TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 59, Issue III, September, 2016

GAS PRESSURE FORMING OF 2024 ALUMINUM ALLOY IN A HEMISPHERICAL DIE

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Abstract: *This paper is focused on forming hemispheres from the commercial 2024-T3 aluminum alloy at different temperatures, pressures and the walls thickness variation for the formed hemispheres. The aluminum alloy do not exhibit superplastic properties under conventional processing conditions and for this it was thermo-mechanical processed for grains refining, in order to improve deformation characteristics. The gas pressure forming tests were carried out at the temperatures of 460°C, 480°C and constant pressures of 0.75 MPa, 0.8 MPa, using aluminum alloy sheets of a 0.67 mm thickness, obtained from thermo-mechanical processing. The polar heights of the sheets have been measured as a function of the forming time. The results of tests showed that for formed hemispheres the walls thickness gradually decreases with increasing of height from base to pole and the largest thinning of the walls is obtained at the pole of these.*
Key words: *2024 aluminum alloy, thermo-mechanical processing, grains refining, gas bulge forming test, thickness distribution.*

1. INTRODUCTION

Superplastic forming is an attractive forming technique that has found application in sheet metal forming in the aerospace and automotive industries. Bulge forming is a superplastic forming process, an advanced method for the fabrication of complex thin-walled parts. To increase the hot forming ability and improve the mechanical properties of the final products, the utilization of superplasticity effect is desired [1], so the ability of some materials to exhibit large strains to failure when are deformed at high temperatures and at lower strain rates. The superplastic materials show elongation more than 200%. These elongations help in producing components with complex shape, in a single operation, to a near final shape, high strength components, with a much lower manufacturing cost, greater design flexibility. Materials such as aluminum alloys shall exhibit the phenomena of superplasticity, when subjected to certain conditions of pressure, temperature and strain-rates [2]. The conditions are summarized as: grain size less than 10 μm, low strain rates within the range $10^{-5} – 10^{-3}$ s^{-1} and temperatures greater than 0,5 T_m, where T_m is the melting point in degrees Kelvin of the material under investigation [3]. High degrees of deformation can be obtained in the case of commercial metallic materials by using grain refinement techniques, for example by thermo-mechanical processing [4]. Superplastic materials are characterized by their total elongation at failure in uniaxial tensile testing and by the strain rate sensitivity exponent. Because commercial superplastic forming processes are performed under multiaxial stress conditions and the material data from the uniaxial tensile tests are insufficient to describe the formability, they began to use the bulge forming tests. In the superplastic forming process the sheet is clamped around its periphery and gas pressure is applied on the sheet surface, forcing it to take die shape. During the initial stage of deformation the sheet is not in contact with the die. The deformation is concentrated at the pole and consequently this region exhibits the greatest flow stresses, strain rates and strains.

When the pole comes in contact with the surface of the die, the material is locked due to friction and forming pressure and this prevents further deformation within the region.

The forming time in superplastic forming process is from 20-30 minutes to several hours, due to very low strain rates [5]. The superplastic forming of hemispherical and box shaped products poses a problem of large thickness variation between pole and base of the product. This variation is inevitable in superplastic forming [6], although the early analysis by Jovane [7] and Belk [8] did not consider the thickness non-uniformity of the bulging profile. The constant gas pressure forming is characterized by changes in the value of strain rate [7] and can lead to a significant variation of thickness.

2. EXPERIMENTAL RESEARCH

The experiments were conducted using a commercial 2024-T3 aluminum alloy received, in the extruded rectangular shape bar with 40 mm width and 20 mm thickness, produced by S.C. ALPROM S.A. Slatina, Romania. Chemical composition (in wt%) is: 4.954 Cu; 1.663 Mg; 0.696 Fe; 0,519 Mn; 0.279 Si; 0.096 Zn; 0,.029 Cr; 0.022 Sb; 0.020 Pb; 0.007 Sn; 0.006 Ni; Al-balance. This bar was heat treated to T3 temper, that means that the extruded bar has been solution heat treated, cold deformed and then naturally aged.

