SUPERPLASTIC FORMING OF A 6XXX ALUMINUM ALLOY

Lillianne P. TROEGER* and Edgar A. STARKE, Jr.*
*Department of Materials Science and Engineering, University of Virginia
Thornton Hall, Charlottesville, Virginia 22903-2442 USA

ABSTRACT

Superplastic forming (SPF) is a process which exploits the phenomenon of superplasticity. SPF is commercially desirable because complex shapes can be produced in a single forming operation, reducing the need for fasteners and connectors. This results in an overall reduction in component weight and decreased fuel consumption. The current project focuses on the development of a microstructure in an Al-Mg-Si-Cu alloy that exhibits superplasticity.

A new thermomechanical process has been designed for the grain refinement of a 6XXX aluminum alloy using particle-stimulated nucleation of recrystallization. The compositional variant under investigation falls within the ranges of both 6013 and 6111. The process results in an equiaxed, thermally stable grain structure with an average diameter of approximately 10 μm, with a nearly random texture.

The fine-grained microstructure exhibits superplasticity above 500 °C. Maximum elongations of 350-375% were achieved for strain rates of $2.8\times10^{-4}\ s^{-1}$ to $5\times10^{-4}\ s^{-1}$ during ambient pressure uniaxial tensile tests at 540 °C. Failure in this regime was due to cavitation damage. The strain rate sensitivity reached a maximum of 0.5 for strain rates of 2×10^{-4} to $5\times10^{-4}\ s^{-1}$.

Constant-pressure cone-forming tests were performed to determine the overall formability and cavitation behavior of the alloy. Cavitation was significantly suppressed by the application of back pressure, leading to true strain values in excess of 1.7 for strain rates on the order of $1\times10^{-3}\ s^{-1}$.

Keywords: Thermomechanical Processing, Grain Refinement, Superplasticity, Aluminum Alloy 6013

INTRODUCTION

Superplasticity is the ability of a material to undergo extensive (200-1000%) elongation without necking when pulled in tension at high temperature, ($T>0.6T_m$). Non-superplastic metals and alloys commonly undergo elongations of less than 100% under similar circumstances. Currently, there is increased commercial interest in the exploitation of the phenomenon of superplasticity through superplastic forming (SPF), a process by which materials can be formed into complex shapes using gas pressure with minimal energy expenditure (gas pressure <1000 psi (7 MPa)) due to the low resistance of such materials to plastic flow. SPF also reduces tooling cost since only a single surface tool is required. Part counts are also reduced since complex components can be formed from one operation, reducing the need for subcomponents and fasteners. [1-3]

Superplastic metallic alloys exhibit flow stresses which vary with strain rate according to the relation

$$\sigma = k\dot{\varepsilon}^m$$

where σ = flow stress
$\dot{\varepsilon}$ = strain rate

m = strain rate sensitivity
k = material constant

The strain rate sensitivity, m, determines the rate at which necking progresses after the onset of localized plastic flow. In superplastic metals, m usually ranges from 0.4 to 0.8. Elongation-to-fracture generally increases with strain rate sensitivity, but cavitation may lead to premature failure. [2,4]

While uniaxial tensile tests are commonly used to assess general superplastic deformation characteristics, biaxial cone tests offer the advantage of more closely simulating a real SPF environment than do uniaxial tests. During the test, a sheet sample is superplastically formed into a conical die cavity using a net forward gas pressure. While the use of back pressure during forming is known to reduce or eliminate cavitation by imposing a hydrostatic compression on the sheet during forming, the level of back pressure required must be determined empirically. Cone tests with back pressure can be used to study the effect of cavitation suppression of formability. Besides preventing the material from reaching is superplastic formability potential, the presence of porosity due to cavitation can degrade post-forming properties. [4-6]

One method of inducing superplasticity involves static recrystallization to refine the grain size prior to forming. The microstructural requirements for this type of superplasticity include a fine (typically <20 μm), equiaxed grain structure which does not experience significant growth at the superplastic forming temperature. For statically-recrystallized materials, a random texture and a predominance of high-angle grain boundaries is also required. A microstructure suitable for SPF can be produced through thermomechanical processing. [4,7-9]

There is a deficiency in the literature of research concerning the grain refinement and superplasticity of Al-Mg-Si and Al-Mg-Si-Cu alloys, especially commercial 6XXX-series alloys, compared with similiar studies of some 2XXX, 5XXX, and 7XXX alloys. A limited number of studies on grain refinement of 6XXX alloys for superplasticity have been reported. [10-14]

A previous investigation of the grain refinement of aluminum alloy 6013 for superplasticity was made by Chung, et al. [14] The process resulted in a ~12-13 μm grain size, which produced a maximum elongation of 230% at 520 °C for a strain rate of $3 \times 10^{-4}\ s^{-1}$. The flow stress under these conditions was 6.7 MPa. The maximum of strain rate sensitivity was 0.38 for a strain rate range of $3 \times 10^{-4}\ s^{-1}$ to $6 \times 10^{-4}\ s^{-1}$ at 563 °C.

