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Superplasticity in cast A356 induced via friction stir processing

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Abstract

Superplasticity was investigated in friction stir processed A356 alloy at temperatures of 470–570 °C and initial strain rates of 3×10^{-4}–1×10^{-1} s^{-1}. Maximum superplastic elongation of 650% was obtained at 530 °C and an initial strain rate of 1×10^{-3} s^{-1} where a maximum strain rate sensitivity of 0.45 was observed.

Keywords: Superplasticity; Friction stir processing; Cast A356

1. Introduction

Friction stir processing (FSP), a development based on friction stir welding (FSW) [1], is a new solid state processing technique for microstructural modification [2,3]. During FSP, the material in the processed zone undergoes intense plastic deformation, mixing, and thermal exposure, resulting in significant microstructural changes. In general, the processed zone is characterized by recrystallized fine grains and uniformly-distributed second phase particles. The characteristics of FSP have led to several applications for microstructural modification in metallic materials, including superplasticity [2,3], surface composite [4], and homogenization of nanophase aluminum alloys and metal matrix composites [5,6].

Among these, the application of FSP to induce superplasticity has attracted extensive research efforts [7–10]. Compared to other processing techniques such as thermo-mechanical processing (TMP) [11,12], equal channel angular pressing (ECAP) [13], torsional deformation under pressure [14], FSP is particularly attractive because it provides a very simple and effective approach to obtain a through thickness fine-grained microstructure for superplasticity. Conventional TMP, generally involving solution treatment, overaging, multiple pass warm rolling with intermittent reheating, and a recrystallization treatment [12], is complex, time-consuming, leads to increased material cost, and can only produce thin gage sheet. For ECAP, usually at least six processing passes, equivalent to an imposed strain of ∼6, are necessary to create a fine-grained superplasticity microstructure [15]. By comparison, one-pass FSP can produce an estimated effective strain of >40 [16], resulting in a very fine 0.5–10 μm grain structure [2,3,7–10,17,18]. High strain rate superplasticity (HSRS) has been induced by FSP in a number of aluminum alloys such as 7075Al [7,8], Al–Mg–Zr [9], and 2024Al [10].

In a previous paper, we reported that FSP results in remarkable homogenization and refinement of a cast microstructure in A356 [19]. The microstructure of FSP A356, characterized by a uniform distribution of fine Si particles in the aluminum matrix, is very similar to that of metal matrix composites. It has been reported that metal matrix composites exhibit superplastic behavior under special conditions [20–22]. Therefore, it is worthwhile to evaluate FSP A356 for superplastic behavior. In this paper, we report the first results on the superplastic behavior of FSP A356.

2. Experimental

A commercial A356 cast billet with nominal composition 7.0Si–0.3Mg–bal Al (in wt.%) was used. Single pass FSP with a tool rotation rate of 700 rpm and traverse speed of 203 mm min^{-1} was performed on 6.35 mm

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thick as-cast A356 plates. Metallography was completed using optical microscopy on both as-cast and FSP samples. Further, the microstructure of the FSP sample was examined on a Philips EM430 transmission electron microscope (TEM). TEM specimens were prepared by the ion-milling technique.

Mini tensile specimens with 1.3 mm gage length were electro-discharge machined from the FSP region in the transverse direction and ground and polished to final thickness of ~0.5 mm. Constant crosshead speed tensile tests were conducted using a computer-controlled, custom-built mini tensile tester. For comparison, tensile tests of as-cast samples were also conducted using the same test procedures.

3. Results and discussion

Fig. 1 shows the microstructure of as-cast and FSP A356. The microstructure of the cast A356 consists of primary α-aluminum dendrites and interdendritic irregular Al–Si eutectic regions (Fig. 1a). This microstructure is typical of modified A356 castings. By comparison, in the FSP sample, fine and equiaxed Si particles were uniformly distributed in the aluminum matrix due to an intense breakup of the as-cast microstructure and subsequent material mixing (Fig. 1b). Generally, grain boundaries are hard to distinguish in FSP A356. However, the grain size in the present FSP A356 is estimated to be on the order of ~3 μm (Fig. 1c). This is in good agreement with that obtained in other FSP aluminum alloys [2,3,7–10,17,18].

