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Superplasticity of a Friction Stir Processed 7075-T651 aluminum alloy

T. Dieguez[a], A. Burgueño[b], H. Svoboda[a,c]*

[a] *Structures and Materials Laboratory, INTECIN, Faculty of Engineering, University of Buenos Aires, Av. Las Heras 2214, Buenos Aires (1127), Argentina*
[b] *National Institute of Industrial Technology, General Paz Av. 4554, San Martín, Prov. of Buenos Aires(B1650WAB), Argentina*
[c]*CONICET, Av Rivdavia 1917, Buenos Aires (C1033AAJ), Argentina*

Abstract

Superplastic forming is a technological process used to produce metallic components with very complex shapes. In the last two decades it has been a topic of major development. In Fine Structure Superplasticity (FSS), the initial grain size exerts a strong influence on the superplastic behavior, affecting the Grain Boundary Sliding (GBS) mechanism. Refining grain size (GS) the parameters of superplastic forming (temperature and strain rate) could be optimized. Thermal stability of grain structure is also an important factor to obtain superplasticity. FSP is technique recently developed used to refine GS. The optimum FSP processing parameters are still under study for different materials. In the present work a 7075-T651 aluminium alloy was friction stir processed in order to improve superplastic behavior. Friction stir processed specimens were tensile tested at temperatures between 350 and 450 °C and initial strain rates between $5x10^{-3}$ and $2.5\ x10^{-2}\ s^{-1}$. A strong influence of both temperature and initial strain rate on the test results was observed. The maximum superplastic elongation was 900% at 400°C and $1x10^{-2}\ s^{-1}$ strain rate. Due to the low temperature and high strain rate used in the tests these results are better to those obtained in previous works and would be associated with the processing conditions and the design of the tool used.

Keywords: friction stir processing; 7075-T651 aluminum alloy; superplasticity; grain size

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* Corresponding author. Tel.: +5411-4514-3009.
E-mail address: hsvobod@fi.uba.ar

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1. Introduction

The study of the superplastic behavior of metallic materials has been a field of great interest and development in last years due to the relevance of superplastic forming of components to obtain products with very complex geometries (Ha and Chang, 1999). Superplasticity is one of several micromechanisms of deformation at high temperature, which is characterized by extensive plastic deformation prior to fracture (Ha and Chang, 1999), being in the case of fine-structure superplasticity (FSS) the grain boundary sliding (GBS) mechanism which controls the superplastic deformation (Sherby and Wadsworth, 1989). The activation of this mechanism is mainly determined by temperature, strain rate and grain size (GS) (Mukherjee, 2002). Superplasticity has been reported in materials with a fine and stable microstructure, which are deformed under strain rates between 10^{-5} and 10^{-2} s^{-1} and temperatures usually above 0.5 T_m, being T_m the absolute melting temperature. The refinement of grain size has a strong influence on the optimum strain rate for FSS, increasing strain rate and decreasing temperature as GS decreases (Ha and Chang, 1999). The thermal stability of the microstructure is a critical aspect for achieved superplasticity.

Al-Zn-Mg alloys have various applications in structural elements due to their high strength, particularly in the aerospace industry. There have been several attempts to obtain complex parts by superplastic forming, being the largest obstacle the refinement of the microstructure and the manufacturing routes (Paton et al., 1982; Jiang et al. 1983; Xinggang et al., 1983).

Processing of materials by friction stir has been recently developed and has great potential as a grain refinement method, having reported the activation of superplasticity in alloys processed by friction stir (Mishra and Mahoney, 2007).

The aim of this paper is to analyze the superplastic behavior under different testing conditions of temperature and strain rate of a high strength aluminum alloy friction stir processed.

Nomenclature

FSP	Friction Stir Processing
FSS	Fine Structure Superplaticity
GS	Grain Size
GBS	Grain Boundary Sliding
HSS	High Strain Rate Superplasticity
SZ	Stirred Zone
T	Testing Temperature

2. Experimental procedure

The plate of the 7075-T651 aluminum alloy with 4 mm thickness was friction stir processed. The tool used was made of H13 tool steel and had a square 2.5 mm side pin with concave shoulder of 12.5 mm in diameter. The tool angle was 1.5°. The tool rotation was 514 rpm and the travel speed was 51 $mm.min^{-1}$. Figure 1 shows an image of FSP carrying out and a processed sample.

