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ALUMINUM WITH ADDITIONS OF Mn AND Zr

C. A. Lavender
M. T. Smith
C. H. Hamilton^(a)

J. S. Vetrano
S. M. Bruemmer

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Pacific Northwest Laboratory
Richland, Washington 99352

(a) Washington State University, Pullman, Washington

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DEVELOPMENT OF SUPERPLASTICITY IN 5083 ALUMINUM WITH ADDITIONS OF Mn AND Zr

C. A. LAVENDER, J. S. VETRANO, M. T. SMITH, S. M. BRUEMMER
Pacific Northwest Laboratory, Richland, Washington 99352, USA

C. H. HAMILTON
Washington State University, Pullman, Washington 99164, USA

ABSTRACT

The superplastic behavior of the 5083 aluminum alloy with additions of Mn and Zr was studied by uniaxial tensile testing and microstructural evaluations. Additions of up to 0.2% Zr and 0.8% Mn were made to a base 5083 aluminum alloy to decrease the grain size and improve superplastic behavior. Constant strain-rate tensile test data were used to determine strain-rate sensitivity (m values) and elongations-to-failure for the alloys at strain rates ranging from 4×10^{-4} to $1 \times 10^{-1} \text{ s}^{-1}$ at temperatures of 450 to 550°C. Elongations-to-failure of up to 400% at $1 \times 10^{-2} \text{ s}^{-1}$ were achieved for the modified alloys. The strain-rate sensitivity for the alloys as a function of strain was determined and two distinct behaviors were observed. For the alloys having composition close to the base 5083 alloy, the m value steadily decreased with increasing strain; however, in alloys with higher levels of Zr, the m value remained stable. A maximum m value of 0.65 was achieved at 0.7 strain for the 1.6% Mn and 0.2% Zr alloy at $1 \times 10^{-3} \text{ s}^{-1}$.

INTRODUCTION

The desire to produce lighter and more efficient ground-based vehicles has pushed the material of choice toward Al. However, Al alloys have seen limited application because of cost and limited formability when compared to the conventional steel alloys used in stamping. One method to produce complex shapes rapidly is superplastic forming (SPF). SPF of Al alloys has been widely studied over many years; however, as a fabrication method it has been characterized as a slow, high-cost method of producing components. The forming rate for the process has typically been limited by strain rates in the 10^{-4} s^{-1} range. Recent studies have shown that increases in the strain rate can be achieved by the development of unique microstructures that are produced by high-rate solidification processes or mechanical alloying. [1-4] Such studies have produced materials that behave superplastically at strain rates of up to $1 \times 10^2 \text{ s}^{-1}$. However, materials produced by these processes are expected to have a very high cost. The challenge is to produce a high-forming rate alloy that can be fabricated by economically viable conventional techniques.

An Al alloy that has been developed for superplastic applications is 5083 (Al-4.5Mg-0.8Mn). This alloy is corrosion-resistant, weldable and moderately high-strength without requiring expensive thermal treatments to develop optimum properties. It has been demonstrated to exhibit superplasticity in the 2 to $4 \times 10^{-4} \text{ s}^{-1}$ strain-rate range [5-7] and is commercially available in "SPF" grades.[8] Alloy modifications of lowering impurities (Fe and Si) [8] and additions of Cu [10] have been made to enhance the superplasticity. However, high-purity alloys have an increased cost and the addition of Cu degrades the corrosion resistance of the alloy.

The focus of this effort was to increase the superplastic strain rates for 5083 by the alloying addition of Zr and changes to the Mn content. Mn additions promote the formation of

Al₆Mn and other Mn-rich second phases. [11] These particles have been shown to reduce grain size and enhance superplastic deformation. [12] The addition of Zr to Al alloys results in the formation of very fine Al₃Zr precipitates. Zr and Zr precipitates are believed to improve superplastic properties by stabilizing substructures, [13-14] by decreasing grain size, [15] and creating dislocation drag resulting in increased matrix strength reducing grain growth. The influence of Zr and Mn additions (and their precipitates) on the superplasticity of 5083 was evaluated by measurement of the total elongation-to-failure, strain-rate sensitivity, and cavitation during uniaxial tensile tests.

