

An analysis of superplastic forming to manufacture aluminum and titanium alloy components

Uma análise da conformação superplástica na fabricação de componentes de ligas de alumínio e de titânio

Daniel Almeida Pereira^{a*}, Mario H. F. Batalha^a, André F. Carunchio^a, Hugo Borelli Resende^b

Abstract

Some alloys with fine grain size can present, under certain conditions, a very high ductility and large deformations before rupturing occurs - a condition known as superplasticity. Superplastic forming is a technique that takes advantage of this material's behavior and consists of heating a metallic blank up to a suitable temperature and blow forming it under gas pressure into a die. There is a growing interest in this manufacturing process in many different areas, such as aeronautical, automotive and medical, due to the possibility of manufacturing complex, lightweight geometries and strong thin shell parts. In this study, analytical approach is used to predict the optimum gas pressure for forming the blank, in order to maintain a controlled strain rate, ensuring superplastic behavior. Two domes are manufactured using aluminum and titanium to test the pressure curves and to understand the phenomena related to superplastic forming.

Resumo

Algumas ligas com tamanho de grão pequeno podem apresentar, sob certas condições, uma alta ductilidade e grandes deformações antes da ruptura, uma condição conhecida como superplasticidade. A conformação superplástica é uma técnica que tira vantagem desse comportamento do material, e consiste em aquecer um *blank* metálico até uma temperatura adequada e conformá-lo em uma matriz através do esforço gerado por um gás sob pressão. Existe um crescente interesse nesse processo de manufatura em diferentes setores da indústria, como a aeronáutica, automotiva e médica, devido à possibilidade de fabricação de cascas metálicas finas de geometria complexa, leves e resistentes. Nesse trabalho,

^a Fundação de Apoio ao IPT, São Paulo-SP, Brasil.

^b Laboratório de Estruturas Leves, Instituto de Pesquisas Tecnológicas do Estado de São Paulo S.A., São Paulo-SP, Brasil

*E-mail: danielpe@ipt.br

Keywords:

superplasticity, superplastic forming, lightweight structures.

Palavras-chave:

superplasticidade, conformação superplástica, estruturas leves.

uma abordagem analítica é utilizada para obter o ciclo de pressão que conformará o *blank*, com o intuito de manter uma taxa de deformação controlada, assegurando assim um comportamento superplástico. Dois domos são fabricados em alumínio e titânio, para testar as curvas de pressão e entender os fenômenos relacionados com a conformação superplástica.

1 Introduction

The superplastic process (SPF) is a forming technique useful for manufacturing structural components with a complex shape, especially for metal alloys such as titanium, magnesium and aluminum. It is useful because the materials, when subjected to the superplastic process, present the ability to undergo exceptionally large tensile strain prior to failure when they are deformed under a limited range of conditions. Under uniaxial tension, elongation in excess of 200% is usually indicative of superplasticity (cf. **Figure 1**). Nevertheless, numerous metallic materials can show elongations of 100% - 500% or more (GIULIANO, 2011). **Figure 1** shows the difference between plastic and superplastic deformation; the first presents the initiation and propagation of necking, resulting in failure in opposition to the superplastic deformation, and such behavior is responsible for ensuring high-value elongations.