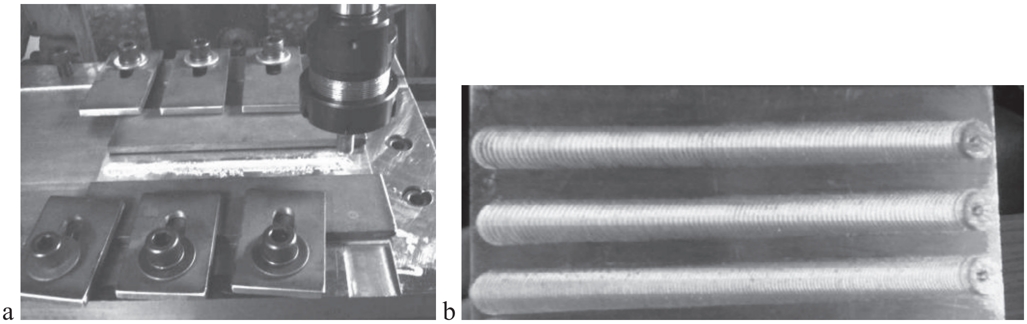

Fig. 1. (a) processing by friction-stir; (b) as-processed sample

Cross sections were extracted from the processed sample for microstructural characterization. The microstructure was analyzed by optical microscopy and the grain size on the stirred zone was measured by mean of lineal intercept procedure according to ASTM E 112.

From the processed specimens were obtained T-bone type tensile specimens, transverse to the processing direction. The tensile test specimens had a gage length of 2.90 mm, 2.70 mm width and 1.70 mm in thickness located in the stirred zone. The tensile tests were carried out at temperatures of 350, 400 y 450°C, with different initial strain rates ($5x10^{-3}$, $1x10^{-2}$ and $2.5x10^{-2}$ s^{-1}). These temperatures were adopted considering the thermal stability of FSP aluminum alloys studied by the authors in a previous work (Dieguez and Svoboda, 2012). Figure 2 shows a scheme of the tensile specimen fabrication and the high temperature tensile testing equipment used.

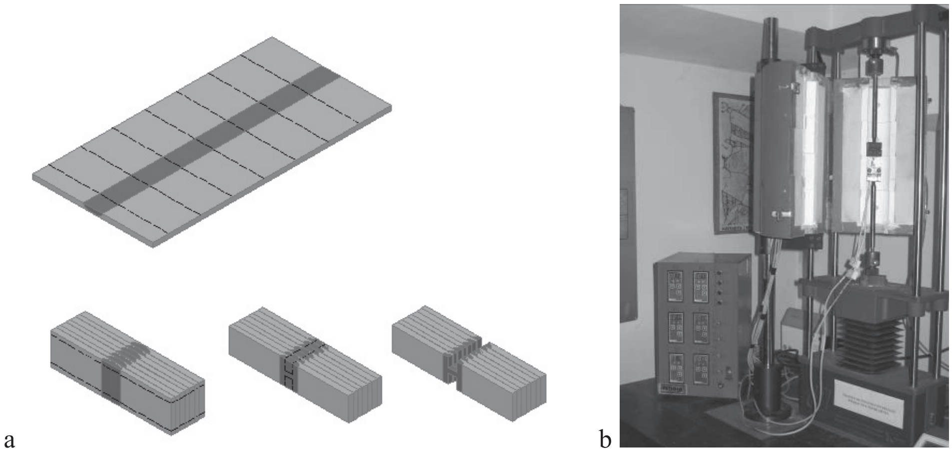

Fig. 2. (a) scheme of the tensile specimens fabrication; (b) high temperature tensile testing equipment

In addition, samples from base metal were tested in the same range of temperature and with an initial strain rate of $1x10^{-2}$ s^{-1}, to use as a reference value.

3. Results and discussion

The chemical composition of the analyzed alloy is shown in Table 1 expressed in weight percent (%).

Table 1. Chemical composition of analyzed alloy

Zn	Mg	Cu	Fe	Cr	Ti	Zr	Mn	Si
6.16	2.69	1.67	0.20	0.20	0.015	0.021	0.05	0.07

Figure 3 shows a macrograph of the processed zone and micrographs of the base material and the stirred zone (SZ).

