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Determination of optimal gas forming conditions from free bulging tests at constant pressure

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ABSTRACT

This study proposes a method for determination of material characteristics by inverse analysis of free bulging tests results. The blow-forming tests were carried out at the temperature of 415 °C using aluminum alloy (AMg-6) sheets of a 0.92 mm thickness. Each test was performed at constant pressure. For each fixed value of pressure, a series of experiments was carried out with different forming times to obtain evolutions of dome height *H* and thickness *s*. Two different constitutive equations were used to describe the dependence of flow stress on the effective strain rate: the Backofen power equation and the Smirnov one taking into account an s-shape of stress–strain rate curve in the logarithmic scale. The constants of these equations were obtained by least squares minimization of deviations between the experimental variations of *H* and *s* and ones predicted by a simplified engineering model formulated for this purpose. Using the Smirnov constitutive model to describe the dependence of flow stress on strain rate, unlike the classical power law, makes it possible to analyze the variation of strain rate sensitivity index *m* with strain rate. On the basis of the obtained data, the optimum strain rate for AMg-6 processing was estimated as one corresponding to the maximum of strain rate sensitivity index. The validity of the proposed method was examined by finite element simulation of free bulging process.

1. Introduction

Gas forming is an advanced method of complex thin-walled parts production which is used mainly in aerospace industry. To increase the hot forming ability and improve the mechanical properties of the final products, the utilization of superplasticity effect is desired. A computer simulation is necessary to optimize the pressure cycles during the development of superplastic forming technologies. Adequacy of the simulation results depends strongly on the accuracy of initial and boundary conditions and constitutive equations of the material.

In isothermal condition, neglecting the effects of strain hardening and grain growth, the mechanical behavior of a material during hot forming is described as a relation between the equivalent stress σ_e, and equivalent strain rate $\dot{\varepsilon}_e$:

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

where $f(\ldots)$ is a single-valued function which should be determined experimentally.

The mechanical behavior of superplastic materials is generally described by standard power relation proposed by Backofen et al. (1964):

$$\sigma_e = K\dot{\varepsilon}_e^m \tag{2}$$

where K and m are characteristics of the material. The most important characteristic in Eq. (2) is the strain rate sensitivity m. Higher values of m are responsible for lower rates of flow localization and better plasticity what was first described by Hart (1967). For superplastic materials the value of m is greater or equal to 0.3 (Vasin et al., 2000).

The Eq. (2) is still the most commonly used constitutive model for simulation of superplastic forming processes. It is a classic power function which forms a straight line with a slope m if it is plotted in logarithmic scale. At the same time it is well known that a sigmoidal variation of the flow stress with strain rate takes place in the logarithmic scale (Vasin et al., 2000). Thus, Eq. (2) may be applied only as a local approximation describing the sigmoidal

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curve within a rather narrow range of the strain rates (Enikeev and Kruglov, 1995).

Smirnov (1979) proposed the rheological model of visco-plastic medium which describes the behavior of superplastic materials in a wide range of strain rates. The constitutive equation corresponding to this model takes the following form:

$$\sigma_e = \sigma_s \frac{\sigma_0 + k_v \dot{\varepsilon}_e^{m_v}}{\sigma_s + k_v \dot{\varepsilon}_e^{m_v}} \quad (3)$$

where σ_0 is the threshold stress which corresponds to the small strain rates, σ_s is the yield stress at large strain rates, k_v and m_v are material parameters.

The main advantage of the Smirnov model is its invariance in a wide range of strain rates. At the same time, once the constants σ_0, σ_s, k_v and m_v are found for a material at a given temperature, the optimal forming conditions can be easily evaluated as a strain rate range corresponding to the required strain rate sensitivity (Aksenov et al., 2013).

The strain rate sensitivity index m can be obtained from Eq. (3) as follows:

$$m(\dot{\varepsilon}_e) = \frac{dln(\sigma_e)}{dln(\dot{\varepsilon}_e)} = \frac{m_v k_v \dot{\varepsilon}_e^{m_v}(\sigma_s - \sigma_0)}{(\sigma_0 + k_v \dot{\varepsilon}_e^{m_v})(\sigma_s + k_v \dot{\varepsilon}_e^{m_v})} \quad (4)$$

This function has a peak at the strain rate:

$$\dot{\varepsilon}_{\text{opt}} = \left(\frac{\sqrt{\sigma_0 \sigma_s}}{k_v} \right)^{1/m_v} \quad (5)$$

Flow behavior of superplastic materials can be described in more details by application of complex microstructure mechanisms based constitutive equations. Khraisheh et al. (2006) described constitutive model of AZ31 alloy taking into account microstructural features including grain growth and cavitation. To calibrate the model they used microstructural investigations as well as results of extensive experimental study proposed by Abu-Farha and Khraisheh (2007). Albakri et al. (2013) recently used this constitutive model to construct forming limit diagrams. Constant pressure free bulging tests were used in their work to correct the constitutive model based on uniaxial tensile testing. The same material was investigated by Taleff et al. (2010), they demonstrated that the initial material model based upon uniaxial tensile data is not accurate enough to describe biaxial forming and the corrections should be made by considering constant pressure bulging tests.

