FEM Analysis of Superplastic PbSn60 Alloy Free Bulging Test

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Abstract

Using the finite element method, this paper analyzes the superplastic flow of PbSn60 alloy submitted to free bulging test. The value of H (defined H*) corresponding to the maximum value of dt/dH is also analyzed. The dependence of H* from the die and the sheet geometry, the process parameters and the material constants is showed. Free bulging tests are conducted at constant pressure using the fine-grained Pb-Sn alloy that presents superplastic properties at room temperature.

Keyword-Superplastic forming, Free bulging test, FEM analysis, PbSn60 alloy, Large strain

I. INTRODUCTION

Superplastic metals have the ability to undergo large strains prior to failure. In tensile tests, elongation to failure in excess of 200% is usually indicative of superplasticity, although several materials can attain extension greater than 1000%. Superplasticity is due to both peculiar process conditions (relatively high temperature and very low strain-rate) and material intrinsic characteristics (a fine and stable grain size) [1].

In the free bulging test represented in the figure 1, the die and the metal sheet are normally kept at the forming temperature; the gas under pressure, applied to the sheet, pushes it into the die. The sheet does not come into contact with the die walls. The following dimensionless height, H, has been introduced as:

$$H = \frac{h}{a} \tag{1}$$

where a is the initial radius of the sheet (equal to die radius) and h is the bulge height measured at the sheet metal apex, respectively.

Finite element method (FEM) represents a numerical tool capable of simulating successfully superplastic forming processes. FEM has the predictive capabilities for obtaining a large quantity of detailed information about the deformation process as pressure-time load curve, stress, strain and strain-rate distributions, thickness distribution in the final product [2-3].

In [4], an analytical model to identify the value of H (defined H*) corresponding to the maximum value of (dt/dH)-H curve was presented. This parameter can represent a practical tool in industrial applications to establish the superplastic behaviour of a sheet metal. The results of the analytical model (in terms of H*) were independent from the die geometry and the sheet but only dependent on the value of the strain rate sensitivity index, m. Analytical modelling is limited only to simple form geometry of the die and to the use of largely approximated assumptions.

The finite element method can be considered to be the most dependable both for analysing complex geometries, and for taking into consideration all the process parameters. In this paper, by FEM the effects of the geometry, the process parameters and the material properties on the H*-value are considered. The numerical simulation of superplastic free forming process is analyzed and is presented a comparison with the PbSn60 alloy submitted to free bulging test.

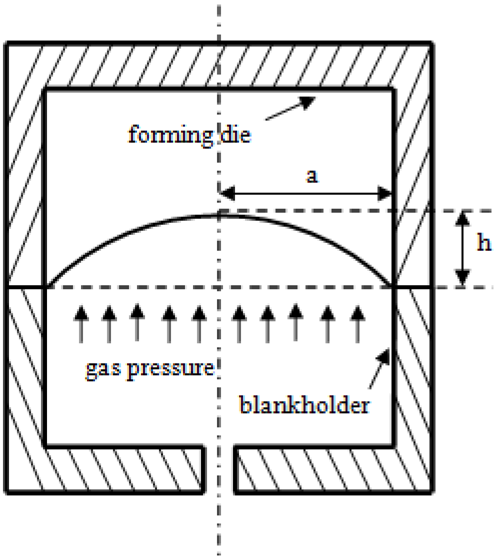

Figure 1. Example of free bulging test

II. NUMERICAL RESULTS

As in previous works [5 to 16], MSC.Marc® FEM code is used as the superplastic forming process modelling tool, and a rigid plastic flow procedure is considered.

Starting from a finite element model, a blank, with a diameter of 64 mm and a thickness in the range of 0.3-1.0 mm, is meshed using four-node isoparametric elements for axisymmetric applications. The element has two coordinates in the global z- and r-direction and two degrees of freedom for node [17]. As reported in figure 2, the die is considered to be rigid with a die inner radius of 30.0 mm and a die entry radius of 2.0 mm. Constant pressure is applied as a distributed load. Because of the symmetry of the geometry, the load and the constraint conditions, half of the cross-section of the blank is analyzed. It is necessary to lock the movement of the nodes along the axis of symmetry in a direction that is orthogonal of the axis of symmetry, to avoid penetration of the adjacent elements. Moreover, it is necessary to impose constraint conditions on the periphery of the blank in order to simulate the action of a blank holder.

