Journal of Materials Processing Technology 237 (2016) 88–95

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

# Design of a gas forming technology using the material constants obtained by tensile and free bulging testing

Sergey A. Aksenov[a,*], Aleksey V. Kolesnikov[b], Anastasia V. Mikhaylovskaya[c]

[a] National Research University Higher School of Economics, Department of Applied Mathematics, 123458 Tallinskaya 34, Moscow, Russia
[b] National Research Irkutsk State Technical University, Laboratory of Progressive Forming Methods in Harvesting and Stamping Production, 664074, Lermontova 83, Irkutsk, Russia
[c] National University of Science and Technology "MISiS", 119049, Leninsky Prospekt, 4, Moscow, Russia

ARTICLE INFO

*Article history:*
Received 25 November 2015
Received in revised form 2 May 2016
Accepted 4 June 2016
Available online 5 June 2016

*Keywords:*
Material characterization
Biaxial tension
Free bulging
Tensile test
Superplastic forming
Finite element simulation

ABSTRACT

Uniaxial tensile testing is a most common way of obtaining the information about the constitutive behavior of a material during gas forming. At the same time for industrial applications it is important to know the material behavior in a biaxial tension mode, which is much closer to the one realized in a shell during forming process. The paper focused on the investigation of the differences between the gas forming technologies designed in FEM based CAE system using the material parameters obtained in conditions of uniaxial and biaxial tension. The rheological characteristics of AMg6 aluminum alloy obtained by tensile and free bulging testing are analyzed and compared. The comparison shows that the constitutive data obtained by these methods are different. The effect which these differences could provide to the design of a gas forming technology was studied. A pressure regime for an aircraft part forming which maintains the maximum strain rate at constant level was calculated using finite element simulation for the both sets of constitutive constants. The calculated pressure regimes were then realized experimentally and the differences between the deformed specimens were analyzed.

## 1. Introduction

Gas forming technology is a method of production of thin sheet parts used mainly in aerospace industry. A sheet specimen is climbed between a dies and formed by pressure of inert gas. Automated pressure controlling systems make it possible to realize superplastic or quasi-superplastic forming regimes ensuring better plasticity of a material. Such technological processes are designed using computer simulations realized in modern finite element method (FEM) based systems.

The accurate describing of constitutive behavior of a material is a key point to the design of forming technologies. Tensile testing is a most common way providing the information about constitutive behavior of a material. At the same time, the data obtained by this way are usually not accurate enough for construction of realistic models of gas forming processes. One of the possible reasons is that during the gas forming the biaxial tension stress mode predominates in the material volume since the stress mode in tensile testing is uniaxial tension. The way of cavitation and microstructure development is different in these different stress modes what can cause the differences in constitutive behavior. Moreover, irregular thinning and necking accruing in tensile tests may produce additional errors. Nazzal et al. (2011) investigated the effect of specimen geometry in superplastic tensile tests. They found that variations in specimen geometry could lead to large disparities in testing results.

In order to avoid the complications, listed above, the corrections of constitutive data obtained by tensile tests are required. These corrections can be provided by additional free bulging testing which produce the biaxial tensile stress mode in the material. Such an approach was used by Albakri et al. (2013) for correction of tensile test data previously obtained by Abu-Farha and Khraisheh (2007) for AZ31 magnesium alloy. Other way, is the determination of constitutive constants by the free bulging tests directly.

Since free bulging tests do not provide the stress-strain rate data directly, different methods were developed to interpret their results. Most of them provide the way to get the constants of a power law constitutive model:

$$\sigma_e = K\dot{\varepsilon}_e^m \varepsilon_e^n \tag{1}$$

Where $\sigma_e$ is effective stress; $\dot{\varepsilon}_e$ is effective strain rate; $\varepsilon_e$ is effective strain; K, m and n are the characteristics of the material. If the strain hardening is neglected (n = 0), the Eq. (1) is similar to

---

* Corresponding author.
*E-mail addresses:* saksenov@hse.ru, aksenov.s.a@gmail.com (S.A. Aksenov).

http://dx.doi.org/10.1016/j.jmatprotec.2016.06.003

the one proposed by Backofen et al. (1964) for describing of superplastic materials flow behavior. This power law equation do not contain any information about the microstructure development and different deformation mechanisms taking place during superplastic deformation which can be taken into account by complex physically-based constitutive models as the ones recently investigated by Alabort et al. (2015). At the same time the Eq. (1) can be adopted as a simple approximation of material properties in a limited strain-rete range and used for the computer simulation of modern SPF technologies. Zhao et al. (2010) used this equation to describe the material properties for three dimensional finite element simulation of a hollow blade forming process. Luckey Jr. et al. (2009) developed a two-stage SPF technology to improve the thickness profile of the final part. As a constitutive equation they used the Eq. (1) with the material constants determined by Raman et al. (2007).

The geometrical data of the domes obtained by free bulging of circular diaphragm under constant pressure can be used to evaluate the constants of Eq. (1). Enikeev and Kruglov (1995) introduced a method for evaluation of the material constants using free bulging tests carried out to a predetermined dome height. El-Morsy et al. (2001) introduced the characterization technique based on a multi-dome forming test. Giuliano and Franchitti (2007) proposed a method for characterization of superplastic materials which is able to evaluate a strain hardening index *n* as well as the constants K and m. Li et al. (2004) simulated bulging processes by finite element method (FEM) and applied an inverse analysis to obtain the constants K and m neglecting strain hardening index *n*. Recently Sorgente and Tricarico (2014) used inverse analysis based on FEM for characterization of the superplastic aluminum alloy ALNOVI-U. Aksenov et al. (2015) proposed a characterization technique based on inverse analysis and semi-analytical model describing the evolution of dome height during the test.

