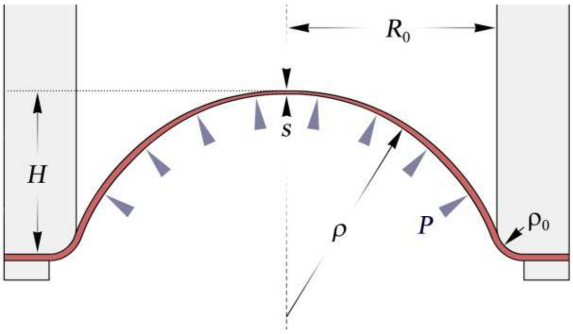

Fig. 1. Scheme of the free bulging process.

Using well known relations for the geometry illustrated in fig. 1 the values of effective stress, effective strain, and effective strain rate could be found as follows:

$$\sigma_e = \frac{P\rho}{2s}, \tag{4}$$

$$\varepsilon_e = \ln\left(\frac{s_0}{s}\right), \tag{5}$$

$$\dot{\varepsilon}_e = -\frac{1}{s}\frac{ds}{dH}\frac{dH}{dt}, \tag{6}$$

Combining the equations (3)-(6) it is possible to construct the differential equation describing the evolution of H:

$$\frac{dH}{dt} = -\frac{s(H)}{ds/dH} f^{-1}\left(\frac{P\rho}{2s}, \ln\left(\frac{s_0}{s(H)}\right)\right), \tag{7}$$

where $f^{-1}(\sigma_e, \varepsilon_e) = f^{-1}(f(\dot{\varepsilon}_e, \varepsilon_e), \varepsilon_e) = \dot{\varepsilon}_e$ is the invers function of the one mentioned in equation (1).

Resolving of equation (7) needs the relation $s(H)$ to be specified. Different geometrical models were proposed for the evaluation of this relation [5, 12-15]. In the given study the following form of relation describing $s(H)$ was used:

$$s = s_0\left(1 - B\frac{H}{\rho + \rho_0}\right), \tag{9}$$

where B is the constant to be determined. The equation (9) can be considered as a generalization of $s(H)$ relation proposed in [15] where it was noticed that s varies linearly with $R_0^2/(R_0^2 + H^2)$. One can observe that this linear relationship is follows form equation (9) if $\rho_0 = 0$. The value of ρ can be geometrically expressed as follows:

$$\rho = \frac{H^2 + (R_0 + \rho_0)^2}{2H} - \rho_0. \tag{10}$$

The processing of experimental results is performed in two steps. First for every experimental point (H_i, s_i) the value of B_i is determined using equation (9). After that, the objective function (3) is minimized using numerical solution of equation (7) for the evaluation of $H(t)$. This technique was realized as computer software and applied for the processing of experimental data available in literature.

Experimental data

The experimental data of AMg6 (AISI/SAE: A95456/A95556) aluminum alloy free bulging available in [9] and AZ31 magnesium alloy free bulging available in [10] were used for the validation of the proposed technique and the computer software developed. The free bulging tests of AMg6 aluminum sheets were performed at the temperature of 688 K and constant pressure of different values: $P_1 = 0.3$, $P_2 = 0.35$, $P_3 = 0.4$, $P_4 = 0.5$, $P_5 = 0.6$ MPa. The die geometry was correspond to the values R_0 =50 mm and ρ_0=5 mm. Mean initial thickness of the specimens was s_0=0.92 mm.

The experimental data of AZ31 blow forming tests presented in [10] was obtained using the equipment which is capable to measure dome thickness during the test. The results of two blow forming tests available in [10] and describing the evolutions of dome height during the forming at constant pressures of 0.16 MPa and 0.29 MPa as well as final apex thickness of domes were used for the characterization of AZ31. These tests were performed for the sheets of initial thickness 0.5 mm using cylindrical die of 35 mm diameter and 3 mm entry radius at the temperature of 793 K.

