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Identification of materials deformation behavior parameters for the design of superplastic forming processes

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State of the problem

Superplastic forming is a perspective technology of shell part manufacturing for of automobile and aerospace industries. During SPF procedure the blank specimen is forming by inert gas at high temperatures. One of the main stages of SPF procedure development is a pressure regime calculation which one have to provide target value of maximum strain rate in a specimen.

For pressure regime calculation Computer Aided Engineering (CAE) software are used commonly. This software allows one to design manufacturing processes applying computer models based on continuum mechanics methods and modern computational algorithms. For simulation of SPF processes it is necessary to set initial and boundary conditions of the process and to describe mechanical properties of the material. These properties are characterized by constitutive equation, which relates the equivalent flow stress with equivalent stain rate at a given temperature. The constants included in constitutive equation or "material parameters" determines empirically.

The degree of reliability of the material parameters directly affects on the accuracy of pressure regime calculation for SPF processes That leads to the need to develop acceptable from the practice point of view methods of material identification. In some of well-known studies the construction of constitutive equation is indicated as an important problem in the study of superplasticity [1,2].

Classical constitutive equation for SP forming processes design is Backofen's equation[3]:

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

where σ_e – equivalent flow stress $\dot{\varepsilon}_e$ - equivalent strain rate K and m – parameters of the material.

This equation describes the behavior of a superplastic material in a narrow range of strain rates. In the study of Smirnov O.M. a rheological model of the superplastic material behavior is proposed in a wide range of strain rates[4]:

$$\sigma_e = \sigma_s \frac{\sigma_0 + k_v\dot{\varepsilon}_e^{m_v}}{\sigma_s + k_v\dot{\varepsilon}_e^{m_v}}, \quad (2)$$

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

Material parameters have to be selected in order to correspond to the developing process. Their values depend on chemical composition of the alloy its initial microstructural state, the value of temperature and strain rate range of forming procedure. Strain rate sensitivity index m have a

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1 Superplastic forming of structural alloys: Proceedings of a symposium (Conference proceedings / the Metallurgical Society of AIME) by eds. Paton, N. E., & C. H. Hamilton, 1982, pp. 122-123

2 Vasin R.A., Enikeev F.U. Introduction to the mechanics of superplasticity [on Russian]. Part 1. Ufa, 1998, pp.44-45

3 Backofen W.A., Turner I.R., Avery D.H. Superplasticity in an Al-Zn Alloy // ASM Trans. Q. 1964. V.57. P. 980-990.

4 Smirnov O.M., Processing of metals by pressure in the superplasticity state [on Russian]. M.: Mashinostroenie, 1979. 184 p.

special role, the value of m influence on the sustainability of material flow and uniformity thinning of the specimen.

More complicate equations can take into account equivalent strain, temperature, maximum or medium grain size, and may contain a wider set of parameters then Backofen equation.

The construction of constitutive equation and identification of its parameters are based on mechanical experiments, when special conditions of material deformation specific for different technological processes are reproduced. This condition includes: temperature, main axes orientation, Method and lasting od the strain, the strain range variation during the process e.t.c. Variousity of material forming procedures requires a significant number of experiments.

Tensile tests are commonly used experimental procedure for material parameters identification for SP forming processes design. However, this standard approach has a number of drawbacks that are connected with ununiform deformation of specimen which can leads to inaccuracies in defining of material deformation behavior. Besides, the tension condition that is observed during tensile tests where uniaxial tension. Whereas during technological processes of SPF prevails biaxial tension conditions. These peculiarities can lead to inaccuracies in designing technological processes connected with the lack of predictability of applied computer simulations.

Thus, for advancing accuracy of the SPF technological process model it is necessary to develop and to extend methods of material behavior identification. Biaxial tension is observed in free bulging experimental procedures that can be used as information's source about material behavior in conditions similar to the ones that appears during industrial forming processes. This study is devoted to the problem of material parameters identification based on the results of free bulging tests.

