Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 207 (2017) 1892–1897

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom

Investigation of stress-strain behavior of a sheet material using free bulging test

Sergey A. Aksenov[a,*], Donato Sorgente[b]

[a]*National Research University "Higher School of Economics",Tallinskaya 34, Moscow 123458, Russia*
[b]*School of Engineering, Università degli Studi della Basilicata, Via Ateneo Lucano, Potenza, Italy*

Abstract

In this work, a new experimental-numerical technique is developed in order to investigate the constitutive behaviour of a sheet material in conditions of superplastic forming. The principal feature of this technique is that unlike classical tensile testing it allows one to obtain stress-strain curves for a material formed in biaxial tension conditions produced by free bulging process. These conditions are much closer to the ones that the material undergoes during the superplastic forming process. Consequently, they give more accurate information about the material behaviour than the ones coming from tensile tests data. The drawback is that the strain (and similarly its time derivative) cannot be directly measured and controlled during free bulging test but its value has to be derived from other macroscopic measurement. Towards this end, a blow forming machine was equipped with a position transducer for the measurement of the dome height during the test. In order to control the stress in the dome apex at a predetermined level the applied pressure was continuously adjusted to current dome height using a special algorithm. After the test, the dome height data were processed to obtain the evolution of stress, strain and strain rate at the dome apex as well as the stress strain curves for constant referenced strain rates. The tests were performed on superplastic aluminium alloy (ALNOVI-U) sheets of 1.35 mm initial thickness at 500 °C. Using the data from two tests with different strain rate paths the stress-strain curves and the strain rate sensitivity index evolution were calculated for two constant referenced strain rates. The obtained constitutive data were verified by finite element simulation of a blow forming.

Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.

Keywords: material characterization; biaxial stress; hot forming; superplastisity; free bulging test

* Corresponding author. Tel.: +7-495-772-95-90; fax: +7-495-772-95-90.
E-mail address: saksenov@hse.ru

1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.957

1. Introduction

Superplastic (SP) materials are commonly used to manufacture complex shaped components [1]. The forming process of SP materials needs an extended and accurate material characterization. Both the optimal temperature and strain rate values should be known before designing the forming process. The pressure profile acting on the sheet has to be calculated to get strain rate values along the sheet close to its optimal value. Commonly this goal is achieved by a computer simulation of the process using finite element method (FEM). In this scenario, the relationships between the stress and the main physical dimensions, such as the strain and the strain rate, have to be found and modelled. Nevertheless, the stress state in forming operation is far from the uniaxial found in tensile tests. Alternative techniques to get more accurate SP material constants exists and it has been extensively demonstrated, both with and without inverse analysis, that constants calculated by these techniques are more reliable than the one calculated by tensile tests data [2–5].

Major results in the stress-strain curves determination by bulge tests have been achieved at room temperature. Slota and Spisak used bulge tests at room temperature for the determination of the hardening law of a steel sheet in a hydroforming application. They compared different analytical models for the thickness prediction on the dome apex finding that each of them can be used in different strain ranges to better fit experimental data [6]. Campos et al. presented an experimental setup with a displacement transducer (for the dome height measurement) together with a spherometer and an extensometer to determine stress-strain curves for different steels at room temperature [7]. Koc et al. extended the temperature range for a steel (up to 150°C) and an aluminium alloy (up to 260°C). They used results from bulge tests equipped with a 3D non-contact optical strain measurement system to get stress-strain curves. They concluded that acceptable accuracy at room temperature can be achieved but larger deviations could be encountered as the temperature increases due to technical issues-[8].