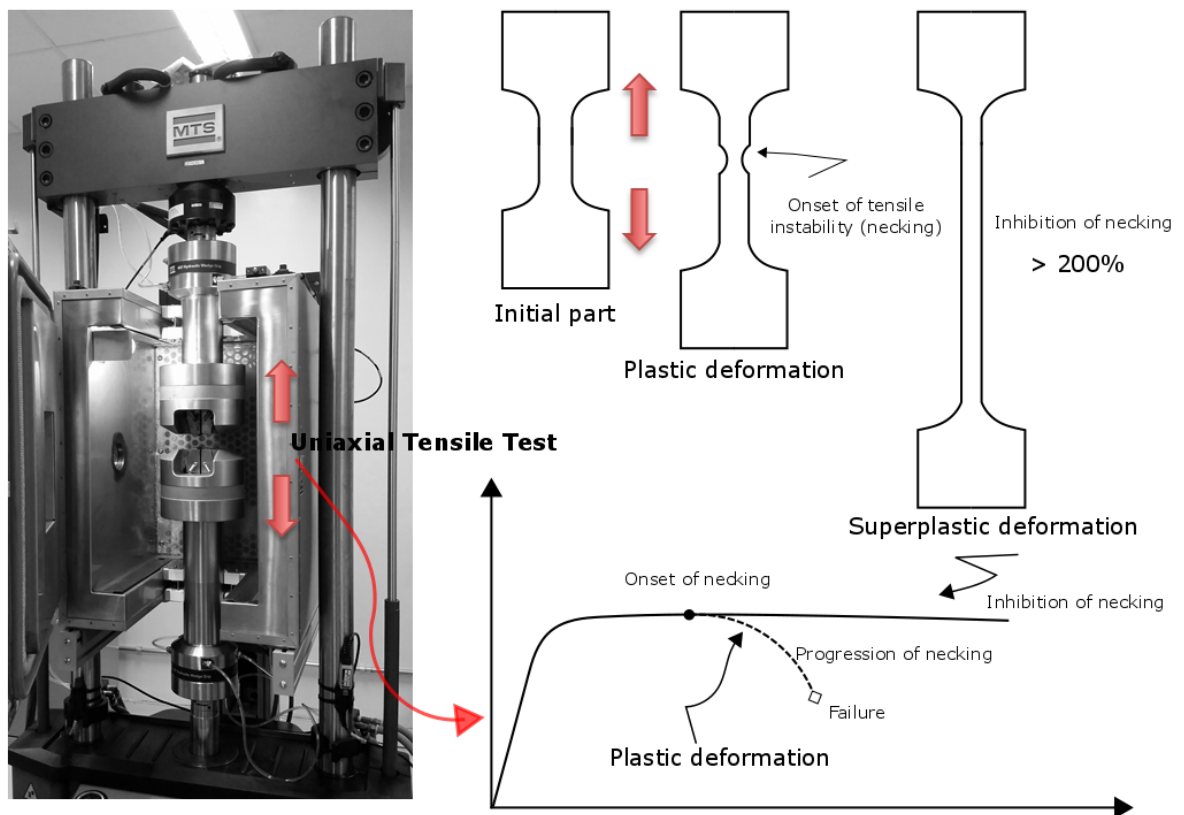


Figure 1 - Schematic representation of the difference between plastic and superplastic forming regarding uniaxial tensile analysis.

The blow forming process is an example of the technique to apply SPF, which consists of a single sheet laid on a female die which is then subjected to gas pressure, resulting in a formed part with the die configuration (cf. **Figure 2**). In **Figure 2**, one can see that there is one female die (lower die) and a counter matrix (upper die) responsible for creating a clamp to avoid the exit of gas. The stages of the process are as follows (a) firstly, the material sheet is inserted between both dies, (b) secondly, forming under gas pressure takes place, (c) then the final geometry of the sheet is completed, (d) finally the finished part is removed from the matrix and a new process cycle can start.

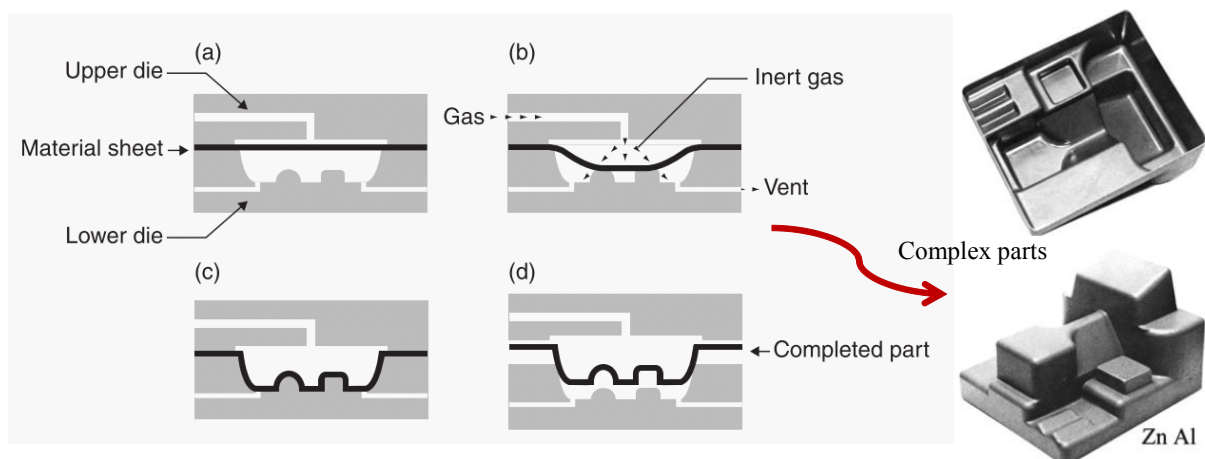


Figure 2 – The blow forming process: (a) initial flat sheet inserted between the upper and lower dies; (b) progression of forming under gas pressure; (c) final shaped part in contact with the lower die; and (d) removal of the part.