The particular objective of this work is to investigate the differences of the gas forming technologies designed in a FEM based CAE system using material parameters obtained by different ways. In the design of superplastic forming (SPF) technologies the pressure regimes are calculated to maintain the strain rate value on a certain constant level. The material constitutive constants are the important inputs of such calculations. Thus the question of how the accuracy of these input data affects the designed technological regimes deserves proper attention.

The forming process of a special industrial shell detail was considered. The material (AMg6 aluminum alloy in as received condition) and the process temperature (415 °C) were taken as initial technological restrictions. Two sets of material constants describing its behavior at 415 °C were obtained separately using free bulging tests and tensile tests. These constants were then used for simulation of forming process. Gas pressure regimes were calculated to provide the maximum strain rate at the same constant value for the both cases. The obtained pressure regimes were then realized till the predicted moments of the first contact between the specimen and the die and the results were compared with the prognosis made by computer simulation.

## 2. Evaluation of constitutive constants

### 2.1. Material

The AMg6 alloy (Mg-6%, Mn-0.65%) is used in the investigated process. This is an aluminum based alloy of the Al-Mg-Mn system which is used in many industries including aerospace and civil engineering. Superplastic behavior of the AMg6 alloy was studied by Valiev and Kaibyshev (1983). It was shown that after proper grain preparation procedures the alloy can demonstrate superplastic behavior. Kaibyshev (1984) obtained the constitutive constants for this alloy at the temperature of 420 °C and initial average grain size of 9.5 $\mu m$. He found that at the given conditions the m value is about 0.45 and the alloy can be deformed at to 410% elongation at the strain rate of $0.6 \times 10^{-3}$. Similar Al-Mg alloy was studied by Guo et al. (1990) in temperature range from 470 to 530 °C. They found that the material can display a superplastic effect at these temperatures having the best plasticity at 490 °C. Chuvil'deev et al. (2008) investigated the improvement of the mechanical properties of the AMg6 alloy, which can be achieved by equal cheval pressing. Portnoy et al. (2013) analyzed the superplastic behavior the AMg6 alloy and effect of chromium addition on grain refinement and superplasticity. Recently the deformation and recrystallization textures of AMg6 alloy after hot extrusion were studied by Rusakov et al. (2015).

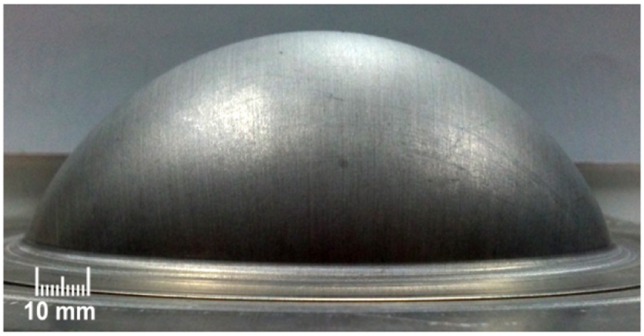

**Fig. 1.** Specimen formed at the pressure of $P_3 = 0.3$ MPa during 3500 s.

In many industrial cases it is possible to avoid the microstructure preparation requiring complicated processing steps and use the material in as received condition. This possibility is discussed by Woo et al. (1997). They investigated Al-Mg alloys containing 5.3, 7 and 11 wt.% of Mg in the temperature range of 300–550 °C and strain rate range $0.5{*}10^{-4}$ to $10^{-1}$. Steady state stress—strain rate curves are presented and it is noted than they can be fitted by Backofen equation with the *m* value equal to 0.3 for each temperature and chemical composition if the strain rate is less than $10^{-2}$. The elongations reached at the temperature of 400 °C and the strain rates of $10^{-3}$ and $10^{-2}$ are in the range of 200–275%. Lower temperatures and higher strain rates leads to abrupt decreasing of tensile ductility.

Due to the initial industrial restrictions, the forming temperature was chosen at 415 °C. Two series of tensile and free bulging tests were performed at this temperature on hot rolled sheets of a 0.92 mm mean initial thickness. In both cases the specimens were annealed during 20 min before the deformation and then deformed in argon atmosphere. Microstructure analysis showed that average grain size was 9.5 ± 0.7 $\mu m$ before and 10.5 ± 0.7 $\mu m$ after the annealing.

### 2.2. Free bulging testing

The experimental conditions of free bulging tests used in this study and the characterization technique used for their interpretation were described by the authors previously (Aksenov et al., 2015). The tests were performed at five different pressures: $P_1 = 0.3$, $P_2 = 0.35$, $P_3 = 0.4$, $P_4 = 0.5$ and $P_5 = 0.6$ MPa; with different forming times $t_i$. The specimens were formed to a cylindrical die of a 50 mm diameter and 5 mm entry radius. Each specimens was measured after the forming to obtain the values of the dome height ($H_i^{exp}$) and thickness at the apex ($s_i^{exp}$). A photograph of the specimen formed at the pressure of 0.3 MPa during 3500 s showed in Fig 1. The results of the tests are presented in Table 1 which is also contains the values of mean strain rate calculated as final strain divided on forming