SP forming temperatures are commonly raise above 400°C for aluminium alloys and above 750°C for titanium ones. In such conditions the application of strain measurement techniques available for room temperatures becomes a challenging issue. Another distinctive feature of SP deformation is the strain rate sensitivity of a material which makes it necessary to control the strain rate during the test. Most of the works on SP materials rely on the direct measurement of the dome height during the test and on the calculation of the equivalent strain on the dome apex by the thickness prediction through analytical assumptions and/or FEM. Kaya et al. investigated the behaviour of a magnesium alloy measuring the dome height trough an LVDT. They found that analytical models for thickness and radius calculations are acceptable only for height values that are much lower than the ones reached for SP materials [9]. Banabic et al. performed bulge tests in spherical, elliptical and conical dies with a pressure profile derived from an analytical model that takes into account the material behaviour by its constitutive constants [10].

In this work, a new methodology for the investigation of the behavior of SP materials and for the consequent determination of stress-strain curves is proposed. The principal novelty of this methodology is the pressure control technique which allows one to maintain constant stress value on the dome apex and, consequently, an approximately constant strain rate without any information about the material properties. This is achieved by real-time closed-loop pressure control algorithm continuously adjusting the forming pressure to the current dome height.

2. Material and Methods

2.1. Aluminium alloy

All the tests were performed on superplastic aluminium alloy sheets (thickness - 1.35 mm) manufactured by Furukawa Sky Aluminum Corp. with a chemical composition that is reported in Table 1.

Table 1. Chemical composition of the investigated aluminium alloy.

Si	Fe	Cu	Mn	Mg	Cr	Ti	Others	Al
0.03	0.06	0.01	1.37	4.60	0.02	0.01	<0.15	Balance

2.2. Bulge test

Specimens were formed by bulge tests on laboratory scale equipment. The tools were embedded in a cylindrical split furnace and assembled on a universal testing machine (INSTRON 4485). The equipment consists in a female die and in a blank-holder by which the gas is inflated in the forming chamber. Two electronic proportional valves with two different maximum pressure values (0.9 and 2.0 MPa) were alternatively used to pressurize the forming chamber. K-type thermocouples were employed to monitor the temperature on the sheet and on the tools. A PC with a data acquisition I/O device allowing one to constantly monitor and manage the pressure, the temperature and the blank-holder force. Bulge tests were performed with a female die having a cylindrical cavity of a 22.5 mm radius (R_0) with an entry fillet of a 3 mm radius (ρ_0). A position transducer was used to acquire during the whole test the dome height of the specimen. To assure a uniform temperature along the sheet, each test was started, i.e. the gas pressure was raised up to the test value, 300 s after positioning the blank between the tools and setting the blank holder force. On the centre of the blank, the temperature was monitored trough a thermocouple that is installed on the slider of the position transducer by which the dome height is measured during the whole test. Tests were performed in optimal temperature (500°C) conditions found in a previous work carried out on the same material [11].

2.3. Pressure profiling

Constant pressure free bulging testing provides significant variation of strain rate. In order to reduce this variation a special pressure control technique was implemented based on a mathematical model of a bulging process. Considering stress equilibrium in a bulge pole one can obtain a classical relation between effective stress in the apex of a dome (σ) and applied pressure (P):

$$\sigma = \frac{P\rho}{2s}, \tag{1}$$

where ρ is a curvature radius and s is a current thickness of the sheet at the dome apex. Assuming that the bulge has a spherical shape and using simple geometrical calculations, the curvature radius can be expressed as follows:

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

where H is the current height of the dome

The thickness of a sheet at the top of the dome is assumed to be related linearly to the dome height normalized by curvature radius and the entry fillet:

$$s = s_0\left(1 - B\frac{H}{\rho+\rho_0}\right) = s_0\left(1 - \frac{2BH^2}{H^2+(R_0+\rho_0)^2}\right), \tag{3}$$

where B is a constant in a range of (0.5 – 1) depending on material properties, s_0 is the initial thickness of the specimen.