Adapted from Barnes (2007) and Giuliano (2011).

There are three primary conditions necessary for achieving the superplastic condition: (I) the temperature, (II) the strain rate and (III) the grain size of the alloy. The process temperature is in the order of $\sim 0.5T_m$, where T_m is the absolute melting temperature of the material. Furthermore, the superplastic behavior only occurs in a narrow range of strain rate, usually between $10^{-4} s^{-1}$ and $10^{-3} s^{-1}$. Finally, the microstructure should have a fine and a stable grain size. Thus, the grain sizes used for materials in the superplastic forming industry are generally in the range of $2 \mu m - 10 \mu m$. This requirement exists due to the physical behavior of the process, obtained owing to the occurrence of intensive grain boundary sliding (GBS) which is believed to be the principal deformation mechanism (ALABORT et al., 2016). GBS is well explained by KAIBYSHEV (2002), and it is associated with a series of accommodation mechanisms such as grain boundary migration, grain rotation, recrystallization, diffusional mass transport and slip in grains (SIENIAWSKI; MOTYKA, 2007) which may depend on important alloy characteristics such as phase architecture and grain morphology. Explained simply, the basic difference between plastic deformation and superplastic deformation is shown in **Figure 3**.

The main advantage of the SPF process is its capacity to produce complex and multiple parts in one operation with an excellent surface finish, i.e., it can dispense with welding and machining, and a series of products can be manufactured using only one tooling. Moreover, there is a slight or no residual stress and "spring back" effects, leading to a high-quality structural integrity. For those reasons, SPF can result in considerable savings in costs and weight in comparison with traditional processes, resulting in a feasible and an attractive method for industry.

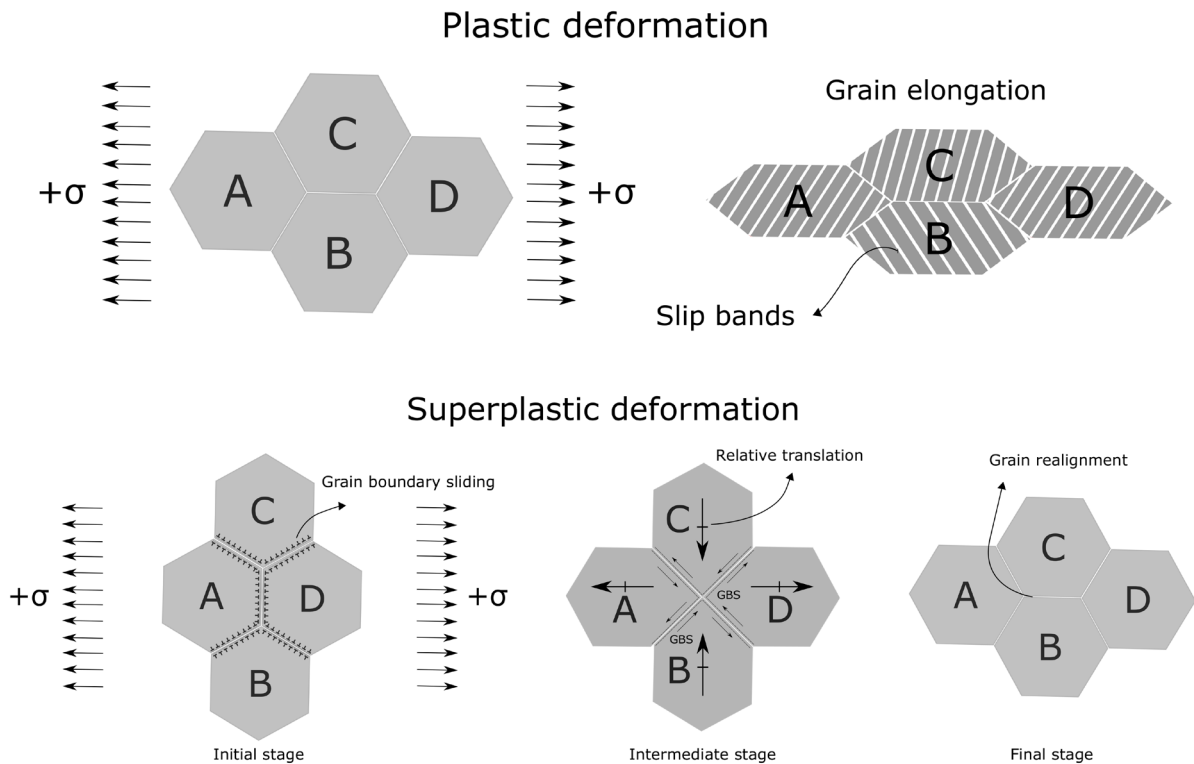


Figure 3 – Comparison between plastic and superplastic deformation regarding intragranular modification.