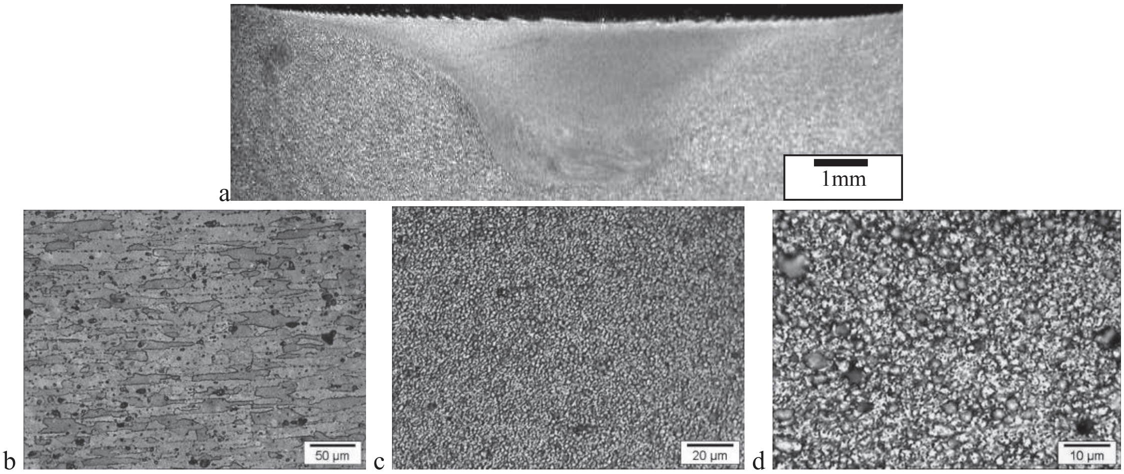

Fig. 3. a: Macrograph of the processed material; b: micrograph of base metal; c and d: micrograph of the stirred zone (SZ)

In Figure 3a is shown the microstructure resulting of friction stir processing. The stirred zone (SZ) presents a recrystallized and refined microstructure. Also, it can be noted that this area is approximately 2 mm wide and 3 mm height. This is in accordance with the tool dimensions (shoulder and pin).

Figure 3b shows elongated grains according to the rolling direction associated with a cold deformation process. Also some precipitates can be observed. Such structure is typical of this alloy and temper (Jiang et al., 1993).

Figures 3c and 3d show the microstructure of SZ. A strong refinement is obtained and the equiaxed grain due to recrystallization. The average grain size measured in the area was of 4.65 µm. This grain size is in accordance with values reported previously for similar materials and processing conditions (Ma et al., 2002). In this sense it has been reported that tools with square pin promotes a higher grain refinement (Elangovan and Balasubramanian, 2008).

Table 2 shows the elongation to fracture obtained for different testing temperatures and initial strain rates, for FSP samples.

Table 2. Elongation to fracture (in %) obtained for different testing temperatures and strain rates for FSP samples

T [ºC]	5x10^{-3} s^{-1}	1x10^{-2} s^{-1}	2.5x10^{-2} s^{-1}
350	260	276	-
400	778	905	329
450	-	95	130

The tests performed on the base material carried out at an initial strain rate of $1x10^{-2}$ s^{-1} and 350 °C gave an elongation to fracture of 90% and a maximum stress of 68 MPa. In the case of 400 °C, the elongation was 105% and a maximum stress 42 MPa; for 450 ° C, the elongation was 98% and the maximum stress 28 MPa. Although, the maximum stress diminished with temperature, the elongation to fracture remained almost constant and low.

The processed samples showed in all cases larger elongations, compared with those measured for the base metal., for same temperatures and strain rate. For 400°C it was observed a substantial variation of superplastic behavior for the processed condition. Figure 4 shows the specimen prior to testing and tested specimens for different strain rates. It could be observed that as elongation to fracture increases; the variation along the section of the specimen becomes more uniform, associated with higher values of strain rate sensitivity *m*.