Substituting eqn. (2) and eqn. (3) to eqn. (1) the value of pressure needed to maintain the equivalent stress at the dome apex at a constant target level (σ_{trg}) can be expressed as a function of dome height:

$$P(H) = 4\sigma_{trg}s_0H\frac{H^2(1-2B)+(R_0+\rho_0)^2}{(H^2+(R_0+\rho_0)^2)(H^2+(R_0+\rho_0)^2-2H\rho_0)} . \tag{4}$$

Tests were performed with two target stress values of 5.46 and 7.72 MPa chosen based on previous work [11]. The value of B was set to 0.75 for the first test and then adjusted to satisfy the eqn. (3) according to the value of thickness measured after the test performed to a final height of H = 25.5 mm corresponding to hemispherical dome.

3. Results and Discussion

The height and pressure evolutions recorded during the first test are illustrated in fig. 1(a). For further processing, the data were filtered as it is shown in the picture. The specimen was cut and the thickness at the dome apex was measured at 0.44 mm. Corresponding value of B was found at 0.674. Using this data and eqns. (1)-(3), the values of thickness (s), effective stress (σ) and effective strain ($\varepsilon = \ln(s_0/s)$) were calculated for each instance of time. The variation of the effective stress with the effective strain is plotted on fig. 1(b) by the dashed red curve labelled "1". It can be seen that the stress is much lower than the target value of 7.72 MPa because of wrong initial guess about the value of B (0.75). The second test was performed for the same target stress of 7.72 MPa with the adjusted value of B=0.674. Final thickness was found at the same value of 0.44 mm. The stress path corresponding to this test is labelled by "2" in fig. 1(b).

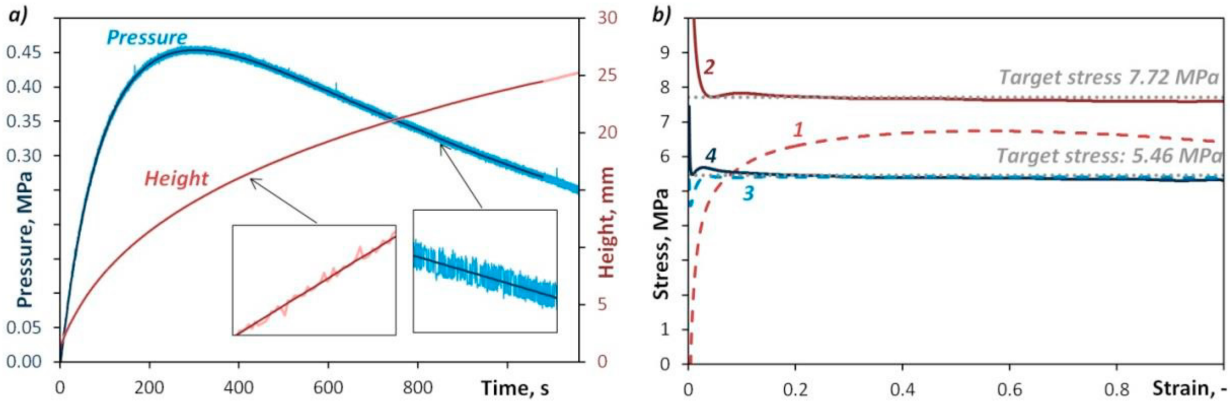

Fig. 1. (a) pressure and height evolutions recorded for the test №1 (σ_{trg}=7.72, B=0.75); (b) variation of the effective stress with the effective strain obtained by four different tests: "1" - σ_{trg}=7.72, *B*=0.75; "2" - σ_{trg}=7.72, *B*=0.674; "3" - σ_{trg}=5.46, *B*=0.674; "4" - σ_{trg}=5.46, *B*=0.662.

Two other tests were performed for the target stress of 5.46 MPa. The pressure control algorithm for the first of them used the value of B = 0.674. After the measurement of thickness at 0.46 mm the value of B was adjusted to 0.662 and the test was replicated. The effective stress variations corresponding to these tests are labeled in fig. 2 (b) by "3", and "4". It can be seen that after the calculation of B according to the measured values of thickness, the target stress is controlled with fine precision. The small variation of B after the third test does not affect the effective stress evolution significantly.