EXPERIMENTAL

A series of controlled-purity Al alloys were prepared by the Kaiser Center for Technology (CFT) by direct chill (D.C.) casting of 7.6 by 22.9 cm ingots approximately 61 cm long. Compositions of seven of the alloys evaluated in this paper are given in Table 1. The base alloy for this study was 5083, with the modified alloys having Mn and Zr additions up to maximum levels of 1.6 and 0.2 wt%, respectively. The principal impurities, Fe and Si, were controlled to levels of 0.08 and 0.03 wt% to simulate levels expected in a "clean" commercial alloy. Alloys identified in Table 1 as 1, 4, 7, and 9 were the principal alloys studied due to the "bounding" nature of their respective alloy compositions.

Table 1. Alloy Compositions of 5083 Based Alloys

Alloy	Mg	Mn	Zr	Cr	Fe	Si
1	4.93	0.81	0.001	0.19	0.084	0.034
2	4.89	0.81	0.054	0.19	0.086	0.036
3	4.81	0.80	0.098	0.18	0.097	0.040
4	4.66	0.83	0.190	0.16	0.082	0.035
7	4.80	1.60	0.002	0.18	0.077	0.033
8	4.59	1.60	0.098	0.19	0.080	0.036
9	4.70	1.57	0.200	0.18	0.086	0.050

Kaiser CFT performed homogenization and breakdown rolling (preheat) using parameters to develop a fine dispersion of Al₆Mn. Each ingot was scalped to a thickness of 64 mm and homogenized at 510°C for 8 hours before hot rolling to a 25-mm thickness. Final rolling, heat treatment, and superplastic tensile testing was performed at Pacific Northwest Laboratory (PNL). As with prior PNL studies, [5,6] a minimum cold reduction of 80% was required to develop maximum superplasticity in the modified alloys. The alloys for this study were rolled cold from 25 to 10 mm, annealed at 500°C for 10 minutes, and cold rolled to a final gage of 2 mm.

Tensile samples were fabricated from the sheets with the tensile axis in the rolling direction, retaining the as-rolled surfaces. The tensile samples were machined with a 6-mm. gage width and a 12.5 mm. gage length. All tensile tests were performed at an exponentially increasing crosshead rate to approximate a constant true-strain rate. Tensile tests were carried out using an MTS servo-hydraulic test frame equipped with a three zone air-circulating furnace. Exponential crosshead rate profiles were supplied to the controller digitally, using a Wavetek 75A waveform generator.

Superplastic tensile tests were conducted at temperatures ranging from 450 to 550°C and strain rates from 1×10^{-4} to $1 \times 10^{-1} \text{ s}^{-1}$. The specimens were loaded into the test system in the as-rolled condition and were held at temperature approximately 10 minutes prior to testing after an initial 15-minute heat up. Total elongation for the alloys was determined from samples tested to failure and m values were determined by bumping the strain rate to a higher level for short periods of strain.

Microstructures for the alloys were evaluated by scanning electron microscopy (SEM), transmission electron microscopy (TEM), and optical metallography using techniques described previously. [6] Cavitation evolution was qualitatively evaluated using as-polished metallography specimens. Grain sizes for the alloys were determined using the ASTM E112 standard intercept method using concentric circles. In addition, grain boundary composition changes during superplastic deformation were determined on selected samples. These results are reported in a companion paper in these proceedings. [16]

RESULTS

Test temperature and strain rate had a significant influence on ductility in the various 5083-base alloys. Examples of temperature effects on measured total elongation are shown in Figure 1 for alloys 1, 4 and 7 at slow ($4 \times 10^{-4} \text{ s}^{-1}$) and relative fast ($1 \times 10^{-2} \text{ s}^{-1}$) strain rates. The largest effect among the heats is seen for base 5083 alloy from 450 to 500°C. Most alloys show a modest increase in elongation over the limited test temperature range examined. Overall, the best behavior was observed at 550°C with maximum elongations of 425, 350, 400, and 425% documented for alloys 1, 4, 7, and 9, respectively. Further study of the alloys was carried out at 550°C, which was considered to be the maximum practical forming temperature for the alloys.