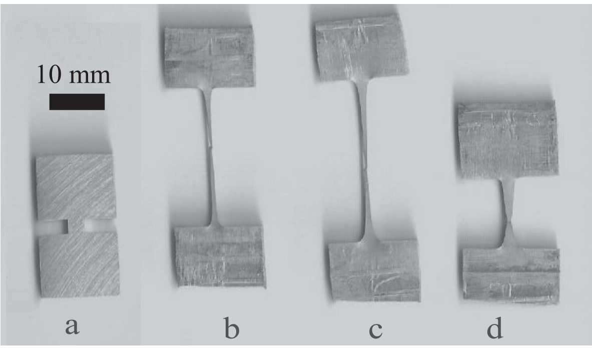

Fig. 4. FSP specimen tested at 400 °C. a: untested sample; b: 5x10-3 s^{-1}; c: 1x10-2 s^{-1}; d: 2.5x10-2 s^{-1}

Figure 5 shows the evolution of the elongation to fracture as a function of initial strain rate for the different temperatures studied.

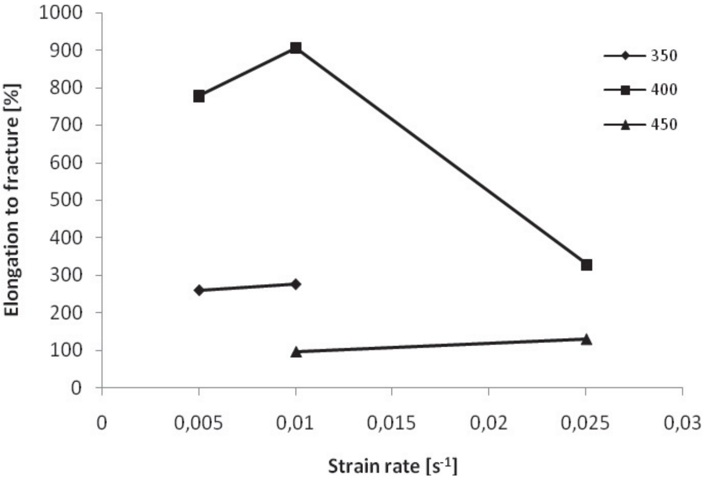

Fig. 5. Elongation to fracture vs initial strain rate, for different testing temperatures

The largest elongations were obtained at 400 °C, being the maximum deformation corresponding to the initial strain rate of 1x10^{-2} s^{-1}. This strain rate is within what is called HSS (high strain rate superplasticity) (JIS-H-7007, 1995). These results are promissory considering the elongations reported in previous works at 400 °C (Mishra and Mahoney, 2007; Ma et al., 2002; Liu and Ma, 2008) are lower. There is a wide dispersion between the results published by different researchers regarding the temperatures and strain rates that maximize the elongation to fracture, for a given alloy. While this is an aspect that has not been widely discussed in the literature, this variability in outcomes would be associated with different processing conditions used which includes, besides the classical variables, effects such as the geometry of the tools and characteristics of the machine used. In this case the use of a tool with a shoulder diameter small could provide a more stable microstructure. From the viewpoint of the superplastic forming process, the strain rate and temperature are parameters of technological and economical importance due to its impact on processing time and power consumption (Liu and Ma, 2008).

For 350 and 450 °C the elongations obtained were lower. At 350 °C, this temperature could be insufficient for the activation of the GBS mechanism, while at 450 °C the limitation is the loss of thermal stability of the structure obtained by FSP, taking place grain growth due to the dissolution of the pinning particles (Dieguez and Svoboda, 2012). Also, for different strain rates examined, in all cases the best performance was observed for 1x10^{-2} s^{-1}. This type of behavior that presents an optimum has been observed previously (Liu and Ma, 2008).

Figure 6 shows the evolution of the maximum stress as a function of initial strain rate for the different temperatures studied.