FEM is based on knowing the material constitutive equation. For many superplastic materials it is shown in [18] that the equivalent flow stress is dependent on both the equivalent strain-rate and the equivalent strain but the most common equation for the superplastic flow is given by:

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

where σ is the flow stress of the material, K is the strength coefficient, $\dot{\varepsilon}$ is the strain-rate and m is the strain rate sensitivity index. This equation is based upon the properties at constant temperature and assumes no work hardening during deformation.

A material model and the pressure values are input into the MSC.Marc® code through user-subroutines.

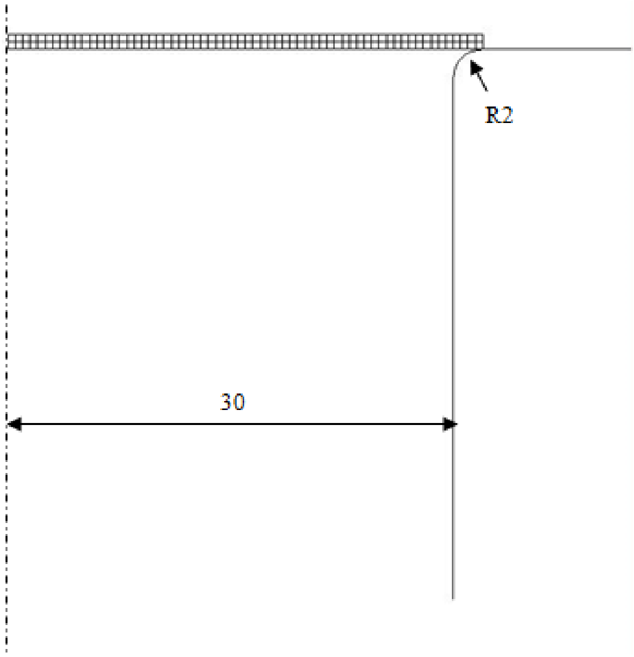

Figure 2. Numerical model of the free bulging process of a circular sheet

Results of numerical simulations in terms of thicknesses distribution (fig.3) are slightly affected by the bending effects of the sheet metal on the die entry radius when the thickness increases from 0.3 to 1 mm (s/s_0 measured to sheet apex increases by 8%). Fixed m-value to 0.3, the effects of parameters K (that ranges from 100 and 1000 MPa•s), p (0.2-2 MPa) and s_0 (0.3 -1.0 mm) on the H*-value were analyzed. The deviations of H* are very low (1%). H*-value corresponding to maximum value of dt/dH is ≈ 0.63. This result is also confirmed by varying the diameter of the blank (from 64 to 104 mm). The results (in terms of H*-value) of comparison between the numerical simulation and the analytical model [4] have shown good agreement.