State of the art

Inaccuracies of identification of material behavior on the basis of tensile tests are indicated in the studies of J. Cheng[5], D. Sorgente et al. [6], J.T. Yoo et al. [7]. In the studies of M. Albakri et al. [8], A. El-Morsy et al. [9], it was shown that the microstructural behavior of polycrystalline materials under hot deformation differs under compression, tension or shear conditions and significantly

[5] Cheng, J.-H., 1996, The Determination of Material Parameters from Superplastic Inflation Tests. Journal of Materials Processing Technology, 58:233–246.

[6] Sorgente, D., Palumbo, G., Piccininni, A., Guglielmi, P., Aksenov, S.A., 2018, Investigation on the Thickness Distribution of Highly Customized Titanium Biomedical Implants Manufactured by Superplastic Forming. CIRP Journal of Manufacturing Science and Technology, 20:29–35.

[7] Yoo, J.T., Yoon, J.H., Lee, H.S., Youn, S.K., 2012, Material Characterization of Inconel 718 from Free Bulging Test at High Temperature. Journal of Mechanical Science and Technology, 26:2101–2105.

[8] Albakri M., Abu-Farha F., Khraisheh M., A new combined experimental–numerical approach to evaluate formability of rate dependent materials International Journal of Mechanical Sciences. Vol. 66. 2013. pp. 55-66.

[9] El-Morsy A., Akkus N., Manabe K., Nishimura H., Superplastic characteristics of Ti-alloy and Al-alloy sheets by multi-dome forming test, Materials Transactions Vol.42(11). 2001. pp. 2332-2338.

depends on the type of material, its chemical composition and the initial microstructure. The obtained results indicate, in particular, that the identifying material parameters on the basis of tensile tests requires refinement for applying during SPF processes design.

The applying of free bulging test results for material behavior identification was considered in the of F.U. Enikeev and A.A. Kruglov, G. Giuliano, D. Sorgente, A.El-Moorsy, F.S. Jarrar, F. Jovane others studies.

Problems that arise in interpreting the results of free bulging tests are associated with the lack of a physical possibility for direct measurement of the values of the equivalent flow stress, equivalent strain, and equivalent strain rate directly during the test. These data have to be calculated based on the parameters of the geometry of the die, the pressure regime, the value of the height of the dome and the thickness of the workpiece at the top of this dome.

There are several types of free bulging tests, depending on the equipment with which they are implemented. First of all, these are "blind" tests, in which the forming is carried out for a given time at a constant pressure. The results of such tests are the height of the dome and the thickness of the workpiece at its top, measured at the end of forming procedure. Another type is tests with fixation of touch moment, in which forming is performed until the contact between the workpiece and the bottom of the matrix, the results are the forming time and the thickness of the shell at the top of the dome at the moment of touch. The most informative are tests with continuous monitoring of the height of the dome, starting from the beginning of forming test. As a result, a curve of dependence of the height of the dome on time and the value of the thickness of the specimen at the top of the dome at the end of the test are obtained.

The approaches presented in the literature for identifying material parameters on free bulging test results are based on direct or inverse methods. Direct methods allow one to calculate the required parameters of the material directly from the results of measurements made during the tests. Inverse ones are based on minimizing of error function procedure, which characterizes the deviation of the measured values from the calculated values obtained by computer simulation.

One of the first methods to identifying rheological characteristics of the material on the basis of the free bulging experiments were presented by F.U. Enikeev and A.A. Kruglov[10]. For industrial titanium alloy VT6, they characterize the material parameters of the Backofen equation. To solve the problem of characterization, a model of forming process, based on the momentless theory of shells was proposed. Material parameters were calculated based on two dome forming tests of the same height obtained by applying different pressures. In order to control the height, the

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[10] Enikeev F.U., Kruglov A.A., An analysis of the superplastic forming of a thin circular diagram, Int. J. Mech. Sci. Vol. 37 1995. pp. 473-483.

geometry of the die of the standard testing equipment was modified, which made it possible to fix the time moment at which the workpiece touches the bottom of the die.