OBJECTIVE

One major goal of the study is to characterize the superplastic performance of the microstructure developed in an Al-Mg-Si-Cu alloy by a new thermomechanical process. A second goal is to study the post-forming microstructure in order to evaluate changes in the grain structure and level of cavitation with strain. The ultimate goal is to gain a fundamental understanding of the interrelationships between processing, microstructure, and superplastic performance.

EXPERIMENTAL APPROACH

Based on the results of Chung, et al. [14] and other factors, the current research focuses on a slight variation of the composition of the 6013 studied previously (Baseline 6013). The composition of the alloy studied, 6013 Variant 1, is lower in iron content but still falls within the compositional limits of 6013, as well as those of 6111. The compositions of Baseline 6013 and 6013 Variant 1 are shown in Table I. The allowable ranges of composition for 6013 and

6111 are shown for comparison. [15] The current investigation focuses only on the composition noted as 6013 Variant 1. (All values are in wt.%; balance is aluminum.)

Table I. Alloy Compositions.

Alloy	Mg	Si	Cu	Mn	Fe	Other
Baseline 6013	0.89	0.74	0.90	0.33	0.26	0.03 Zr
6013 Variant 1	0.80	0.70	0.80	0.30	0.10	
6013 Range	0.8-1.2	0.6-1.0	0.6-1.1	0.2-0.8	0.5	0.1 Cr+ 0.25 Zn+ 0.1 Ti
6111 Range	0.5-1.0	0.7-1.1	0.5-0.9	0.15-0.45	0.4	0.1 Cr+ 0.1 Zn+ 0.1 Ti

After samples of 6013 Variant 1 were solution heat treated and water quenched, room-temperature deformation was applied. Aging times and temperatures were varied to optimize the size, shape, and distribution of overaged precipitates. The overaged material was further deformed at room temperature and statically recystallized. Grain structures were analyzed using microtexture data obtained via the Electron Back Scattering Patterns (EBSP) technique, also known as Backscattered Kikuchi Diffraction (BKD). [16-19] The resulting grain orientation data was used to generate maps of grain boundaries with greater than 10° misorientation. Quantitative image analysis of the grain boundary maps was used to calculate average grain diameters. Processing parameters were thereby identified which produced the finest and most equiaxed grain structure.

Uniaxial tensile tests were performed at atmospheric pressure using a computer-driven Instron test rig fitted with a five zone, ATS clamshell-type furnace. All uniaxial experiments were conducted at constant crosshead velocity using dogbone-type samples with a 0.5" gage length cut from statically-recrystallized material. Strain rate sensitivities were established at 500 and 540 °C using a step strain rate method. [20] The temperature and crosshead velocity range resulting in the maximum strain rate sensitivity were thereby established. Samples were pulled to failure under conditions which bracketed the optimum strain rate sensitivity. A single temperature/strain rate combination was thus identified which produced maximal tensile elongation. For comparison, samples cut from commercially-available Baseline 6013-T4 sheet were tested at the optimum temperature and strain rate.

Cone tests were performed at NASA Langley Research Center for a 59° cone with base radius of 1 inch. The starting material was unrecrystallized sheet (0.07 inches thick) held at the test temperature for five minutes prior to forming. Constant-pressure forming experiments were carried out at 520, 540, and 560 °C for back pressures of 400, 425, and 450 psi. The forward pressure remained constant at 500 psi; i.e., the net forming pressure (forward pressure minus back pressure) was varied from 50 to 100 psi. Each cone was allowed to form until rupture or until one hour had elapsed, whichever occurred first. The cones were measured to determine their height and thickness (at the crown).

The tallest *smooth* cone produced in under one hour was sectioned and analyzed in terms of grain size and porosity as functions of strain. Grain sizes were determined using grain boundary maps generated from microtexture data. Porosity data were obtained through image analysis of backscattered electron images from SEM. The entire cone thickness was analyzed for each level of strain. One cone was formed without back pressure using the same temperature and *forming* pressure that produced the tallest cone.