This comprehensive approach allows one to achieve accurate constitutive model of investigated alloys but it needs a large amount of experimental work including tensile tests in wide strain rate range, microstructure investigations and bulging tests for calibration of the model. The purpose of this work is to provide a method determining the main characteristics of the material on a base of free bulging tests only.

The determination of material constants on the basis of bulging tests is in the focus of many studies. Enikeev and Kruglov (1995) proposed a method for calculation of constants in Eq. (2) on the basis of free bulging tests carried out to a predetermined dome height. Li et al. (2004) simulated SPF processes by finite element method (FEM) and applied an inverse analysis to obtain the true material constants in Eq. (2). Giuliano and Franchitti (2007) proposed a method of superplastic material characterization which is able to predict a strain hardening index as well as the constants K and m. Giuliano then used this method to determine the Backofen constitutive equation constants for Ti-6Al-6V alloy (Giuliano, 2008) and most recently to AA-5083 alloy (Giuliano, 2012). All of these methods use a Backofen constitutive equation what makes it difficult to determine the optimal forming conditions.

Inverse analysis applied by Li et al. (2004) appears to be the most universal way to determine the material constants. This approach is based on multiple simulations of bulging process and searching the material constants which produce the closest results to the experimental ones by minimization of error function. Using of FEM for simulation of the process provides appropriate accuracy, but calculations are very time consuming. In this regard using of simplified engineering models which provides the solution in analytical or semianalytical form could be more suitable.

Hill (1950) provided one of the earliest formulations of the free bulging process model and general solution for cold-worked metals. Woo (1964) formulated a general method of analysis for axisymmetric forming processes and applied it to cold hydrostatic bulging process using numerical iterative procedure for the solution. Similar numerical procedure was used by Holt (1970) for simulation of superplastic free bulging and bulging in conical grooves. Holt's formulation is based on the assumption of a balanced biaxial stress state, while Guo and Ridley (1989) assume that the ratio of the circumferential and tangential stresses varies with fractional height in a logarithmic manner. Yang and Mukherjee (1992) consider a bulging contour to be a part of an ellipsoid instead of most commonly used sphere to increase an accuracy of the model for a low m materials.

All the approaches of superplastic bulging simulation mentioned above results in equation systems supposed to be solved numerically. Yu-Quan and Jun (1986) proposed a method which provides simple differential equation describing the dependence of dome height in respect to forming time. This equation can be obtained for any constitutive model allowing the construction of inverse function for the $f(\ldots)$ from Eq. (1). The week point of this approach is that it uses the expression of dome apex thickness versus dome height in a form which does not depend on material properties.

Since the main goal of this investigation is the interpretation of bulging forming experiments, the dependence of apex thickness on dome height was obtained as an approximation of the experimental results. This approximation was then used to produce the model of dome height evolution using an approach which is similar to one described by Yu-Quan and Jun (1986). The model of dome height evolution produced by this way is then used in inverse analysis to determine the material constants.

The proposed method was applied to determine the constants σ_0, σ_s, k_v and m_v of Smirnov constitutive equation (Eq. (3)) as well as K and m of Backofen one (Eq. (2)) for AMg6 aluminum alloy. In order to validate the obtained material constants, they were used in finite element simulation of the bulging experiments. Another validation procedure was performed by comparison of obtained strain rate sensitivity values with ones calculated by the method based on Enikeev and Kruglov (1995) equations.

2. Mathematical model of a bulging process

The scheme of a free bulging process is illustrated at Fig. 1. A metal sheet of initial thickness s is formed by pressure P in a die

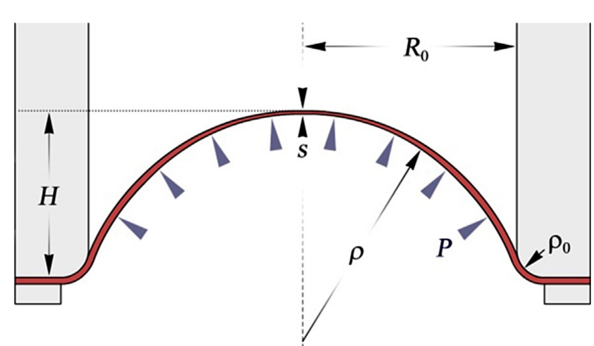

Fig. 1. Scheme of the free bulging process.