For the strain rate sensitivity index m, the following expression was obtained:

$$m = \frac{\ln(P_1/P_2)}{\ln(t_2/t_1)}, \qquad (3)$$

where t_1 и t_2 are the duration of bulge forming at constant gas pressures P_1 и P_2 respectively.

In order to calculate the parameter K, the following expression was proposed:

$$K_i = \frac{P_i R}{2s_0}\left[\frac{t_i}{2I_m(\pi/2)}\right]^m, i = 1{,}2 \qquad (4)$$

where P_i – is the value of constant pressure, R– is the radius of the die, s_0 – is the initial thickness of the workpiece, a $I_m(\varphi)$ – is expressed through a definite integral:

$$I_m(\varphi) = \int_0^{\varphi}\left(\frac{\sin^3 x}{x^2}\right)^{1/m}\left(\frac{1}{x} - \operatorname{ctg} x\right)dx \qquad (5)$$

where φ- half the angle formed by the domed surface at the center of its curvature.

For verification of the method the experiments were carried out at constant strain rates in accordance with the pressure regimes, calculated by applying values of m and K obtained by method. A satisfactory agreement was obtained between the calculated forming duration and the experimental one.

The idea of Enikeev and Kruglov direct method were used in a number of studies. G. Giuliano applied it for material characterization of Ti-6Al-6V alloy. In this study modification of Backofens equation with nonzero strain hardening index was used. The constitutive equation was $\sigma_e = K\dot{\varepsilon}_e^m \varepsilon_e^n$, where ε_e- equivalent strain, n -strain hardening index.

By applying direct methods aluminum and titanium alloys AA-5083, AZ31, AMg6, AMg4, Ti-6Al-6V, OT4-1 were characterize by G.Giuliano, F.S. Jarrar, F.K. Abu-Farha and by a number of researches from Institute for metals superplasticity problems of the Russian Academy of Science.

A serious obstacle to apply direct methods for material characterization is the lack of constructive capabilities in commercial experimental equipment for carrying out height monitoring tests. The disadvantage of currently known direct methods is that they are developed for a specific type of state equation.

The main advantage of applying inverse analysis for material characterization is the ability to use different equations of state.

Inverse analysis is an iterative process its algorithm is illustrated on figure 1. The relation connecting the flow stress (σ), the strain (ε) and the strain rate ($\dot{\varepsilon}$) of deformation depends on the parameters $p_1 - p_n$: $\sigma = f(\varepsilon, \dot{\varepsilon}, p_1, \dots, p_n)$.

The aim of the inverse analysis is to obtain the parameter values, such that the results of simulation modeling of the forming process deviate to the least extent from the experimental data. The degree of this deviation is determined by the objective function $F(p_1, \dots, p_n)$. It is usually constructed as the sum of quadratic errors obtained by simulation the forming process using a given set of parameters. Hence, the problem of identifying material parameters is reduced to the problem of finding the minimum of a function of many variables.