The most conventional superplastic materials with commercial applications are titanium and aluminum alloys. More than 40 “in-production” aircraft and twenty different automobiles models are already using superplastically formed aluminum components (BARNES, 2007). The most common applications for titanium alloys in the aeronautical industry are pylon panels, nacelle panels, engine parts, fan and OGV blades and auxiliary power exhaust (cf. **Figure 4**); and for the aluminum alloys, lightly loaded or non-structural components, such as inlets, wing tips, access doors and equipment covers (cf. **Figure 5**). **Table 1** shows the most common alloys, their compositions, SPF temperatures, strain rates and maximum deformation values.

Table 1 – Some of the commercially available titanium and aluminum superplastic sheets with optimum SPF temperatures, strain rates and typical elongations.

	Alloy	Composition (%)	SPF temperature (°C)	Strain rate (s ⁻¹)	Elongation (%)
Titanium	Ti-6/4	Ti-6Al-4V	880-920	5x10 ⁻⁴	~ 1000
	SP700	Ti-4Al-3V-2Fe-2Mo	750-800	3x10 ⁻⁴	≥ 300
	Ti-6242	Ti-6Al-2Sn-4Zr-2Mo	850-940	5x10 ⁻⁴	> 500
Aluminum	2004	Al-6Cu-0.4Zr	460	~ 10 ⁻²	800 – 1200
	5083	Al-4.5Mg-0.7Mn-0.1Zr	500-520	10 ⁻³	~ 300
	7475	Al-5.7Zn-2.3Mg-1.5Cu-2Cr	515	2x10 ⁻⁴	800

The efforts to increase alloy superplastic properties resulted in the creation of a new material called SP5083 which complies with aerospace standards. Hefti (2007b) discusses Boeing's implementation of SP 5083, which is a special SPF alloy, and the advances that have been made at Boeing Commercial Airplanes during the manufacture of SP 5083 components for aircraft applications (cf. **Figure 5**). Due to the needs of industries and

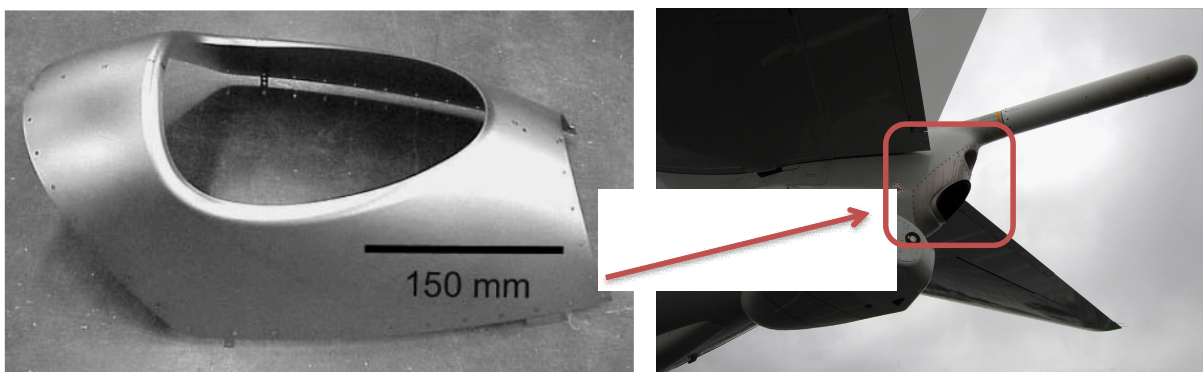


Figure 4 - Boeing auxiliary power unit exhaust faring, Ti-6Al-4V. Adapted from Comley (2004).

