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Determination of superplastic properties from the results of technological experiments

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ABSTRACT

The problem to determine experimentally the values of material parameters for two material models of superplastic flow, $\sigma = K\xi^m$ and $\sigma = K'\xi^{m'}\varepsilon^n$, from the results of technological trials is considered. With this in view, a special computational procedure is developed to minimize the deviation of the theoretically predicted forming times from experimental data recorded during constant pressure forming trials of a sheet into a circular die. As compared with similar procedures known in the literature the methods suggested enable one to obtain a unique set of material parameters by using the whole set of available experimental data. The validity of the procedures suggested is confirmed by means of comparing the results obtained with corresponding finite element solutions. The accuracy of modeling of the experimentally measured values of the forming time is found to be better than 5% for all cases considered.

1. Introduction

Structural superpalsticity is known to be the ability of fine-grained materials to exhibit unique tensile elongations under relatively low strain rates and high homologous temperatures [1]. Therefore, tensile tests are often used to establish the boundaries of superplastic flow. The most important characteristic of superplastic flow is the high value of the strain rate sensitivity index, m, which is defined as

$$\sigma = K\xi^m \tag{1.1}$$

where σ is flow stress,ξ is strain rate, K is a material parameter which depends on the average grain size and other structural characteristics.

Material model (1.1) has been suggested in the pioneering work [2]. Mathematically, Eq. (1.1) represents a straight line when plotted in the logarithmic coordinate's $\log\sigma - \log\xi$. However, the experimental dependencies $\log\sigma - \log\xi$ have conventionally a specific sigmoidal shape with the point of inflection corresponding to the optimum values of the strain rate, ξ_{opt}, and flow stress, σ_{opt}. The slope of the sigmoidal curve, $M = \partial\log\sigma/\partial\log\xi$, depends on the strain rate so that $M(\log\xi)$ curve has a specific dome like shape, the maximum slope, $M_{\max}$, being corresponding to the optimum strain rate ξ_{opt}. The boundaries of the optimum strain rate interval are conventionally determined from the condition $M > 0.3$ [1,3].

In spite of the strain rate dependency of M is recognized for a limited number of materials and for specific temperature conditions…, the material model (1.1) is often used in practical calculations when considering superplastic metal working techniques [4–13].

Most superplastic crystalline materials have this unique property because they are fine-grained (grain size less than about 10 μm). Starting from 1990th the ultra-fine grained materials of grain size less than about 1 μm have attracted the attention of due to their unique microstructures and exceptional properties [14–18].

Analysis shows [19] that one of the most serious problems in developing new technologies in metal working of nanostructured materials (grain size less than 0.1 μm) is concerned with the necessity to take into account the influence of the grain growth in describing the mechanical behavior of such kind materials. Therefore, the strain hardening index, n, is introduced into the phenomenological model of superplastic flow $\sigma = K\xi^m$ as follows

$$\sigma = K'\xi^{m'}\varepsilon^n \tag{1.2}$$

where ε is the strain, K′, m′ and n are the material constants to be determined experimentally. The material model (1.2) is also used in practical calculations of superplastic metal working processes [20–24].

Thus, the material models $\sigma = K\xi^m$ and $\sigma = K'\xi^{m'}\varepsilon^n$ are widely used in practical calculations when finite element modeling the superplastic metal working processes. The values of material param-

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Nomenclature

D	Depth of the die
F_m	Common notation for the functions $2I_m$ and J_m
H	Current dome height
I_m	Definite integral determined by Eq. (4.4)
J_m	Definite integral determined by Eq. (4.4J)
K	Material constant
m	Strain rate sensitivity index
N	Total number of available experimental data
p	Gas pressure
R	Radius of the dome
R_0	Radius of the die
R_0	Radius of the die
s, s_0	Current and initial sheet thickness respectively
t_i	Forming time
α	Angle between the axis of symmetry and the radius of the dome corresponding to the fastened boundary of the circular membrane
σ	Flow stress
σ_m, σ_t	Meridian and tangential stress respectively
σ_e	Effective von Mises stress
ξ	Strain rate
ε	Strain
Ψ(K,m)	Goal function

eters needs to be known in advance to fulfill the finite element calculations, it explains the interest to the methods of experimental determination of the values of material parameters K, m and K′, m′, n has revived within last decade. The aim of the present paper is to develop robust computational procedures enabling one to determine reliably the values of K, m in Eq. (1.1), as well as the values of K′, m′, n in Eq. (1.2) from the results of technological experiments.