Ductility was found to be a much stronger function of test strain rate among the modified 5083 heats. The total elongation as a function of strain rate (4×10^{-4} to $1 \times 10^{-1} \text{ s}^{-1}$) at 550°C is presented in Figure 2 for alloys 1, 4, 7, and 9. Alloys 7 and 9 show much better behavior than alloys 1 and 4 at strain rates of $1 \times 10^{-3} \text{ s}^{-1}$ or greater. The results show that for the 0.8 Mn alloys (1 and 4) maximum elongations were achieved at the slower strain rates and decreased with increasing strain rate. However, for the 1.6 Mn alloys (7 and 9), elongations reach a maximum at intermediate strain rates.

Strain-rate sensitivity measurements (m values) revealed the individual effects of alloying additions on superplastic behavior. Values were determined as function of strain at 550°C using a strain rate of $1 \times 10^{-3} \text{ s}^{-1}$. The results for the modified 5083 alloys are summarized in Figure 3. For the base 5083 (alloy 1), a maximum m value of 0.58 was observed at the lowest strain. Similar values were measured for the low-Zr, 0.8 Mn alloys (2 and 3). Alloy 4 with 0.2 Zr exhibited significantly higher m values at nearly all strains. The observed m values decreased with increasing strain for the 0.8 Mn alloys containing 0.05 and 0.1 Zr; however, the m value for the 0.2 Zr alloy remained relatively constant with true strain up to 1.2. The 1.6 Mn alloys (7, 8 and 9) had higher overall m values than the 0.8 Mn alloys with a maximum of 0.65 observed for the 0.2 Zr-containing alloy 9. In the no- and low-Zr alloys (7 and 8), m values decreased with increasing strain as for the 0.8 Mn heats, while in the 0.2 Zr alloy 9 the strain-rate sensitivity remained relatively constant up to 1.2 true strain.

The microstructure of the base 5083 alloy contained $\text{Al}_6(\text{Mn,Cr})$ precipitates ranging in size from 0.2 to 2 μm in size, and Al-Mn-Fe-Cr containing dispersoids with sizes up to 10 μm . The density of dispersoids was increased four times in the 1.6 Mn alloys, whereas the 0.2 Zr alloys contained an additional population of 50 to 100 nm diameter, generally incoherent Al_3Zr precipitates. [6] These differences in second phase particles among the various alloys directly impacted the initial grain size. The 1.6 Mn alloys consistently show finer grain sizes than the 0.8 Mn heats. An addition of 0.8 Mn (alloy 7) to the 5083 alloy 1 resulted in a 10% decrease in grain size (from 6.7 μm to 5.9 μm), while the 0.2 Zr addition slightly increased grain size to 7.5 μm . The combination of high Mn and high Zr in alloy 9 resulted in the minimum grain size of 4.8 μm .

Grain sizes for all alloys were found to increase during superplastic deformation at 550°C. Dynamic grain growth was evaluated in the alloys 1, 4, and 9 at a strain rate of $1 \times 10^{-3} \text{ s}^{-1}$ for strains of 0.7 and 1.1. The rate at which grain growth occurred with strain did not vary with the alloying content. Alloys 1, 4, and 9 had approximately a 20% increase in grain size at 1.1 strain reaching final average sizes of 8.3, 9.0 and 7.4 μm , respectively.