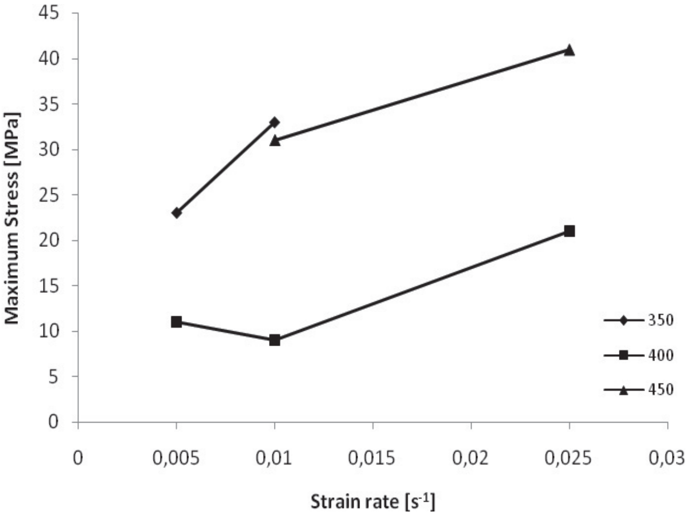

Fig. 6. Maximum stress vs. initial strain rate, for different testing temperatures

Consistently with what was observed for elongations to fracture, the lowest value of maximum stress was obtained for 400 °C. In particular, for a strain rate of 1x10^{-2} s^{-1}, the maximum stress was below 10 MPa. This value is lower than those reported in the literature for this alloy at this strain rate and temperature (Mishra and Mahoney, 2007). It is known that superplastic behavior is optimized by minimizing the flow stress (Mishra and Mahoney, 2007) or the maximum stress. Also, it could be mentioned that the maximum stress for 450 ºC and $1x10^{-2}$ s^{-1}, was similar to that obtained for the base metal (~30 MPa), as well as the elongation to fracture (~100%). This could be related with the occurrence of grain growth in the processed sample.

Figure 7 shows the relationship between maximum stress and elongation to fracture for different specimens tested in FSP condition.

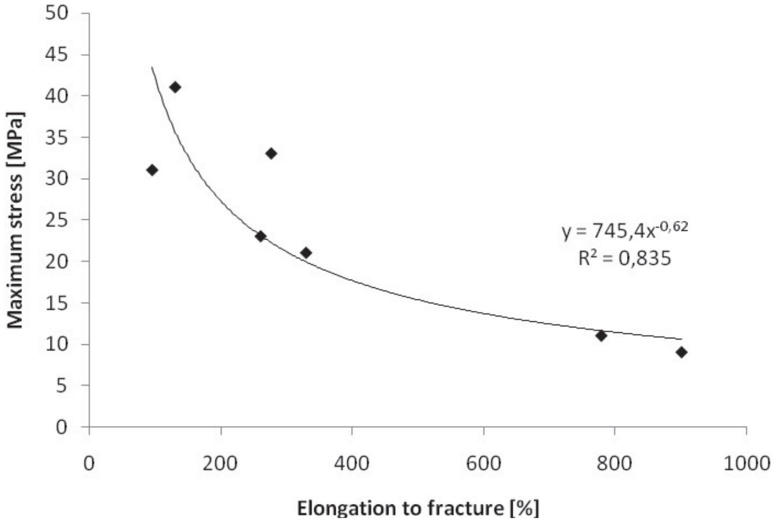

Fig. 7. Maximun stress vs. elongation to fracture for different testing conditions

It can be observed that as decreasing the maximum stress, the elongation to fracture increases. These experimental data were adjusted with a potential curve, which allows estimating the elongation to fracture with the maximum stress, for the different test conditions analyzed, with a good level of correlation.

From the values of low stresses and strain rates for the processed condition tested at 400 °C was obtained the strain rate sensitivity, which reached a value of m = 0.39. For this alloy, Liu and Ma, 2008 reported that the largest elongations were obtained with m values between 0.33 and 0.42.

4. Conclusions

Samples of high strength aluminum alloy 7075-T651 were processed by friction-stir (FSP) producing a refined area with average grain size of 4.65 μm. The processed samples were tested in tension at temperatures between 350 and 450 °C and initial strain rates ranged $5x10^{-3}$ and 2.5 $x10^{-3}$ s^{-1} in order to evaluate superplastic behavior.

There was a strong dependence on temperature and strain rate on the elongation to fracture and maximum stress reached. The best results were obtained for 400 ºC and $1x10^{-2}$ s^{-1}, reaching 900% strain to fracture and 9 MPa of maximum stress. This testing condition corresponds to low temperature and high strain rate for this alloy. These results are superior to those reported in the literature, and are associated to the characteristics of the structure obtained as determined by the processing conditions and the tool used. It was obtained an experimental expression that relates the maximum stress with the elongation to fracture.

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