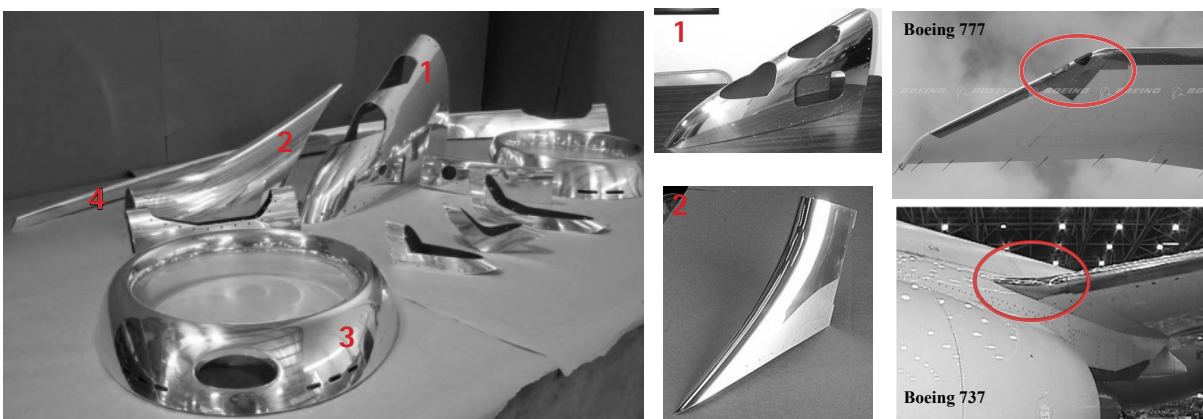


Figure 5 - Superplastic components designed for aerospace applications formed with SP 5083: 1- wing tip light housing, 2- strakelets, 3- engine intake lipskins and 4- winglets (SUPERFORM®). Adapted from Barnes et al. (2012) and Hefti (2007a).

the great capacity of the SPF process, more studies should be carried out to understand the phenomenon with the aim at reducing forming time and improving structural characteristics. Hence, the purpose of this work is to study the influence of the pressure curve, the temperature and the strain rate in AA5083 and Ti-6Al-4V alloy bubble shapes. The study presents an optimized pressure cycle of an Accudyne® SPF machine. The paper also evaluates the quality of the finished product by analyzing the smoothness and symmetrical characteristics of the parts using an ultrasound technique. The SPF machine is installed in the Lightweight Structures Laboratory (LEL) of the Institute for Technological Research (IPT) located in Sao José dos Campos, Brazil. The focus of the lab is to support industries with R&D, helping them to pass through the "Death Valley" to the Technology Readiness Level desired (KALAWSKY, 2010) and assisting them to become more competitive, achieving results close to real application.

2 Methodology

The gas pressure curve, which should be studied carefully to keep the strain rate close to the target value that ensures a superplastic behavior, was obtained following Dutta and Mukherjee (1992) and the equations and material properties of this study can be found in (PEREIRA et al., 2016).

The used machine in the experimental procedures, presented in **Figure 6**, works with a system range of 140 kN to 1400 kN of hydraulic clamp force and has a work area of approximately 760 mm × 860 mm. The gas pressure has a range of 1 bar to 40 bar and can work with gas injection on both sides of the blank (a necessary condition for any work using back pressure). The control system allows different values of the gas level step, the ramp gas rate, the dwell time and the clamp force during the forging process which should be specified according to final part geometry and material.



Figure 6 – Lightweight Structures Laboratory's superplastic forming Accudyne machine.

The forming process steps are presented below and are depicted in **Figure 7**:

- I. Initially, the press was heated until reaching the desired temperature and the blank was inserted;
- II. After the homogenization time, the up part of the press was moved down to clamp the blank's edge, in order to seal the blank against the die and avoid escaping of the gas;
- III. Finally, the gas flow followed the pressure × time curve, forming the part.

The samples were inspected with ultrasonic scanning to verify if the process resulted in a homogeneous thickness reduction. The equipment used was an Olympus Omniscan SX: type UT, mode pulse-echo, with a transducer that generates longitudinal waves at 5 MHz and sound velocity of 6172.8 m s^{-1} and 7000.8 m s^{-1} for the AA 5083 and Ti-6Al-4V alloys, respectively.