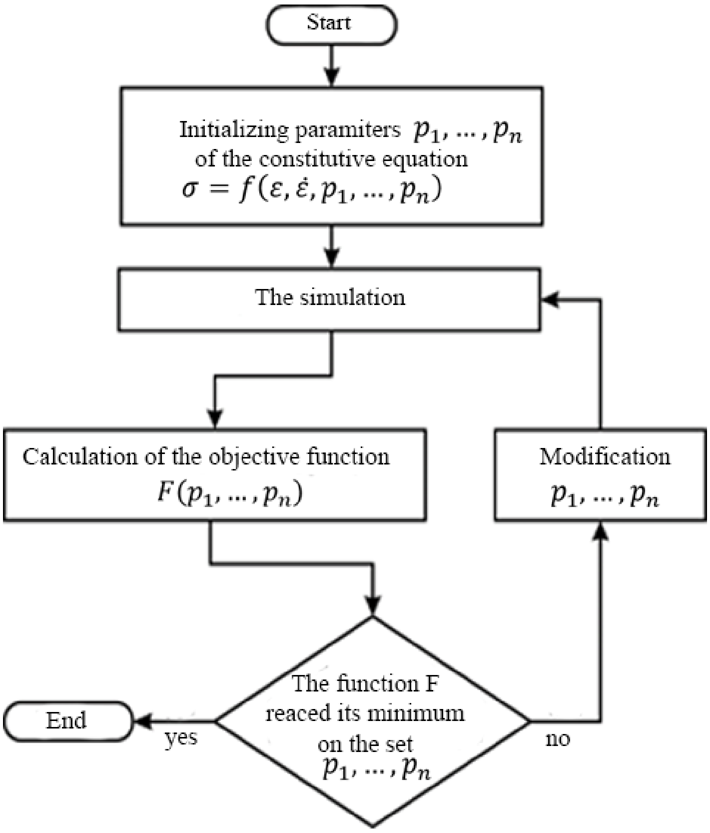

Figure 1. Algorithm for identifying rheological parameters based on the inverse method.

The applying of inverse method to characterize material parameters of superplastic materials was presented in the studies of G.Y. Li and et al.[11], D. Sorgente and et al.[12]. Numerical simulation of the forming process was made by finite element method (FEM).

FEM is one of the most common and well-established numerical methods for simulation a slow flow of a viscous medium, which describes material behavior during the SPF. It is implemented in various industrial CAE systems and is widely used in the design of technological processes of material forming. However, the applying of the FEM requires a significant amount of time to solve the problem of material forming. the implementation of Inverse analysis is

[11] G.Y. Li, M.J. Tan∗, K.M. Liew, Three-dimensional modeling and simulation of superplastic forming. Journal of Materials Processing Technology, vol. 150 (2004), 76 – 83

[12] Sorgente D., Tricarico L. Characterization of a superplastic aluminium alloy ALNOVI-U through free inflation tests and inverse analysis, International Journal of Material Forming. 2014. Vol. 7. pp. 179–187.

associated with a great number of iterations, at every iteration it is necessary to simulate all the experimental procedures under study, so the calculation time increases many times over. It seems more preferable to use simplified forming models that allows one to quickly design reliable predictions of the dome shape change.

A significant number of studies are devoted to the construction of such simplified models [8,13,14,15]. Most of them are based on the balance of forces applied to an elementary section of the sample located at the top of the dome. When creating models, a number of hypotheses about the distribution of thickness over the workpiece and its relationship with the shape of the dome are used. The dependences of the dome thickness on its height proposed according to such hypotheses are given below:

In F. Jovane study the hypothesis of a uniform thinning of the dome throughout the volume of specimen was used:

$$s(H) = \frac{s_0 R^2}{R^2 + H^2} \tag{6}$$

The hypothesis of uniform stretching of the meridian of the dome was used by F.U. Enikeev and A.A. Kruglov:

$$s(H) = s_0 \left(\frac{\sin\varphi}{\alpha}\right)^2, \tag{7}$$

where $\alpha = arcsin\left(\frac{2HR}{R^2+H^2}\right)$

The assumption that an ideal biaxial tension is observed at each point of the dome allows us to construct the dependence proposed by R. Hill[16] and used by S. Yu-Quan and Z. Jun:

$$s(H) = \frac{s_0 R^4}{(R^2+H^2)^2}, \tag{8}$$

Generalization (6)-(8) was proposed by M.J. Nategh and B. Jafari:

$$s(H) = s_0 \left(\frac{R^2}{R^2+H^2}\right)^{2-m} \tag{9}$$

The common disadvantages of relations (6)-(8) is that none of them takes into account the influence of material properties on the thinning of the workpiece. It is inconsistent with the experimental data, which indicate that the greater value of strain rate sensitivity index, the higher the equality of thickness distribution over the specimen and, as a result, the higher thickness at the top. An attempt to take this fact into account was made by M.J. Nategh and B. Jafari, however, their equation (9) describes influence of strain rate sensitivity index only at a qualitative level

[13] F. Jovane, An approximate analysis of the superplastic forming of a thin circular diaphragm: theory, and experiments, International Journal of Mechanical Science 10, 1968, 403-424.