RESULTS AND DISCUSSION

Grain boundary maps taken from the LS, LT, and ST planes following a five minute soak at the recrystallization temperature (540 °C) revealed the presence of an equiaxed grain structure with average grain size of 10.3 μm overall. The average increased to 10.7 μm after a one hour exposure to the same temperature. ECC images of the recrystallized grain structures following the five minute soak is shown in Figure 1.

Uniaxial tensile tests of recrystallized 6013 Variant 1 material showed a maximum strain rate sensitivity of 0.5, which occurred at 540 °C for strain rate range of $2x10^{-4}$ to $5x10^{-4}$ s^{-1} (based on initial gage length). Under these conditions, the elongation to fracture reached 375% with a maximum stress of ~680 psi (4.7 MPa), with failure due to cavitation damage. (Baseline 6013-T4 sheet tested under the same conditions fractured after about 120% elongation with a maximum stress of ~860 psi (6.0 MPa)). The maximum elongation decreased to about 160% for strain rates of $5x10^{-4}$ to 5 x 10^{-3} s^{-1}. with failure by strain localization. The current processing technique significantly increases the strain rate sensitivity and elongation as compared with previous work [14] and triples the maximum uniaxial elongation as compared with unprocessed material.

Cone tests revealed improvements in formability with the application of back pressure. Figure 2 shows that the dependence of cone height (non-dimensionalized with cone base radius) on forming time is weak at higher strain rates as long as back pressure is used. This is industrially significant since one major disadvantage of superplastic forming is that it is a slow process. The data obtained thus far from cone tests of thermomechanically-processed 6013 Variant 1 show that reduced forming times are worth investigating.

Though one cone formed at 560 °C appears to be tallest, it exhibited a slight flaring of the rupture site, so the tallest *smooth* cone was considered for analysis. The tallest smooth cone produced (height-to-radius ratio of 1.15) was formed at 540 °C with 75 psi forming pressure (500 psi forward pressure minus 425 psi back pressure). It ruptured near the crown after 26 minutes of forming, corresponding to a strain rate on the order of $1x10^{-3}$ s^{-1}. Figure 3a shows the variation of grain size with strain for this cone. (The grain size of the undeformed region of the cone has yet to be determined). It is important to note that the starting material for the cone test was unrecrytallized sheet, allowed to recrystallize in the forming tool for 5 minutes prior to forming. For the deformed areas of the cone, the grain size remains steady around 15 µm up to strains near 1.2. Very near the site of fracture, the average grain size is less than 17.5 µm. The presence of manganese in the alloy leads to the formation of manganese-bearing dispersoid particles which are available to pin grain boundaries. This should retard grain growth. [21,22] Though the grain structure has been shown to be statically stable, some dynamic grain growth occurred at high strain levels.

Figure 3b shows the variation of porosity with strain for the same cone. The scatter of data reflects the variation of porosity through the thickness of the material for a given level of strain. Several micrographs were required to span the cone thickness. Each data point represents the total areal fraction of voids in one micrograph. (There was no clear relationship between the level of porosity at a given location and its depth below the surface of the cone). The average volume fraction of voids remained modest at around 2-3% for true stain values up to 1.4. Examination of a section of the cone near the crown showed that failure was probably due to the interlinkage of pores. The level of back pressure used was apparently enough to suppress but not eliminate cavitation. An increase in the level of back pressure above 425 psi might improve forming perfomance in terms of cavitation, strain, and cone height.