The commercial 2024 aluminum alloy was thermo-mechanical processed in order to induce superplastic behavior. The test specimens from a received material with a width 40 mm, thickness of 20 mm and a length of 45 mm, were homogenized at 500ºC for 8 hours, to remove residual thermal stresses present in the non-homogenized material and to improve the deformability. Hot rolling was performed at temperatures between 440÷480ºC with a total reduction of 90%, until a thickness of 2 mm. After hot rolling, followed by cooling in cold water, cold rolling was performed with a total reduction of 66.5%, until a thickness of 0.67 mm. Because during the cold rolling the material was hardened, the recrystallization annealing was intercalated after 4-5 passes, by heating the alloy to 480ºC and keeping at this temperature for 15 minutes, followed by fast cooling in water. Then the rolled samples were recrystallized by fast heating to 480ºC, kept for 15 minutes and fast cooling in water, to obtain a fine grain structure before gas bulge forming.

The experimental installation for gas pressure bulge forming designed for material testing at high temperatures consists of: the preparation and filtration group of air (which includes: pressure source (compressor), air filter, pressure valve, lubricator); horizontal electric furnace CARBOLITE CTF 12/75/700 type; gas pressure forming die; inductive displacement transducer of 100 mm, precision proportional valve; strain gauge deck with six channels; SUPER 12 bit AD/DA acquisition board; IBM PC 386 computer system; SUPERPLAST software which performs signals acquisition from the displacement transducer, the pressure transducer and the command of the pressure pneumatic regulator.

The tools used to gas pressure bulge forming are two halves of the die from refractory steel. By means of two rods with a length of 300 mm, made of refractory steel, which are pierced, is provided the air access in the die, during the process of superplastic forming (fig. 1).

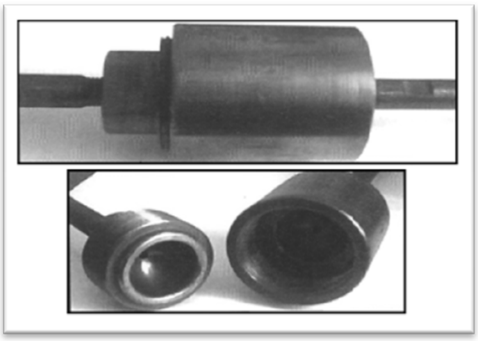


Fig. 1. The die halves for gas bulge forming.

The half die which gives the final form of the piece has a cylindrical portion with a diameter of 32 mm and height of 8 mm (which has the role to reduce and even cancel the friction between the semi-finished products and die during deformation) with a die entry radius of 3 mm, and a half sphere.

It has performed an experimental research for obtaining hemispheres through gas pressure bulge forming at constant pressure with interest for evolution of height and thickness non-uniformity of formed components.

The disks from 2024 aluminum alloy which has been thermo-mechanical processed, with a diameter of 49 mm and with thickness of 0.67 mm were deformed super-plastically in spherical cavity of the die with diameter of 32 mm, at the constant forming pressures of 0.75 MPa, 0.8 MPa and at temperatures of 460ºC, 480ºC. Each test-piece was clamped between the two heaves of die. The die was introduced within the furnace and after heating the sample to the required forming temperature, the air was introduced in the deformation room with the help of preparation and filtration group of air and of proportional valve. Each specimen was formed at a constant pressure by rapidly increasing of the pressure to a prescribed level. As the bulge forming process progresses a significant thinning in the aluminum alloy sheet becomes obvious. During each forming test which has been performed until material failure, the polar heights of the sheet have been measured as a function of the processing time.

In order to determine the hemispheres profile and the thickness of formed components in bulging tests, was used a Zeiss Eclipse coordinates measuring machine which generates through rigorous touching by a stylus with a radius of 1.5 mm, the meridian profile passing through pole, with a step of 1 mm (fig. 2).