While the magnitude of stress in the apex of a dome is controlled at a constant level, the strain rate can vary over a several range due to the strain hardening (or softening) of the material. In order to analyze the strain rate path corresponding to every test the effective strain evolution was differentiated numerically. The strain rate paths obtained by this way are plotted in fig. 2(a). It can be seen that for the tests "2"-"4" where the stress is maintained near the target value, the strain rate is highest at the beginning of a test and decrease with the strain which indicates the presence of strain hardening. Assuming the Bakofen power relation between stress and strain rate, the obtained stress and strain rate paths can be transformed to a stress-strain curve corresponding to a constant reference strain rate ($\dot{\varepsilon}_{ref}$) as follows:

$$\sigma(\varepsilon) = K(\varepsilon)\dot{\varepsilon}_{ref}^{m(\varepsilon)} , \quad (5)$$

$$m(\varepsilon) = ln\left(\frac{\sigma_2(\varepsilon)}{\sigma_4(\varepsilon)}\right) / \, ln\left(\frac{\dot{\varepsilon}_2(\varepsilon)}{\dot{\varepsilon}_4(\varepsilon)}\right) , \quad (6)$$

$$K(\varepsilon) = \sigma_2(\varepsilon)/\dot{\varepsilon}_2(\varepsilon)^{m(\varepsilon)} , \quad (7)$$

where $\sigma_2(\varepsilon)$, $\sigma_4(\varepsilon)$, $\dot{\varepsilon}_2(\varepsilon)$ and $\dot{\varepsilon}_4(\varepsilon)$ - are the stress and strain rate paths for the tests “2” and “4”. The stress strain curves for the referenced strain rates of 0.0005 and 0.001 s^{-1} as well as the evolution of strain rate sensitivity (m) calculated using eqns.(5)-(7) are presented in fig. 2(b).

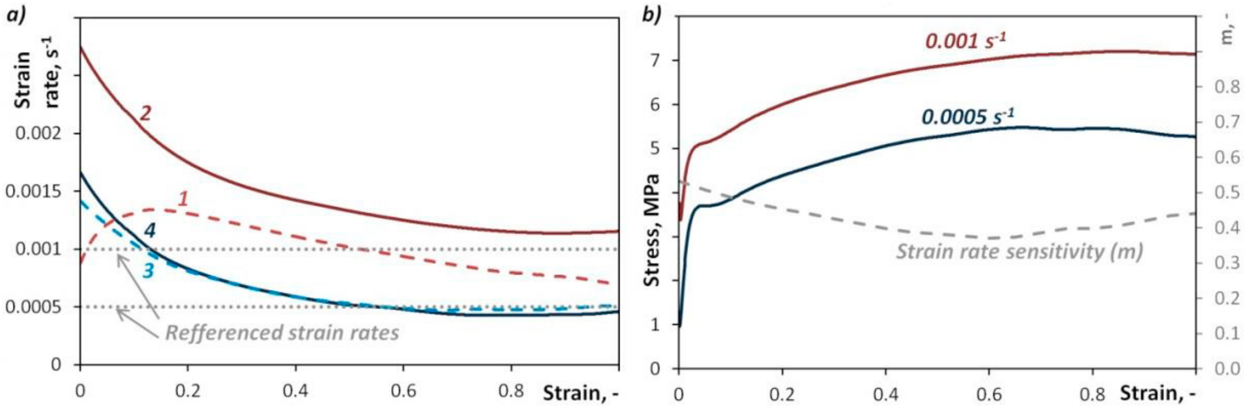

Fig. 2. (a) strain rate paths corresponding to different tests; (b) stress-strain curves calculated for the referenced strain rates 0.001 and 0.0005 s^{-1} and the evolution of strain rate sensitivity

The stress strain data obtained by eqns. (5)-(7) were verified by a FEM based computer simulation implemented in ABAQUS software. Axisymmetric formulation of forming task was used with rectangular finite elements. Coulomb friction law with a friction coefficient of 0.1 was used for the contact nodes. A pressure was applied to the bottom surface of a specimen according to the regimes realized in the experiments. The material constitutive equations were specified in table form according to the data calculated by eqns. (5)-(7) and plotted in fig, 2(b). The results of simulation are shown in fig. 3.