[14] M.J.,Nategh, B. Jafari, Analytical and Experimental Investigations on Influential Parameters of Superplastic Forming of Titanium Based Workpieses, *JAST*, (2007), 4 (2), pp. 43-51.

[15] S. Yu-Quan, Z. Jun, A Mechanical Analysis of the Superplastic Free Bulging of Metal Sheet, Materials Science and Engineering, 84, 1986, pp. 111- 125.

[16] Hill, R., A Theory of the Plastic Bulging of a Metal Diaphragm by Lateral Pressure. The London Edinburgh and Dublin Philosophical Magazine and Journal of Science, 1950, 41, pp. 1133–1142.

In addition, none of the presented equations takes into account the geometric parameters of the die, which also affect the thinning of the specimen during forming. The noted drawbacks do not allow one to use of well-known semi-analytical models of the free bulging process when implementing inverse analysis procedure. To solve the problem of material parameters identification based on the results of test forming, models of the dome growth that take into account the properties of the material and the geometry of the die are needed.

<u>**Relevance of the problem**</u>

The design of superplastic forming technology process processes requires the development of pressure regime that provide the strain rates within a given range. The regimes are usually calculated by computer simulation. The most important characteristic of the simulation procedure are the material parameters that describe material behavior. Superplastic material behavior describes by constitutive equation that connect equivalent stress and equivalent strain rate. The most common methods of identification the parameters of constitutive equation are based on processing experimental data obtained by tensile test. During this test material is in uniaxial tension condition which is different from the one during real forming procedure. This differs can lead to significant discrepancies between computer simulation predictions and actual technological procedure. As a result, the implementation of a pressure regime calculated at the design stage can lead to the exceeding of the strain rates ranges of superplasticity and as a result provoke the appearance of the defects.

The existing methods for identifying the parameters of the material behavior in biaxial tension conditions are based on the free bulging experiments when sheet specimen is forming by inert gas into cylindrical matrix.

This approach allows the material to be tested under conditions as close to industrial as possible, but complicates the identification of the parameters for constitutive equation. The problem of identification can be solved either by a number approximate analytical relationships or with the aid of cumbersome finite element calculations. Thus, the creation of new methods for identification of constitutive equation parameters, based on the results of free bulging test is a relevant scientific task.

<u>**Aim and tasks of the study**</u>

The aim of this study is to develop a methodology for identifying the parameters of superplastic materials on the basis of experiments for forming a sheet blank into a cylindrical matrix.

During the study, the following tasks were solved:

- The analysis of known analytical relationships linking the thickness of the blank to its height at the top of the dome;

- The simulation of the free bulging test and analysis of the dome forming process in order to identify and analyze the key patterns of specimen shaping;

- The development of the model of the specimen at the top of the dome during free bulging test, taking into account the influence of material parameters;

- The construction of a methodology for identifying superplastic parameters of the materials on the basis of the shape-change developed model;

- The development of a computer program that implements the constructed methodology;

- Carrying out computational experiments to analyze the applicability of the developed methodology;

- Determination of rheological characteristics of industrial aluminum and titanium alloys.

Methodology

The methodology of the study is based on computer simulation and computational experiment, which, in combination with reverse analysis, made it possible to create a method for identifying material parameters using the results of forming a sheet blank into a cylindrical matrix. The study was carried out under the assumption that the material of the formed workpiece is homogeneous, isotropic and incompressible, and the process of superplastic forming is isothermal.