2. Superplastic properties

Presently, the commercial finite element software available on the market, such as ABAQUS, LS-DYNA, ANSYS, DEFORM, MARC, etc are now wide-spread and constantly in use by most of employers. Therefore, now it is possible to fulfill the finite element modeling of superplastic metal working processes without appealing to the developers of the specific software, e.g., SPLEN [25] or similar products (see, e.g, the corresponding references in the review [21]). However, the availability of the software is not enough to solve the problem of constructing the effective finite element models of the technological processes of interest. The point is that one has to solve at least three problems before starting the modeling:

(i) to select the material model for describing the superplastic flow
(ii) to determine the values of material constants for the material model chosen
(iii) to state the boundary value problem in the mechanics of solids

Finite element software used in modeling the superplastic metal working processes is intended to solve the boundary value problem in the mechanics of continuum. This problem can be stated in different ways [3,21]. For example, the boundary value problem can be stated in terms of mechanics of fluids [25], or theory of creep [3], or in terms of some another approach [26]. Independently of the method chosen to state the boundary value problem, the same values of material parameters (e.g., K and m) should be introduced into the FEM-software when fulfilling the calculations.

Thus, the material constants to be used in practical calculations are to be determined from the results of mechanical experimentation independently of the finite element software used and/or method to state the boundary value problem chosen, based on that, the methods to determine the material constants from the results of experiments needs to be developed and then tested in accordance with the requirements that are well known in the mechanics of solids [3]. It is to be emphasized that the material parameters are to be considered to be constant in value from the very beginning and up to the end of calculations. In the case when the strain rate dependency of m-value is to be taken into account, the material model $\sigma = K\xi^m$ is to be rejected and replaced by *another* material model containing *different* material constants. Correspondingly, *other* methods to determine experimentally the specific values of these new material constants are to be developed and tested in accordance with the requirements of the general theory of constitutive equations.

The term ‘superplastic properties’ means, from the mechanical point of view, the specific values of the material constants to be used in calculations. For elastic body the value of Young's modulus as well as that of Poisson coefficient do not depend upon the strain *by definition*. Otherwise, the Hook's law is to be rejected and then replaced by some another material model which is more appropriate for the case of, say, non-linear elastic body. Similarly, from the mechanical point of view, the values of material parameters, K and m, do not depend on the strain rate *by definition*. Otherwise, the standard power law $\sigma = K\xi^m$ is to be rejected and replaced by another material model. In doing so, it is necessary to remember, that to change the material model means to redefine the term ‘superplastic properties’. In this case, the term ‘superplastic properties’ will be accounted for the specific values of the material constants for the new material model chosen. For example, when introducing the well-known concept of threshold stress, the material model $\sigma = K\xi^m$ can be modified, e.g., as follows: $\sigma = \sigma_0 + K''\xi^{m''}$. Correspondingly, the term ‘superplastic properties’ will be accounted for the values of material constants σ_0, K″ and m″, the value of σ_0 being accounted for the mechanical threshold.

Considering the above considerations the values of material parameters K, m in Eq. (1.1), as well as those of K′, m′, n in Eq. (1.2) are assumed to be material constants *by definition* in the present work.

As stated by Barnes [27], current and likely future trends in further developing superplastic metals forming techniques include applications in the aerospace and automotive markets, faster-forming techniques to improve productivity, the increasing importance of computer modeling and simulation in tool design and process optimization and new alloy developments including superplastic magnesium alloys. The following task among above mentioned ones is placed at the center of attention in present work: the increasing importance of computer modeling and simulation in tool design and process optimization.

It is noted that the inaccuracies in determining the material parameters from the results of mechanical experimentation cannot be reduced for the sake of usage the advanced numerical methods and/or powerful computers. Such kind inaccuracies could occur both as due to inappropriate experimental procedures used as well as due to ambiguous procedures of treating the primary experimental data. Classic example is the report of Hedworth and Stowell [28] where 5 independent procedures to treat the same set of experimental data have been suggested. The analysis of the inaccuracies arising from the inappropriate experimental procedures used lies beyond the framework of the present study. The main attention is paid to developing robust computational methods enabling one to determine the values of material constants of interest from the experimental data recorded.