The stress–strain behavior of FSP A356 is shown in Fig. 2 as a function of initial strain rate and temperature. Clearly, FSP samples exhibited superplastic behavior. The optimum strain rate for maximum elongation at 530 °C was 1×10^{-3} s^{-1}. At an initial strain rate of 1×10^{-3} s^{-1}, the optimum temperature for maximum elongation was 530 °C. Generally, the stress–strain curves of FSP A356 exhibited significant strain hardening. This is consistent with that in FSP 7075Al and Al–4Mg–1Zr [2,9]. The strain hardening during superplastic flow is generally attributed to concurrent grain growth [9].

Fig. 3a and b show a comparison of elongation for both the FSP and cast conditions as a function of strain rate and temperature. Elongation of the cast A356 was low (<200%) and did not exhibit any appreciable dependence on strain rate or temperature. By comparison, FSP A356 exhibited a maximum elongation of 650% and demonstrated a strain rate and temperature sensitivity with optimum test parameters of 530 °C at an initial strain rate of 1×10^{-3} s^{-1}. Recently, Kim et al. [23] investigated high-temperature deformation behavior of

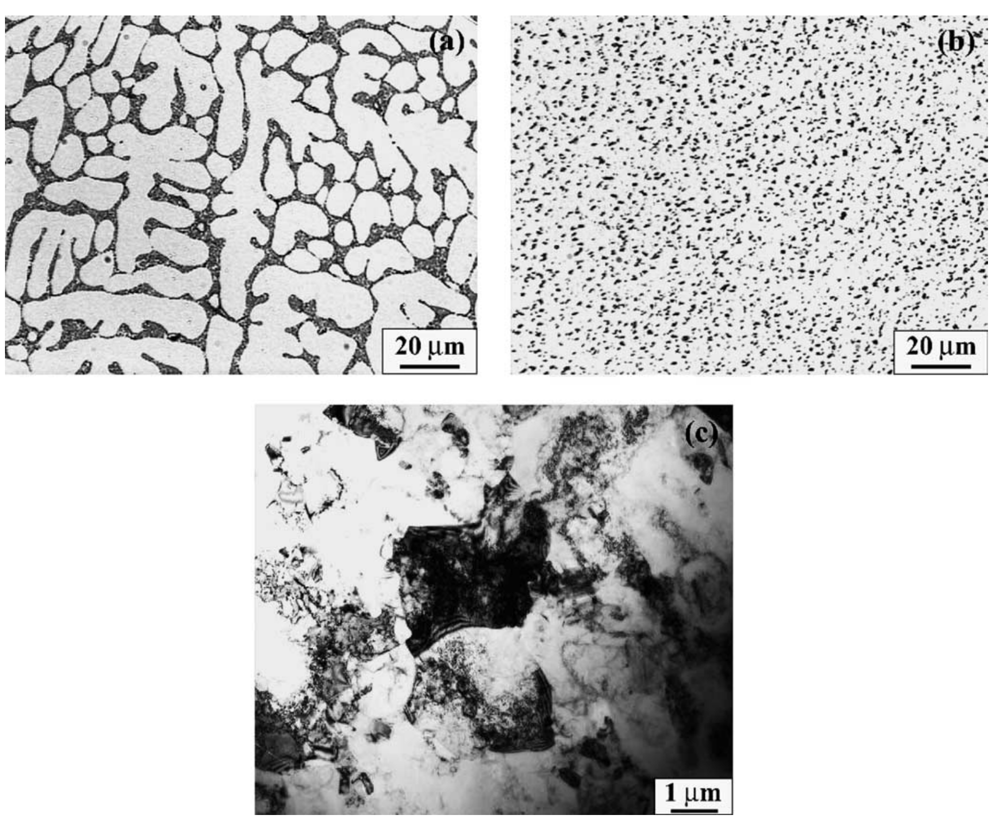

Fig. 1. Micrographs of (a) cast A356, (b) FSP A356, and (c) bright field TEM micrograph of FSP A356.