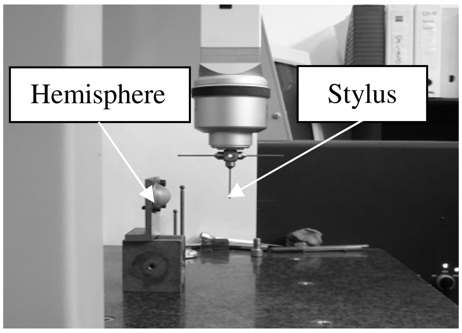


Fig. 2. Zeiss Eclipse coordinates measuring machine.

Accurately locating of the pole has imposed several measurements of profile for deformed sheet, according to the two perpendicular directions to 0º and 90º in relation to the X axis. In this way it was precisely located the maximum height that is desired. Then, using the offered facilities by the AUTOCAD, was plotted the meridian profile of hemispherical shape and were established the points for determining of thickness along the profile. These selected points were obtained taking the current heights of hemispherical profile from its base (periphery) to pole. Then, local thicknesses were determined at selected points along the meridian profile.

For analysis of superplastic forming behavior, the disc-shaped specimens of 2024 aluminum alloy sheet were likened to spherical membranes of uniform thickness, formed by the constant pressure of compressed air. An applied pressure p, in a hemispherical die of radius R, a disk specimen with the initial thickness g_o will deform into a spherical membrane of radius R_d and the thickness at the pole g (fig.3).

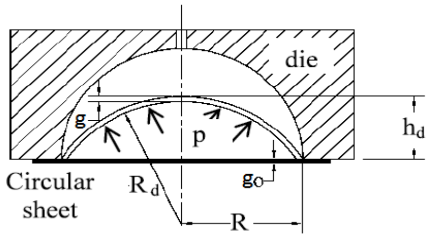


Fig. 3. The gas pressure bulge forming.

Knowing the value of the bulge height h_d and assuming the volume constancy of the material, can be calculated the instantaneous radius of curvature R_d, the equivalent stress σ, the thickness strain δ, the strain rate $\dot{\varepsilon}$, at the pole of the formed component, using the following relations [9]:

$$R_d = \frac{D^2 + 4h_d^2}{8h_d} \tag{1}$$

$$\sigma = \frac{R_d \cdot p}{2g} \tag{2}$$

$$\delta = \ln\left(\frac{g}{g_0}\right) \tag{3}$$

$$\dot{\varepsilon} = \frac{\ln\left(\frac{g}{g_0}\right)}{t} \tag{4}$$

where: g is the wall thickness at the pole of the bulge profile, g_o is the initial sheet thickness, h_d

is the height at the pole of bulge profile, t is the forming time, p is the forming pressure, D is the diameter of the cavity.

The as-processed aluminum samples were cut in the transversal and longitudinal direction, polydol mounted, and mechanically polished. Keller's reagent was used to reveal microstructure in this material. Microstructures were observed through optical microscopy using a optical microscope.

3. RESULTS AND DISCUSSIONS

Figure 4 shows an optical micrograph of the commercial 2024 aluminum alloy after thermo-mechanical processing, with grain size smaller than 10 µm. Such fine structure is suitable for superplastic deformation at high temperatures.

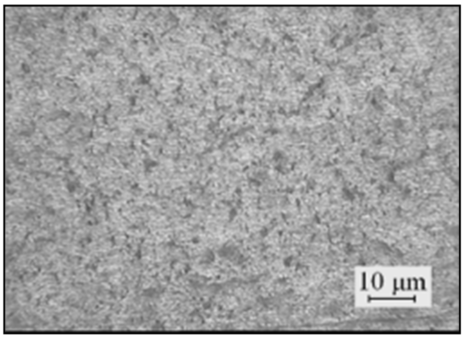


Fig. 4. Optical micrograph of 2024 aluminum alloy after thermo-mechanical processing.

The variation of the bulge height with forming time at pressures of 0.75 MPa, 0.8 MPa and at temperatures of 460°C, 480°C is shown in figure 5.