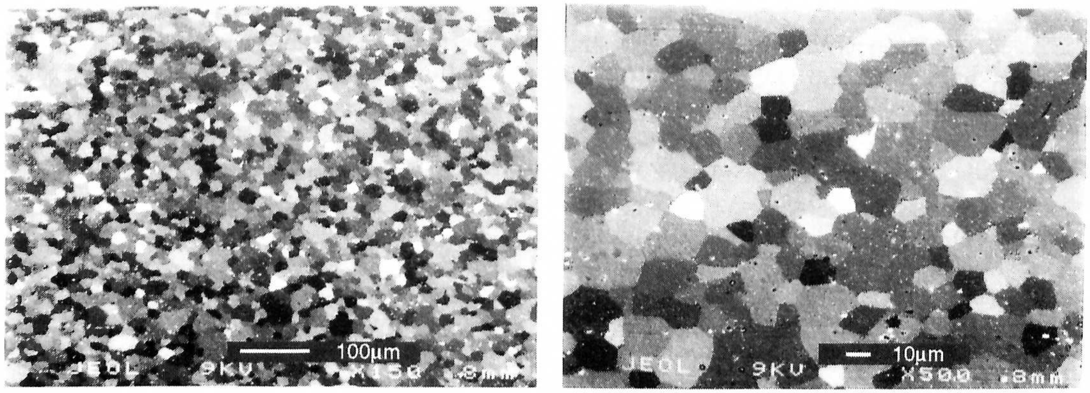
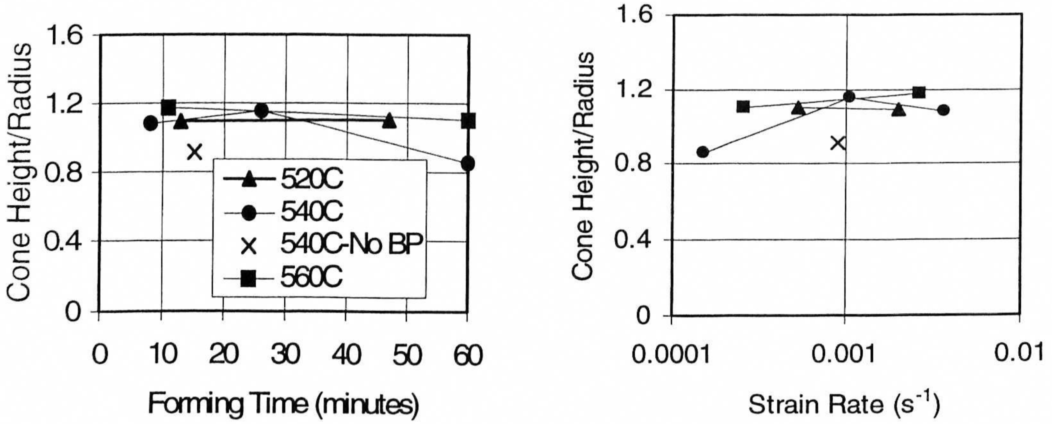
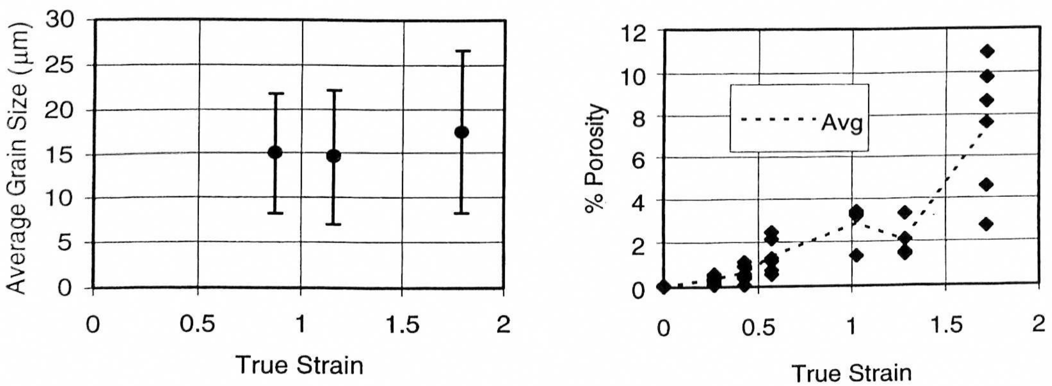


Figure 1. Recrystallized grain structure. LS plane, midthickness.



a) b)**

Figure 2. Variation of cone height-to-radius ratio (h/r) with a) forming time and b) strain rate. **Note that the cones formed at the two slowest strain rates were not formed to failure. Therefore, the height noted for those two is not indicative of the forming potential at those strain rates.



a) b)

Figure 3. Variation of a) grain size and b) porosity with strain for the cone sample.

CONCLUSIONS

The grain size for a 6XXX alloy has been successfully refined to give an equiaxed grain structure with an overall grain size of 10.3 μm. A maximum strain rate sensitivity of 0.5 has been achieved for statically recrystallized material, with a corresponding uniaxial elongation of 375%. During tests with back pressure, the tallest cone formed in under one hour had a height-to-radius ratio of 1.15 and true strain in excess of 1.7. The grain size near the point of fracture reached an average of 17.4 μm. The level of porosity remained below 3% for true strains of almost 1.4.

ACKNOWLEDGMENTS

This work was funded by the NASA Graduate Student Researchers Program and Zonta International. The authors wish to thank Dr. Terry McNelley and Mr. Rich Hashimoto of the U.S. Naval Postgraduate School for assistance with uniaxial testing, and Dr. Robert Ramage of Reynolds Metals Company for supplying 6013 Variant 1. 6013-T4 sheet was supplied by ALCOA.

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