Cavitation was qualitatively evaluated by examining the as-polished surfaces of metallographically prepared tensile specimens, which were interrupted at different strains. The addition of Zr or Mn+Zr resulted in a decrease in the density of cavities of all strain levels of samples tested at 1×10^{-3} and 550°C . The 1.6 Mn, 0.2 Zr alloy 9 exhibited virtually no cavitation at true strain levels of 1.1, while the base 5083 showed extensive cavities at much lower strains. Figure 4 illustrates differences in cavitation behavior for alloys 1, 4, and 9.

DISCUSSION

The addition of Mn to the baseline 5083 had the largest effect on the total elongation, particularly at higher strain rates. An increase in elongation of 25% at 1×10^{-3} and of 150% at $1 \times 10^{-2} \text{ s}^{-1}$ was documented along with an increase in the m value. The improvement in elongation and m value can be explained by the reduction in grain size associated with the increased number of Mn-rich particles. Finer grain sizes promote grain boundary sliding which, in turn, results in increased strain-rate sensitivity and elongation during superplastic deformation.

The addition of Zr had only a small effect on the total elongation observed in the alloys and actually decreased the elongation observed in the baseline 5083 alloy at higher temperatures. Surprisingly, the Zr did not reduce the dynamic grain growth of the alloys as has been previously observed. [15] One possible explanation for the difference in behavior could be the size and distribution of the Al_3Zr precipitate. Prior studies [3,12,13] of Zr additions to Al alloys were conducted on alloys that were processed using higher solidification rate techniques such as 25-mm DC ingots, book mold casting, and powder metallurgy processing. The higher solidification rates produced fine coherent Al_3Zr precipitates. The use of the 76-mm DC ingot for this study resulted in the formation of primarily incoherent Al_3Zr precipitate with less control on the precipitate size distribution and homogeneity.

Zr additions of 0.2 wt% had a pronounced effect on strain-rate sensitivity and cavitation behavior during superplastic deformation at 550°C . The stabilization of the m value and reduced cavitation cannot be attributed to grain refinement due to the Al_3Zr precipitates as expected. It is not clear at this time what role the Zr played to reduce cavitation and improve strain-rate sensitivity. However, differences in grain boundary composition are detected for the 0.2 Zr alloy versus commercial 5083 which may influence grain boundary sliding and cavitation behavior. [16]

CONCLUSIONS

Tensile test results show that the strain rate at which 5083 will exhibit superplastic behavior can be increased with the addition of Mn and Zr. The effect of the alloying additions on the superplasticity of 5083 were manifested in increased elongation, decreased cavitation, and increased m value with strain. Increasing the bulk Mn content of 5083 to 1.6 wt% produced a higher density of second-phase particles in the microstructure and prompted a finer grain size than the standard 5083 aluminum alloy. The finer grain size promoted higher elongations for the alloys, particularly when tested at strain rates in the range of 1×10^{-3} to 1×10^{-2} .

Small additions of 0.05 or 0.1 Zr to 5083 had little effect on the superplastic behavior of the alloys. However, the addition of 0.2% Zr resulted in stable m values up to 1.2 true strain and improved cavitation resistance. The combination of 0.2 Zr and 1.6 Mn produced the best high strain-rate elongation, lowest cavitation, and highest m value for the alloys. Fine grain sizes associated with the additional Mn combined with the fine dispersion of Al_3Zr produced the best overall superplastic response.

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Figure 1. Measured Total Elongation as a function of Test Temperature for Al Alloys 1, 4 and 9 at two different strain rates.

Figure 2. Measured Total Elongation as a Function of Test Strain Rate for Al Alloys 1, 4, 7 and 9.

Figure 3. Measured m Values as a Function of True Strain for Al Alloys 1, 2, 3, 4, 7, 8 and 9.

Figure 4. Optical Micrographs Illustrating Differences in Cavitation for Alloys 1(a), 4(b) and 9(c) After Tensile Deformation to 1.1 True Strain at 550°C and Strain Rate of $1 \times 10^{-3}/\text{s}$.

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