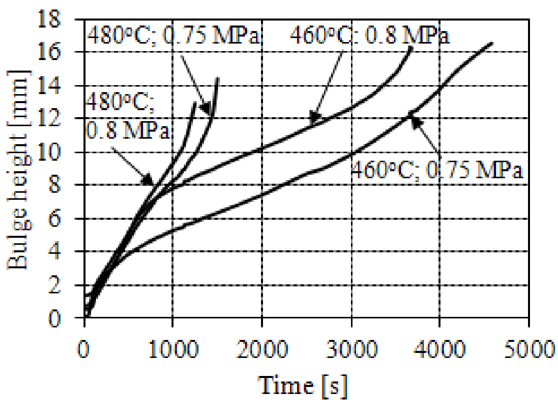


Fig 5. Bulge height versus forming time at temperatures of 460°C and 480°C and different pressures.

The curves in figure 5 indicate that there are tree distinct region. Initially, the height increases rapidly. Then, follows a period of apparent steady-state deformation characterized by o minimum deforming rate. Finally, the deformation rate increases again and the height approaches that of a hemisphere.

The sigmoidal variation of bulge height with the time in condition of constant pressure, may be attributed to the large stresses existing in the early stages of forming, when the height is small [10].

At a given temperature, as the forming pressure increases, more deformation is obtained within the material and hence the forming time decreases. It also can be observed that the bulge height reduces while the forming pressure increases.

At a given forming pressure, forming time decreases with an increase in temperature. The reduction of the forming time is due to decrease in flow stress of the material at high temperatures. At higher temperature, the yield strength of the material decreases thereby reducing the forming load and the forming time.

The various stages in superplastic forming of hemispherical shape is shown in figure 6.

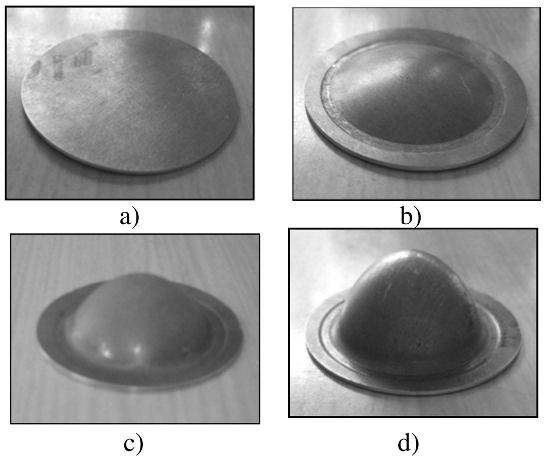


Fig. 6. Various stages in forming of hemispherical shape at temperature of 460^{0}C and pressure of 0.75 MPa:
a) initial sample; b) bulge height of 4.7 mm; c) bulge height of 12.12 mm; d) bulge height of 16.32 mm.

The results obtained during bulge forming analysis of the aluminum alloy sheets are given in table 1. The higher bulge height of 16.32 mm and the highest thickness variation of 0.477 mm were obtained at the formed hemisphere to the pressure of 0.75 MPa and temperature of 460°C.

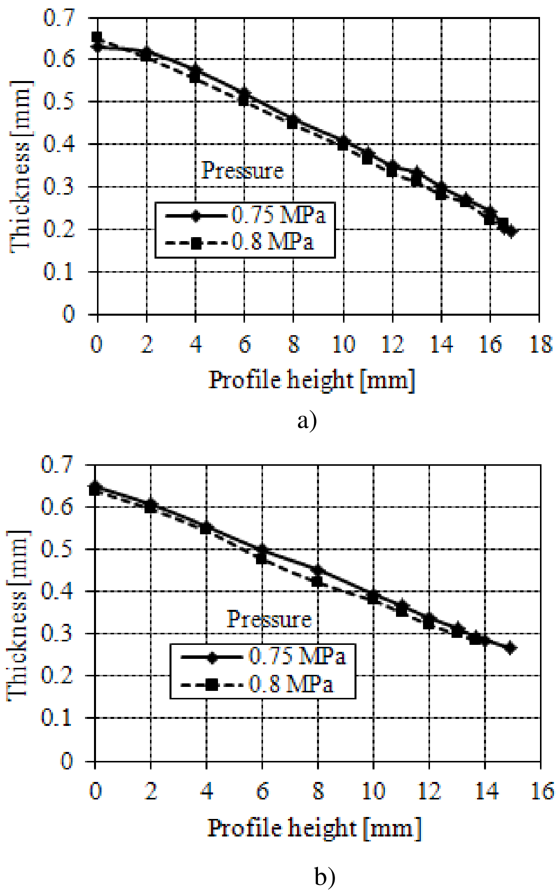
For a particular pressure, the thickness strain decreases as the forming temperature increases.