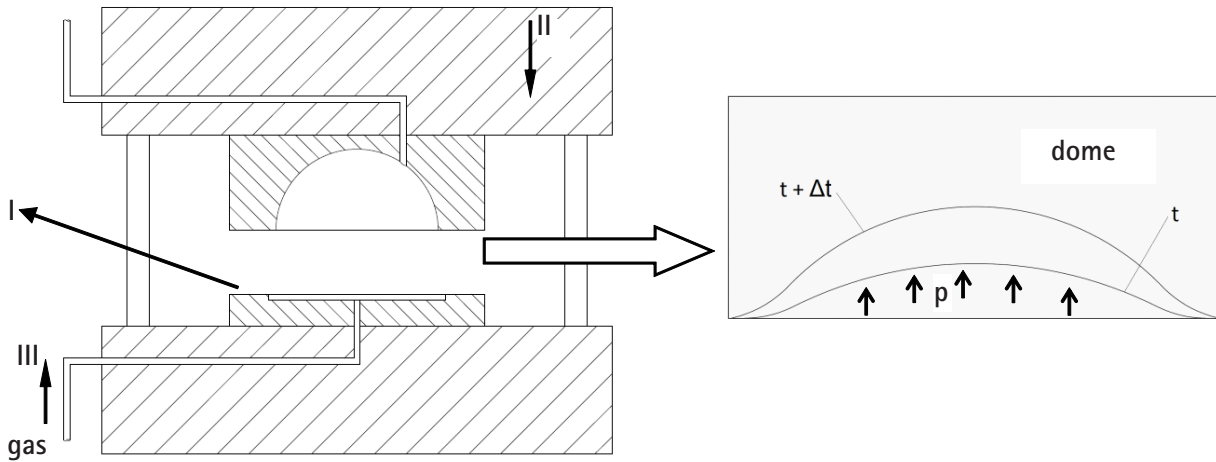


Figure 7 – Superplastic press and forming scheme, (I) the press was heated, (II) the up part of the press was moved down to clamp the blank’s edge and (III) the gas is released.

3 Results and discussion

3.1 Aluminum

Figure 8a shows the calculated and the experimental pressure x time curves. The formed sample is depicted in Figure 8b.

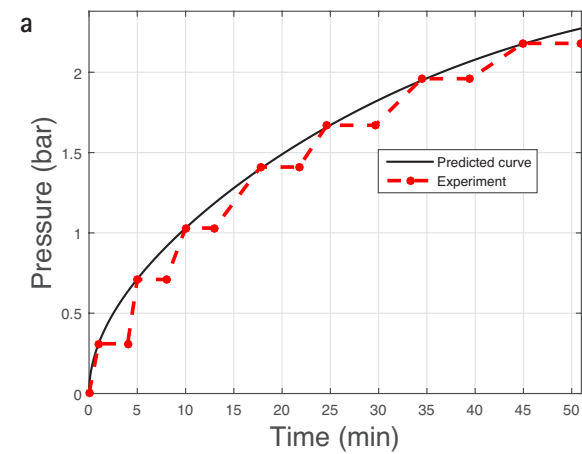


Figure 8 – (a) Numerical pressure curve (solid line) and the approximated curve (dashed line) for the equipment and (b) the dome formed by the SPF process.



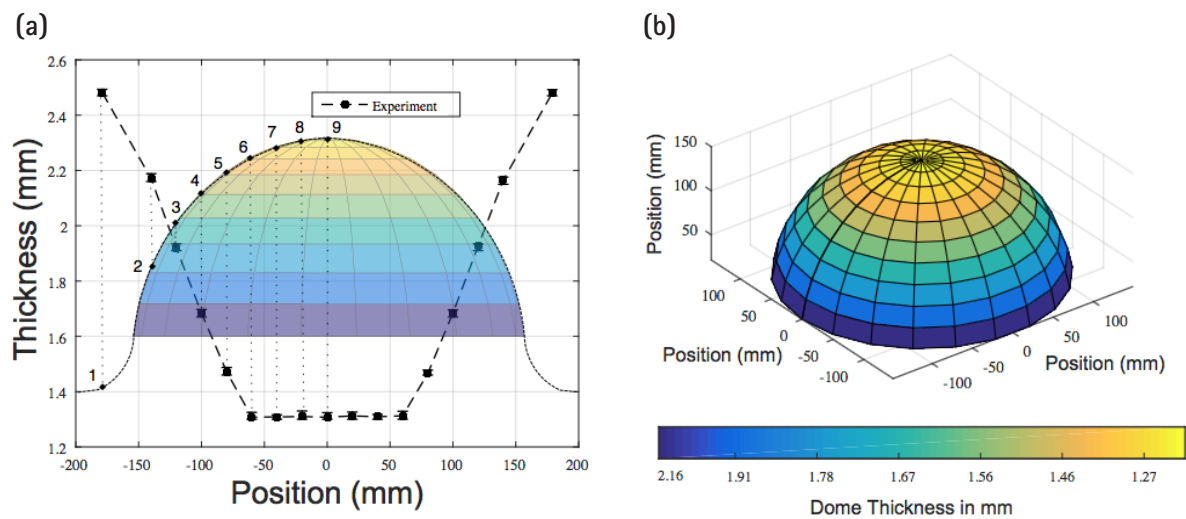


Figure 9 – Thickness distribution around the dome measured by the ultrasound technique.

In the end of the forming cycle, the gas pressure that forms the hot metal suddenly dropped to a very low level, indicating a rupture in the part. As expected, an inspection of the part showed a failure in the pole area that prevented it to reach the final height. A common phenomenon in superplastic forming of aluminum alloys is the so-called cavitation in which voids are created in the material due to the deformation mechanism (GBS). The stress concentration in these voids contributes to the rupture of the forming part.