Results and discussion

Using the technique mentioned above the experimental data was processed and following information about the material constants was obtained. For AMg6 alloy: σ_0=0.0, K=165, m=0.272 and n=0.0. For AZ31 alloy: σ_0=0.0, K=152, m=0.477 and n=0.04. Although the strain hardening n and initial stress σ_0 were varied by optimization procedure, their values were found almost zero (less than 10^{-5}) for the AMg6 alloy so they can be neglected and considered as 0 same as the value of σ_0 obtained for AZ31 alloy.

The constitutive constants obtained by the proposed technique are very close to the ones obtained elsewhere using different methods. In [9] the constants K and m were found for AMg6 alloy as 155.7 and 0.275. In [10] the values of K, m and n were found as 136.63, 0.457 and 0.013.

In order to verify the obtained constitutive constants, FE simulation of bulging process was performed using the obtained constants. The simulations were realized by authors own finite element code solving 2D asymmetrical task with three-node triangle elements and sticking contact conditions. The results of simulations are presented in fig. 2. It should be stressed that no FE simulations were used at the characterization stage so the correspondence between the $H(t)$ curves obtained numerically and the experimental results confirms the accuracy of the proposed technique.

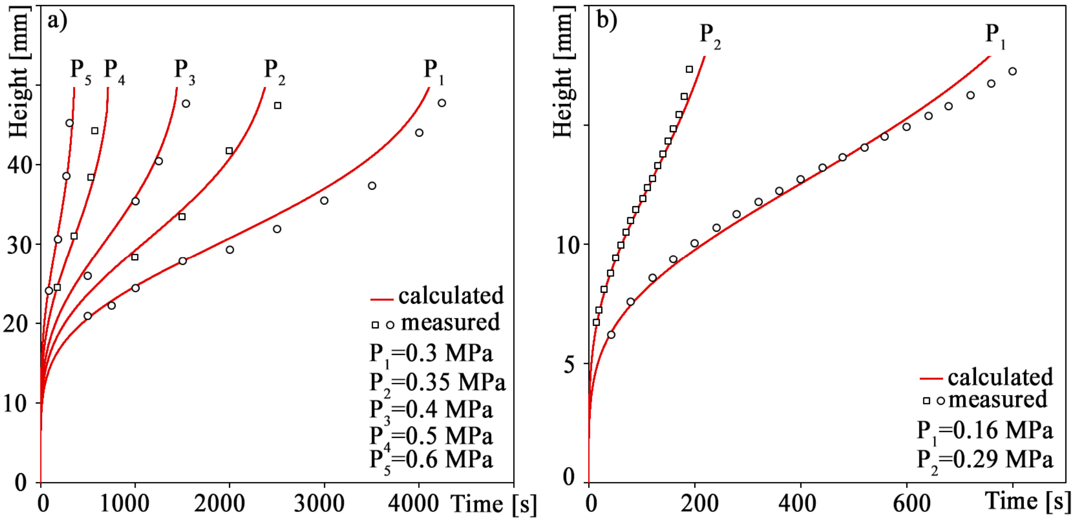

Fig 2. Comparison between the results, obtained by numerical simulation and the experimental blow forming results of a) – AMg6 [9] and b) – AZ31 [10] sheets

Conclusions

A simple technique which enables one to characterize a material by blow forming tests is presented. This technique is universal and may be used for the determination of material constants for different forms of constitutive equations. The main idea is using the inverse analysis with semianalitical solution of the direct task which is based on the $s(H)$ relation obtained in experiment. Using the assumption of linear character of s variance with $H/(\rho+\rho_0)$ allows one to decrease the number of experiments for the material characterization. Verification of the proposed technique was performed using finite element simulation and the experimental data available in the literature and it was shown that the accuracy is acceptable.

Acknowledgements

The study was implemented in the framework of the Basic Research Program at the National Research University Higher School of Economics (HSE) in 2015.

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