Table 1

Results obtained during bulge forming analysis, at different temperatures and pressures

Specimen	T [^{0}C]	h_d [mm]	p [MPa]	t [s]	g_0 [mm]	g [mm]	σ [MPa]	$\dot{\varepsilon}$ [$x10^{-4}$ s^{-1}]	δ
Gazo 1	460	16.32	0.75	4557	0.67	0.193	31.09	2.72	1.24
Gazo 2	460	16.17	0.8	3630	0.67	0.213	30.05	3.17	1.15
Gazo 3	480	14.43	0.75	1498	0.67	0.268	22,51	6.14	0.92
Gazo 4	480	12.96	0.8	1249	0.67	0.284	23.04	6.89	0.86

The thickness distribution along the bulge profile from base to the pole, during deformation at temperatures of 460ºC, 480ºC and different constant pressures (0.75 MPa, 0.8 MPa) is shown in figure 7.a respective figure 7.b.



b)

Fig. 7. Hemispheres walls thickness distribution from base to the pole, along the meridian profile at temperatures of: a) 460ºC; b) 480ºC.

It is observed that the thickness gradually decreases with increasing of profile height from base to the pole, so the largest thinning of the hemispheres walls is obtained at the pole.

Hemispheres from figure 8 were obtained by gas bulge forming tests at temperatures of 460ºC, 480ºC and pressures of 0.75 MPa, 0.8 MPa. The cracks are present only at the pole of the hemispheres, where was obtained the largest thinning of the walls thickness.

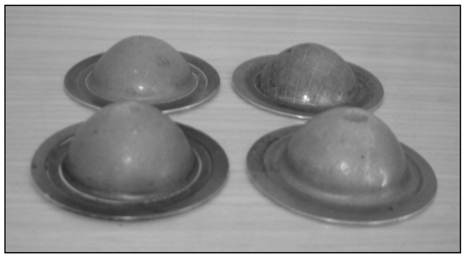


Fig. 8. Gas pressure formed hemispheres.

4. CONCLUSIONS

- Gas bulge forming of 2024 aluminum alloy in a hemispherical die was performed at high temperatures (460ºC, 480ºC) and constant pressures (0.75 MPa, 0.8 MPa).
- By means of gas bulge testing it demonstrated the possibility to obtain some pieces of hemisphere type from the 2024 aluminium alloy sheet with thickness of 0,67 mm, obtained by thermo-mechanical processing.
- The highest bulge height of 16.32 mm was obtained at the formed hemisphere to the pressure of 0.75 MPa and temperature of 460ºC.
- The forming time decreases when the gas pressure or temperature increase.
- The area of the bulge profile increases during forming with consequent decrease in thickness.
- The largest thinning of walls is obtained at the pole of hemispheres.

5. REFERENCES

[1] Aksenov, S.A., Chumachenko, E.N., Kolesnikov, A.V., Osipov, S.A.,

Determination of Optimal Conditions for Gas Forming of Aluminum Sheets, Proceeding of 11th International Conference on Technology of Plasticity (ICTP 2014), Editor Ishikawa, T. et al., Procedia Engineering, Volume 81, pp. 1017-1022, ISBN 978-1-63439-498-7, Nagoya Congress Center, 19-24 October 2014, Nagoia, Japan.