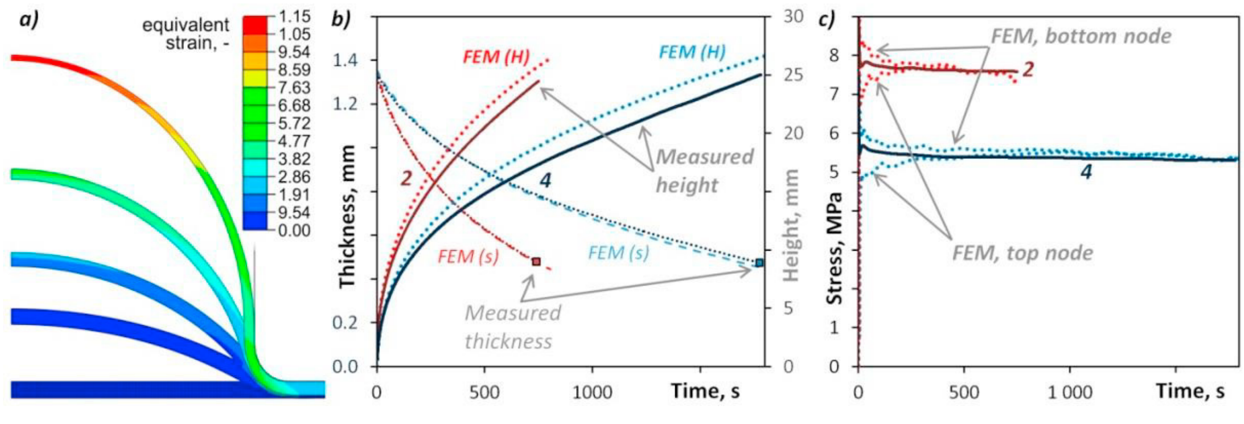

Fig. 3. (a) shape evolution of a radial section of the specimen with the equivalent strain distribution obtained by FE simulation; (b) comparison of height and thickness evolutions obtained by FEM simulation with the measured values; (c) comparison of the equivalent stress evolution obtained by FEM (solid lines) and by application of eqn.(1)-(3) to the experimental data.

The evolution of a radial section of the specimen during the test №2 with the equivalent strain distribution is shown on fig. 3(a). Height and thickness evolutions of a specimen are illustrated on fig. 3(b). Experimental tests at both strain rate values were replicated three times. The first test allowed to calculate the effective B value after sectioning the specimen (as mentioned at the beginning of this section) and the other two tests were used to quantify the replicability of the test itself. A mean deviation in the height versus time curves between the two replications of 2.4% and 3.7% was recorded for target stress of 5.46 and 7.72 MPa, respectively. It can be seen that the predictions of a specimen thickness are in a very good agreement with the experiment. Measured thickness values are shown by markers. The data plotted by thin dotted lines are obtained by eqn. (3) applied for measured height evolution and final thickness. The results of FEM simulations are plotted by thin dashed lines. Maximum deviation is less than 0.03 mm. At the same time the predictions of a dome height made by FEM (bold dotted lines) exceeds the values measured during the tests (bold solid lines). Maximum overestimation is about 1.84 mm. These deviations could be related to the assumption on the shape of the dome which is not perfectly spherical especially for elevated strain values as reported in [9]. Further analyses on this aspect are currently under investigation.