In the first stage**,** a mathematical model of the free bulging test was constructed in order to be used for the free bulging test results interpretation. Significant number of FE simulations of a free bulging tests were conducted with the commercial finite element computer code ABACUS. The FE numerical simulation was axially symmetric with four node elements. Becofen's exponential relation was used as a material model.

The simulations were carried out with different material parameters, various values of constant pressure regimes, different geometric parameters of the die and the equipment. The values of the material parameters were chosen in the ranges of possible values for the parameters of superplastic and quasi-superplastic materials. The strain rate sensitivity index m was in ranged from 0.2 to 0.9, with a step of 0.5. The proportionality factor ranged from 75 to 3200. The value of constant pressure ranged from 0.1 to 1.2 with a step of 0.2 MPa. The thickness of the blank ranged from 0.5 to 4 mm with a step of 0.5 mm. The radius of the inner cavity of the tooling R varied in the range from 20 to 60 mm, the radius of the edge – fillet radius ρ_0- from 0 to 18 mm.

The analysis of the results made it possible to establish the dependency of the specimen thickness from the specially normalized height of the dome. Furthermore, the proposed dependency[17], unlike to the ones presented in the literature, took into account the influence of the material parameters of the specimen. This dependency takes into account parameter B, and the parameter ρ_0 – fillet radius when the blank enters the die:

$$\frac{s}{s_0} = 1 - \frac{BH}{\rho+\rho_0} \tag{10}$$

where s – current workpiece thickness at the top of the dome, s_0 – start workpiece thickness, H – dome lift height, ρ – radius of curvature of the dome surface at its top, B – coefficient depending on material properties and tooling geometry.

The paper[17] shows that the value of the coefficient B does not depend on the value of the pressure P, nor on the coefficient K of the Beckofen equation. The dependence is proposed that makes it possible to calculate the value of B for given values of the geometric parameters of the tooling (ρ_0 и R) and the value of the strain rate sensitivity index of the material:

$$B = 0.5 + \frac{1}{\alpha(1+m)^{\beta}}, \tag{11}$$

where $\alpha = -2.3\frac{\rho_0}{R} + 2.1$, $\beta = 1.8\frac{\rho_0}{R} + 2.5$

Equations (10) and (11) allows one to estimate the value of strain rate sensitivity index, based on the values of the height of the dome and the thickness of the specimen at its top.

At the second stage of the study, relation (10) was used to build a model that describes the change in the height of the sample during forming in the form of an ordinary differential equation[18]:

$$\frac{dH}{dt} = \frac{\rho+\rho_0-BH}{BH} f^{-1}\left(\frac{P\rho}{2\left(S_0-\frac{s_0BH}{\rho+\rho_0}\right)}, \ln\left(\frac{s_0}{S_0-\frac{s_0BH}{\rho+\rho_0}}\right)\right), \tag{12}$$

where $f^{-1}(\dots)$ – inverse function to the constitutive equation, linking the equivalent stress, the equivalent strain and equivalent strain rate of the material: $f^{-1}(\sigma_e, \varepsilon_e) = f^{-1}(f(\dot{\varepsilon_e}, \varepsilon_e), \varepsilon_e) = \dot{\varepsilon}_e$. P - pressure value. Applying the Backofen's constitutive equation $\sigma_e = K\dot{\varepsilon}_e{}^m$ to the equation (12), it takes the form of:

$$\frac{dH}{dt} = \frac{\rho+\rho_0-BH}{BH}\left(\frac{P\rho}{2Ks_0\left(1-B\frac{H}{\rho+\rho_0}\right)ln\left(\frac{\rho+\rho_0}{(\rho+\rho_0-BH)}\right)}\right)^{\frac{1}{m}} \tag{13}$$

On the basis of this model of dome growth, a method for material characterization on the basis of the free bulging test results was developed. The characterization procedure consists of two steps. In the first step, the value B_i was determined for each experimental point (H_i, s_i):

$$B_i = \frac{(s_0-s_i)\left(H_i{}^2-(R_0+\rho_0)^2\right)}{s_0 H_i{}^2} \tag{14}$$

[17] Zakhariev I. Y. Aksenov S. A. Influence of a material rheological characteristics on the dome thickness during free bulging test // Journal of Chemical Technology and Metallurgy. - 2017. - Vol. 52. No. 5. - pp. 1002-1007.