[2] Hamilton, C.H., Paton, N., *Superplasticity and superplastic forming,* Proceedings of an International Conference on Superplasticity and Superplastic Forming, Edited by C. Howard Hamilton and Neil E. Paton, pp. 706, ISBN 978-0-87339-089-7, Held in Blaine, Washington, 1-4 August 1988, The Minerals, Metals and Materials Society, USA, 1988.

[3] Langdon, T.G., *Mechanisms of Superplastic Flow,* Superplasticity: 60 Years after Pearson, Proceedings of the Conference Organized on Behalf of the Superplastic Forming Committee of the Manufacturing Division of The Institute of Materials, Edited by Norman Ridley, pp. 9-13, ISBN 0-90171-677-4, The Institute of Materials, London, 1995.

[4] Nieh, T.G., Wadsworth, J. and Sherby**,** O.D., *Superplasticity in Metals and Ceramics,* Cambridge University Press, pp. 64-65, ISBN 978-0-521-56105-1, Cambridge, 1997.

[5] Horita, Z., Furukawa, M., Nemoto, M., Barnes A.J., and Langdon, T.G., *Superplastic Forming at High Strain Rates after Severe Plastic Deformation,* Acta Materialia, Vol. 48, Issue 14, pp. 3633-3640, ISSN 1359-6454, September 2000.

[6] Akash, D.J., Babu, J., *Experimental Studies on Thinning Characteristics of Superplastic Hemi-spherical Forming,* International Journal of Emerging Technology and Advanced Engineering, Volume 5, Issue 1, pp. 104-109, ISSN 2250-2459, January 2015.

[7] Jovane, F., *An Approximate Analysis of the Superplastic Forming of a Thin Circular Diaphragm: Theory and Experiments,* International Journal of Mechanical Science, Volume 10, Issue 5, pp. 403-427, ISSN 0020-7403, May 1968.

[8] Belk, J.A., *A Quantitative Model of the Blow-Forming of Spherical Surfaces in Superplastic Sheet Metal,* International Journal of Mechanical Science, Volume 17, pp. 505-511, ISSN 0020-7403, August 1975.

[9] Gutscher, G., Wu, H.C., Ngaile G. and Altan, T., *Determination of Flow Stress for Sheet Metal Forming Using the Viscous Pressure Bulge (VPB) Test*, Journal of Materials Processing Technology, Volume 146, Issue 1, pp. 1-7, ISSN 0924-0136, February 2004.

[10] Senthil Kumar, V.S., Viswanathan D. and Natarajan, *S., Theoretical Prediction and FME Analysis of Superplastic Forming of AA 7475 Aluminum Alloy in a Hemispherical Die,* Journal of Materials Processing Technology, Volume 173, Issue 3, pp. 247-251, ISSN 0924-0136, April 2006.

Formarea sub presiunea gazului a aliajului de aluminiu 2024 in matriţă emisferică

Rezumat: Această lucrare este axată pe formarea de emisfere din aliajul comercial de aluminiu 2024-T3, la diferite temperaturi, presiuni şi pe variaţia grosimii pereţilor pentru emisferele formate. Aliajul de aluminiu nu prezintă proprietăţi superplastice în condiţii de procesare convenţională şi pentru aceasta a fost procesat termo-mecanic pentru afinarea grăunţilor, cu scopul de a îmbunătăţi caracteristicile de deformare. Testele de formare sub presiunea gazului s-au efectuat la temperaturile de 460°C, 480°C şi presiunile de 0.75 MPa, 0.8 MPa, folosind table din aliajul de aluminiu cu o grosime de 0.67 mm, obţinute prin procesare termo-mecanică. Înălţimile polare ale tablelor au fost măsurate în funcţie de timpul de formare. Rezultatele testelor au arătat că pentru emisferele formate, grosimea pereţilor scade treptat odată cu creşterea înalţimii de la bază la pol şi cea mai mare subţiere a pereţilor se obţine la polul acestora.

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