An ultrasound inspection was used to evaluate the final thickness after the superplastic forming. This result was important to give the maximum real thickness reduction and a reference about how the strain field was distributed in the sample's surface. The experimental results are shown in **Figure 9**.

This analysis shows a maximum thickness reduction of 51 %, while the model prediction value was about 35 %. This difference results from a limitation in the analytical model in representing the true stress-strain state which the material is subjected to during the process. Additionally, the model does not consider other intrinsic process phenomena as friction and thermal effects. In this case, the use of more complex numerical methods such as finite elements would allow a better representation of the experimental case. It was possible to observe that the maximum reduction of thickness is homogenous in a considerable area near at the center of the dome. This information is relevant in this context because it represents a substantial capacity of the process in distributing forging efforts without inducing local necking.

To avoid the appearance of the cavitation phenomenon, the appropriate technique consists in the application of a backpressure in the opposite direction of the deformation. Therefore, the system should be adapted to have two gas exits. The literature is vast and many authors have noticed that after a backpressure equal to 10 bar the cavitation volume is extremely reduced (GERSHON et al., 2004).

3.2 Titanium

The pressure curve adjusted and the analytical functions are presented in **Figure 10**.

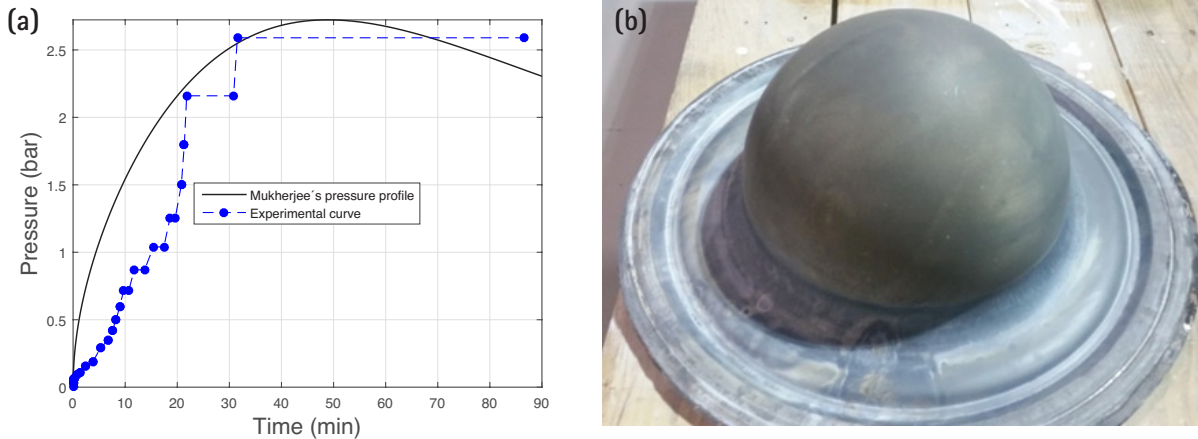


Figure 10 – Numerical (solid line) and experimental (dashed line) pressure curve.

The forming process resulted in a dome with the desired geometry, apparently free of oxidation, as presented in **Figure 11**. The process, in this case, was concluded after 88 min.