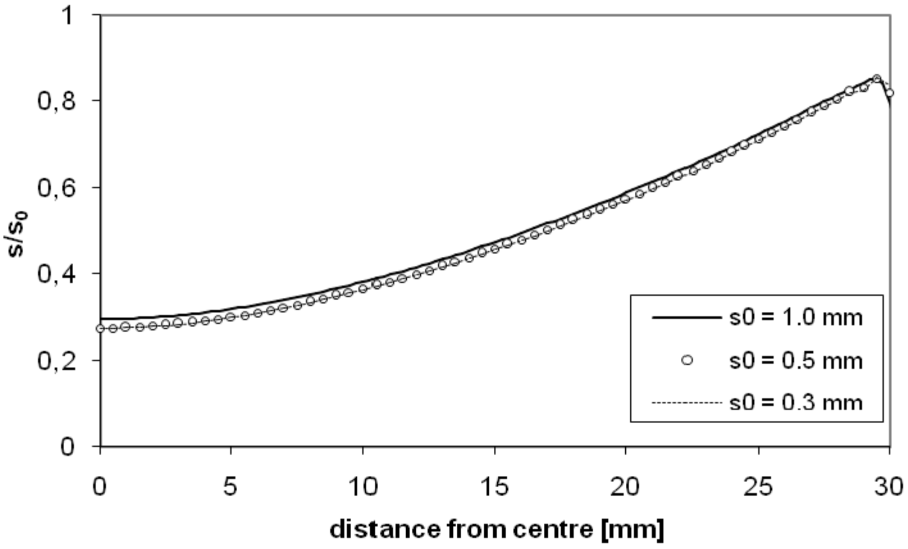

Figure 3. FEM results: thicknesses distribution by varying the initial thickness, s_0, of the sheet metal

III. COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

In this study, PbSn60 alloy was selected as experimental material for free bulging test by using the forming apparatus designed and set up at Cassino University [19].

The PbSn60 alloy is a non-ferrous alloy 60% lead and 40% tin in weight, commercially available in the form of PbSn60-marked soldering bars. In order to obtain an extremely fine grain, the bars were submitted to repeated lamination and folding processes [~~2 and~~ 12 to 16]. The alloy has mechanical properties that are too low to be used in industrial applications, but proves to be advantageous for laboratory activity. In [16], PbSn60 alloy was shown to depend on the strain rate as in Eq. (2) and free bulging tests were used to evaluate the material constants. The free bulging tests, at room temperature with sheets of circa 0.3 mm thickness, were carried out at pressures of 0.10 and 0.18 MPa. Material constants are m = 0.518 and K = 144 MPa•s.

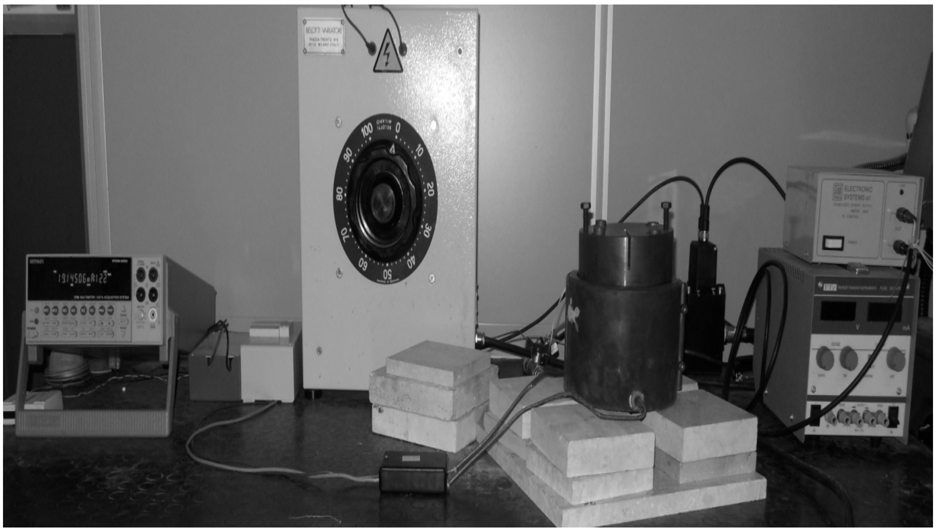

Figure 4. Equipment used at the Cassino University Laboratory for the free bulging process

The forming system layout is shown in Figure 4. A circular specimen is interposed between two steel dies. The upper die has a circular geometry with an aperture radius of 30.0 mm and a die entry radius of 2.0 mm. The lower die works as a blankholder. From the lower die a pressure gas acts on one side of the sheet forcing it to expand into the upper die cavity. The air pressure is obtained by a compressor and it is regulated by a proportional valve. A pressure transducer is inserted on the air injection line to ensure that the pressure inside the die is equal to the one set for the bulging test. During the whole test, the sheet metal can freely expand; the dome height of the specimen is monitored by the acquisition of a laser device and recorded as a function of time. Further details about the forming system are reported in [19].