[18] Zakhariev, I.Y. Aksenov, S.A., Logashina, I.V. Application of inverse analysis for a determination of material rheological constants basing on forming tests of circular membranes, Letters on Materials. - 2017. - № 1. – pp. 49-54.

In the second step, parameters of the constitutive equation were chosen by minimizing the target function, calculated as the total deviation of the solutions of the differential equations (13) $H_i(t)$ from the corresponding experimental point (H_i, t_i):

$$F = \sum_{i=1}^{N} \min_{t} \left(\sqrt{\left(\frac{H(t)-H_i}{H_i}\right)^2 + \left(\frac{t-t_i}{t_i}\right)^2} \right), \quad (15)$$

where N is the total number of experiments, $H(t)$ - is the height of the dome at moment of time t, obtained by solving equation (8) at $B = B_i$, $t_i$and H_i are experimental values of time and height of the dome.

Based on the developed model and the method for determining the material parameters, a methodic for characterization Backofen constitutive equation parameters to describe the deformation behavior of superplastic materials based on the results of free bulging test was proposed. The proposed methodic was applied to characterize the rheological parameters of aluminum alloys AMg6, AA5083, AZ31, free bulging tests[18]. And to obtain characteristics of titanium alloy OT4-1 based on multi-dome forming tests[19]. The chemical compositions of alloys AMg6, AA5083, AZ31 and OT4-1 are presented in tables 1-4.

Table 1 Chemical composition in % of AMg6 alloy

Fe	Si	Mn	Ti	Cu	Be	Mg	Zn	Al
0.4	0.4	0.5	0.02	0.1	0.0002	5.8	0.2	balanced

Table 2 Chemical composition in % of AA5083 alloy

Mg	Si	Fe	Cu	Mn	Zn	Ni	Ti	Cd	Zr	Pb	Al
3.20	0.031	0.25	0.24	0.20	1.02	0.95	0.14	0.09	0.37	0.02	balanced

Table 3 Chemical composition in % of AZ31 alloy

Al	Zn	Mn	Cu	Ni	Si	Fe	Mg
2.60	0.86	0.2859	0.0012	0.01	0.0092	0.0015	balanced

Table 4 Chemical composition in % of OT4-1 alloy

Fe	C	Si	Mn	N	O	Al	Zr	Ti
0.3	0.1	0.12	2	0.05	0.15	2.5	0.3	balanced

The solution of the differential equation (13) was carried out by the Runge Kutta method of the 4th order. The minimization of the error function (15) was carried out by the deformed

[19] Zakhariev I. Y. Aksenov S. A., Kotov A., Kolesnikov, A. Characterization of OT4-1 Alloy by Multi-Dome Forming Test // Materials. - 2017. - Vol. 10. - No. 8. - pp. 1-10.

polyhedron method[20], which does not require the calculation of the derivative of the objective function when minimizing the error function, while being a method of the second order of accuracy. Verification of the obtained data on the properties of the studied materials was carried out by comparing the results of finite element modeling with experimental data.

Provisions for the defense

- Model of dome forming during free bulging test;
- Method for constitutive equations parameters characterization for superplastic materials based on the results of free bulging test;
- Constitutive equations parameters of industrial aluminum (AMg6, AMg4, AMg2) and titanium (OT4-1) superplastic alloys under biaxial tension conditions.

Scientific novelty

A new model for superplastic free bulge experiment is proposed, which, unlike the known ones, allows taking into account the parameters of the superplastic material and geometry of the die.