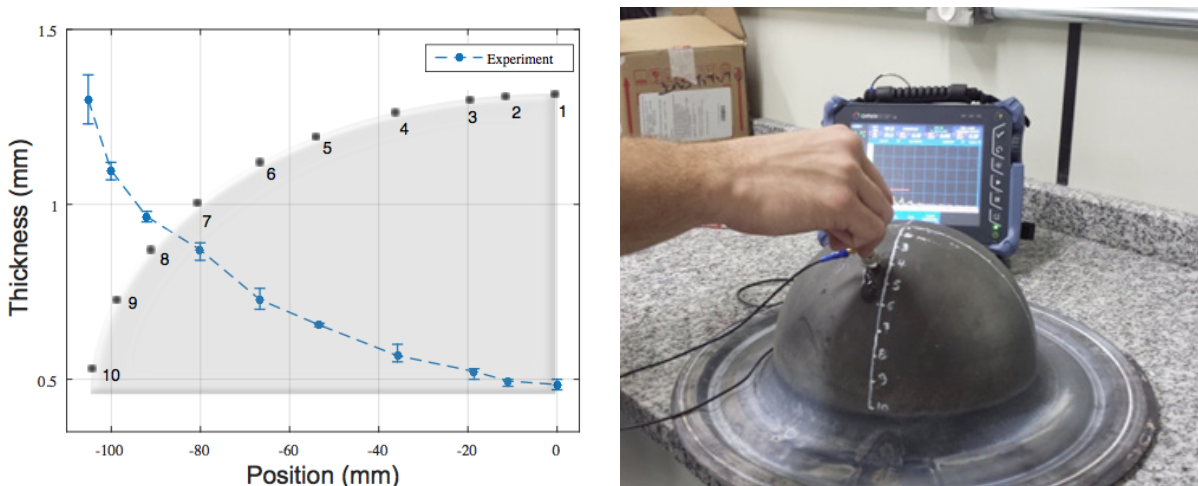


Figure 11 – Ultrasound inspection process and the ultrasonic results.

The analysis shows a maximum thickness reduction of 70 %, while the analytical prediction is about 56 %. Again, this difference is generated due to a limitation in the analytical model in representing the true stress-strain state which the material is subjected to during the process.

4 Conclusion

The main objective of this work was the manufacture of a titanium and an aluminum dome by superplastic forming. Analytical analysis of the process were carried out in order to obtain the ideal pressure curve and to predict the thickness of the formed part, and an ultrasound inspection was used to compare the formed part with the numerical data. The results for both materials show that the predicted pressure curve obtained following the analytical approach is adequate to reach a low strain rate during the experiments. In the experimental conditions, the domes reached the highest deformation after 51 min (aluminum) and 88 min (titanium), which is an expected time for the SPF process according to the literature. However, the percentage of thickness reduction in the experiments showed important deviations from the analytical model due to the limitation of the Mukherjee's analytical formulation, probably because it does not consider some intrinsic process phenomena such as friction and thermal effects. An important improvement for both materials in the next experiments would be the obtainment of real-superplastic-behavior material constants through uniaxial tensile analysis, instead of using data information found in literature which could have been a source of the thickness deviation.

5 Acknowledgments

The author would like to thank a number of individuals and institutions: FIPT for funding this research; all technicians and researchers from Lightweight Structures Laboratory, for the support during this work development and finally the Escola Politécnica from the University of São Paulo, mainly to Prof. Dr. Gilmar Batalha for the assistance during this research.

6 References

- ALABORT, E. et al. On the mechanism of superplasticity in Ti – 6Al – 4V. *Acta Materialia*, v. 105, p. 1–42, 2016.
- BARNES, A. J. et al. Recent application of superformed 5083 aluminum alloy in the aerospace industry. *Materials Science Forum*, v. 735, p. 361–371, Dec. 2012.
- BARNES, A. J. Superplastic forming 40 years and still growing. *Journal of Materials Engineering and Performance*, v. 16, n. 4, p. 440–454, 5 July 2007.
- COMLEY, P. N. Manufacturing advantages of superplastically formed fine-grain Ti-6Al-4V alloy. *Journal of Materials Engineering and Performance*, v. 13, n. 6, p. 660–664, 2004.
- DUTTA, A.; MUKHERJEE, A. K. Superplastic forming: an analytical approach. *Materials Science and*

Engineering A, v. 157, n. 1, p. 9–13, 1992.

GERSHON, B. et al. Problems encountered in superplastic forming of Al 5083 parts. Materials Science Forum, v. 447–448, p. 259–264, 2004.

GIULIANO, G. Superplastic forming of advanced metallic materials. Cambridge: Woodhead Publishing Limited, 2011.

HEFTI, L. D. Advances in the superplastically formed and diffusion bonded process. Materials Science Forum, v. 551–552, p. 87–93, Dec. 2007a.

HEFTI, L. D. Commercial airplane applications of superplastically formed AA5083 aluminum sheet. Journal of Materials Engineering and Performance, v. 16, n. 2, p. 136–141, 24 Apr. 2007b.

KAIBYSHEV, O. A. Fundamental aspects of superplastic deformation. Materials Science and Engineering: A, v. 324, n. 1–2, p. 96–102, Feb. 2002.

KALAWSKY, R. S. Grand Challenges for Systems-Engineering Research. INSIGHT, v. 13, n. 2, p. 39–45, July 2010.

PEREIRA, D. A. et al. Analysis of Superplastic forming process applied to aerospace industry: case study of Al 5083 Alloy. In: AEROSPACE TECHNOLOGY CONGRESS, 2016, Solna, Stockholm, Sweden. Proceedings... Stockholm: Meetagain, 2016.

SIENIAWSKI, J.; MOTYKA, M. Superplasticity in titanium alloys. Journal of Achievements in Materials and Manufacturing Engineering, v. 24, n. 1, p. 123–130, 2007.