Figures 5 and 6 show the comparison between numerical and experimental results in terms of H-t and (dt /dH)-H curves. It is possible to notice that for the PbSn60 alloy the H*-value is equal to 0.67 at a temperature of 298K and at pressures of 0.10 and 0.18 MPa.

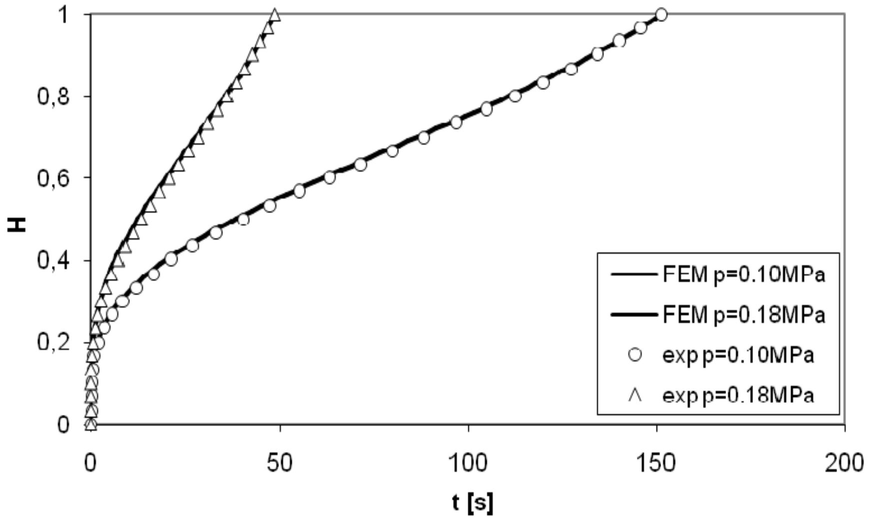

Figure 5. PbSn60 alloy: comparison between fem and experimental results in terms of H-t curves

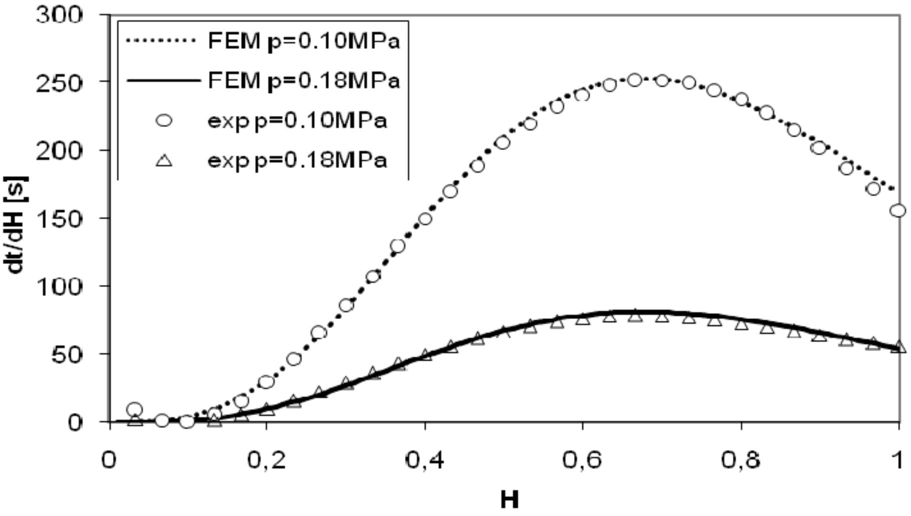

Figure 6. PbSn60 alloy: comparison between fem and experimental results in terms of (dt/dH)-H curves

IV. CONCLUSION

Free bulging tests were simulated by the FEM. The effects of the geometry, the process parameters and the material properties were considered. The numerical results have shown that the H*-value is independent from the strength coefficient value, the sheet metal thickness and the applied pressure. To the contrary, the H*-value is dependent from the strain rate sensitivity index. The results of the experimental activity carried out using the superplastic PbSn60 alloy were in good accordance with the numerical predictions. From the numerical model, for m=0.3, the H*-value is ≈ 0.63. For the PbSn60 alloy the H*-value is equal to 0.67 at a temperature of 298 K and at forming pressure of 0.10 and 0.18 MPa.