The comparison between the equivalent stress at the dome apex predicted by FEM and calculated based on the experimental measurements and eqns. (1)-(3) is presented on fig. 3(c). It can be seen that the results are in a good agreement and deviations are less than difference between the effective stress at the top and the bottom central nodes of the FE model. Thus it can be concluded that the pressure control based on eqn. (4) allows one to control the equivalent stress on a specified level without a priori knowledge of the material properties.

4. Conclusion

A new experimental-numerical technique is proposed for investigation of stress-strain behavior of a sheet material. A stress-strain curve for a constant reference strain rate can be calculated on a base of four free bulging tests with a special pressure control technique allowing one to maintain the equivalent stress on a specified level.

The stress strain curves for commercial aluminum alloy ALNOVI-U were constructed for the referenced strain rates of 0.0005 and 0.001 s^{-1} using the proposed methodology. Finite element simulation confirmed the efficiency of the equivalent stress control technique and adequacy of the obtained stress-strain data.

Acknowledgements

The authors wish to express their gratitude to Valeria Ruggiero, Prof. Luigi Tricarico and Prof. Gianfanco Palumbo (Politecnico di Bari) for their support in experimental and in numerical activities. The study was implemented in the framework of the Basic Research Program at the National Research University Higher School of Economics (HSE).

References

[1] N. Chandra, Constitutive behaviour of superplastic materials, Int. J. Non Linear Mech. 37 (2002) 461–484.

[2] S.A. Aksenov, A.V. Kolesnikov, A.V. Mikhaylovskaya, Design of a gas forming technology using the material constants obtained by tensile and free bulging testing, J. Mater. Process. Technol. 237 (2016) 88–95. doi:10.1016/j.jmatprotec.2016.06.003.

[3] G. Giuliano, S. Franchitti, The determination of material parameters from superplastic free-bulging tests at constant pressure, Int. J. Mach. Tools Manuf. 48 (2008) 1519–1522. doi:10.1016/j.ijmachtools.2008.05.007.

[4] D. Sorgente, G. Palumbo, L. Tricarico, Material Superplastic Parameters Evaluation by a Jump Pressure Blow Forming Test, Key Eng. Mater. 334 (2007) 119–126. doi:10.4028/www.scientific.net/KEM.344.119.

[5] A.W. El-Morsy, K. Manabe, FE simulation of rectangular box forming using material characteristics from the multi-dome forming test, J. Mater. Process. Technol. 125-126 (2002) 772–777. doi:10.1016/S0924-0136(02)00389-8.

[6] J. Slota, E. Spisak, Determination of flow stress by the hydraulic bulge test. METALURGIJA 47 (2008) 13–17.

[7] H. Campos, A.D. Santos, B. Martins, K. Ito, N. Mori, F. Barlat, Hydraulic bulge test for stress-strain curve determination and damage calibration for Ito-Goya model, Proc. World Congr. Comput. Congr. XI, Barcelona, Spain., Barcelona: 2014.

[8] M. Koç, E. Billur, Ö.N. Cora, An experimental study on the comparative assessment of hydraulic bulge test analysis methods, 32 (2011) 272-281. doi:10.1016/j.matdes.2010.05.057.

[9] S. Kaya, T. Altan, P. Groche, C. Klo, Determination of the flow stress of magnesium AZ31-O sheet at elevated temperatures using the hydraulic bulge test 48 (2008) 550–557. doi:10.1016/j.ijmachtools.2007.06.011.

[10]D. Banabic, M. Vulcan, K. Siegert, Bulge Testing under Constant and Variable Strain Rates of Superplastic Aluminium Alloys, CIRP Ann - Manuf. Technol. 54 (2005) 205–208. doi:10.1016/S0007-8506(07)60084-5.

[11]D. Sorgente, L. Tricarico, Characterization of a superplastic aluminium alloy ALNOVI-U through free inflation tests and inverse analysis, Int. J. Mater. Form. 7 (2014) 179–187. doi:10.1007/s12289-012-1118-3.