The proposed method for characterization parameters of the constitutive equations of deformable materials based on the results of free bulging proposed by a new dome forming model can significantly improve the adequacy of the results without the use of finite element simulations.

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General conclusions

The study is devoted to the problem of identification of the parameters that characterize the deformation behavior of materials, which plays one of the most important roles in the design of superplastic forming technology.

An original model that describes the change of the height and thickness at the dome pole during the free bulging experiment taking into account the influence of material parameters and geometry of the die is proposed.

Based on the proposed model, a method for rheological parameters characterization of superplastic materials based on the results of free bulging tests is developed.

By applying the developed method the parameters of constitutive equation that characterize the deformation behavior of a number of aluminum and titanium alloys were found. The reliability

[20] Nelder J. A. and Mead R., Computer Journal, 1965, vol. 7, pp. 308—313.

of these parameters was confirmed by good agreement between the finite element simulation results and the experimental data.

<u>Contribution of the author</u>

All results presented for defense were obtained by the candidate personally. The participation of the co-authors of the published articles was as follows: S.A. Aksenov. - Statement of the problem and general scientific leadership, Logashina I.V. - bibliographic information retrieval, S.A. Osipov, A.V. Kolesnikov, A.D. Kotov - carrying out experimental procedures.

<u>List of papers on the topic of the dissertation work presented for the defense</u>

All articles are published in peer-reviewed scientific journals indexed by the international citation databases Web of Science and Scopus:

1. Zakhariev I. Y. Numerical simulation of superplastic bulge forming test. // Journal of Physics: Conference Series. -2021. -Vol. 1740. -P. 012021
2. Zakhariev I. Y. The effect of finite element type on the results of superplastic forming simulation // Procedia Manufacturing. -2019. -Vol. 37. -P. 85-90
3. Zakhariev I. Y. Aksenov S. A., Kotov A., Kolesnikov, A. Characterization of OT4-1 Alloy by Multi-Dome Forming Test // Materials. - 2017. - Vol. 10. - No. 8. - P. 1-10.
4. Zakhariev I. Y. Aksenov S. A. Influence of a material rheological characteristics on the dome thickness during free bulging test // Journal of Chemical Technology and Metallurgy. - 2017. - Vol. 52. No. 5. - P. 1002-1007.
5. Zakhariev, I.Y. Aksenov, S.A., Logashina, I.V. Application of inverse analysis for a determination of material rheological constants basing on forming tests of circular membranes // Letters on Materials. - 2017. - № 1. - C. 49-54.
6. Aksenov S. A., Zakhariev I. Y., Osipov S. A., Kolesnikov A. V. Characterization of superplastic materials by results of free bulging tests // Materials Science Forum. - 2016. - Vol. 838-839. - P. 552-556.

<u>Approbation of the obtained results</u>

The main results of the dissertation work were reported at the following international conferences:

- Computer Simulations in Physics and beyond» CSP2020 (Moscow, Russia, 2020), report title – «*Numerical simulation of superplastic bulge forming test*»;

- The 13th European Conference on Superplastic Forming EuroSPF 2019 (Matera, Italy, 2019), report title – «*The effect of finite element type to the prognosis of thickness distribution obtained by simulation of superplastic forming*»;
- Physical and Numerical Simulation of Materials Processing *ICPNS'2019* (Moscow, Russia, 2019), report title – «*The effect of finite element type on the results of superplastic forming simulation*»;
- 13th International Conference in Superplasticity in Advanced Materials - ICSAM-2018 (St. Petersburg, Russia, 2018), report title – «*The effect of finite element geometry on superplastic forming simulation*»;
- 8th International Conference on Computational Methods and Experiments in Material and Contact Characterization (Tallin, Estonia, 2017), report title – «*Characterization of superplastic alloy by multi-dome bulging tests*»;
- International Conference on Metallurgy and Materials – ICMM 2016 (Sofia, Bulgaria, 2016), report title – «*Influence of a material rheological characteristics on the dome thickness during free bulging test*»;