REFERENCES

[1] J. Pilling and N. Ridley, Superplasticity in Cristalline Solids, The Institute of Metals, 1989.

[2] L. Carrino, G. Giuliano and C. Palmieri, “Analysis of superplastic bulge forming by the finite element method”, Mater. Tech. vol. 16, 4 pp. 237-241, 2001.

[3] G. Giuliano, “Comparison between finite element commercial codes to simulate high-temperature AA5083 bulge forming”, Adv. Mater. Res. vol. 457-458, 1 pp. 387-390, 2012.

[4] C. Bellini, G. Giuliano and L. Sorrentino, “Free bulging at constant pressure of superplastic sheet metal”, Int. J. Eng. Tech. vol. 7, 4 pp.1173-1178, 2015.

[5] G. Giuliano, “Failure analysis in superplastic materials”, Int. J. Mach. Tool Manu. vol. 46, 12-13 pp. 1604-1609, 2006.

[6] S. Franchitti, G. Giuliano, G. Palumbo, D. Sorgente and L. Tricarico, “On the optimisation of superplastic free forming test of an AZ31 magnesium alloy sheet”, Int. J. Mater. Form. vol. 1, 1 pp. 1067-1070, 2008.

[7] G. Giuliano, “Thickness and strain rate at the sheet dome apex in superplastic bulge forming tests”, Int. J. Mater. Form. vol. 2, 1 pp. 375-378, 2009.

[8] G. Giuliano, “Constitutive modelling of superplastic AA-5083”, Technische Mechanik vol. 32, 2 pp. 221-226, 2012.

[9] R.D. Wood and J. Bonet, “A review of the numerical analysis of superplastic forming”, J. Mater. Process. Tech. vol. 60, pp. 45-53, 1996.

[10] N. Rebelo and T.B. Wertheimer, “Finite element simulation of superplastic forming”, MARC users conference, MARC Analysis Research Corp., USA, pp. 81-87, 1988.

[11] M.A. Khaleel, K.I. Johnson, C.H. Hamilton and M.T. Smith, “Deformation modeling of superplastic AA-5083”, Int. J. Plasticity vol. 14, 10-11, pp. 1133-1154, 1998.

[12] L. Carrino, G. Giuliano and S. Franchitti, “Modelling the free forming of superplastic PbSn60 at constant pressure”, J. Mater. Process. Tech. vol. 177, pp. 95-97, 2006.

[13] G. Giuliano, L. Carrino and S. Franchitti, “Formability of superplastic PbSn60 alloy”, Mater. Lett. vol. 59, pp. 2156-2158, 2005.

[14] G. Giuliano, “Analysis of forming limit diagram for superplastic materials”; Int. J. Adv. Manuf. Tech. vol. 31, 3-4 pp. 244-246, 2006.

[15] S. Franchitti and G. Giuliano, “The determination of material parameters from superplastic free-bulging tests at constant pressure”; Int. J. Mach. Tool Manu. vol. 48, 12-13 pp. 1519-1522, 2008.

[16] S. Franchitti and G. Giuliano, “On the evaluation of superplastic characteristics using the finite element method”; Int. J. Mach. Tool Manu. vol. 47, pp. 471-476, 2007.

[17] MARC Analysis Research Corporation, Element Library, Vol.B. MARC Analysis Research Corporation, Palo Alto, California, USA, 1994.

[18] N. Chandra, “Constitutive behaviour of superplastic materials”, Int. J. Non Linear Mech. vol. 37, pp. 461-484, 2002.

[19] G. Giovinco, G. Giuliano and G. Testa, “Forming apparatus to investigate the effect of temperature on the superplastic behaviour of alloys”; AIP Conf. Proc. vol. 1252, pp. 304-311, 2010.