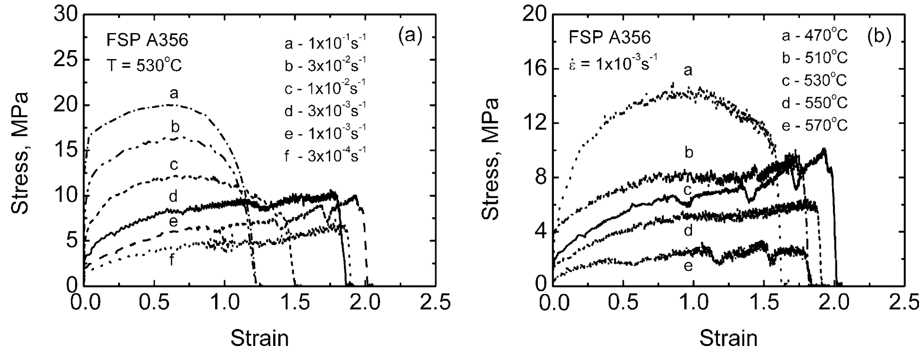

Fig. 2. Stress–strain behavior of FSP A356 as a function of (a) initial strain rate at 530 °C and (b) temperature at an initial strain rate of 1×10^{-3} s^{-1}.

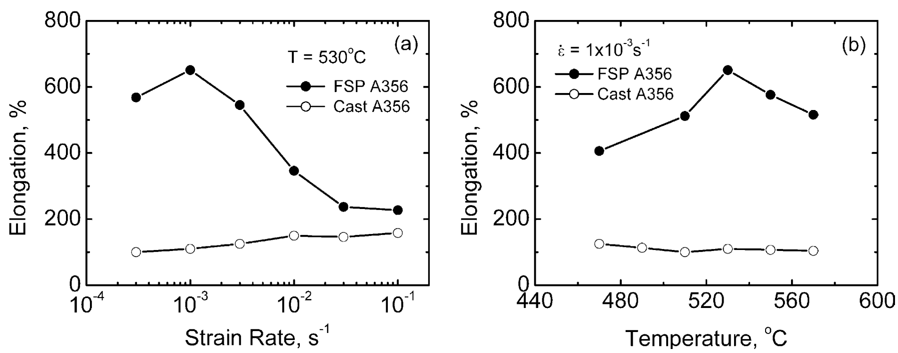

Fig. 3. Variation of elongation with (a) initial strain rate and (b) temperature for both FSP and cast A356.

ECAP A356. It was reported that an ~2–3 μm fine-grained structure was produced in A356 after six-pass ECAP. However, no superplasticity was obtained in the ECAP A356 with a maximum elongation of ~100% and a strain rate sensitivity of ~0.2 in the investigated strain rate range. This result was attributed to the occurrence of grain growth by Kim et al. [23]. For the present FSP A356, it appears that the fine-grained structure is stable at higher temperature. This is supported by the fact that even at the highest temperature of 570 °C, FSP A356 still exhibited a relatively high elongation of 515% (Fig. 3b). This may be attributable to the pinning effect of fine Si particles on grain boundaries. Partial melting in as-cast A356 is reported to start in the temperature range of 560–563 °C [24]. Therefore, the largest superplasticity observed in FSP A356 was not associated with the appearance of a liquid phase as reported for aluminum matrix composites [20–22]. Thus, it is proposed that the development of superplasticity in FSP A356 is attributed to the fine-grained microstructure created by FSP [2,3,7–10].

Previous studies have exhibited HSRS in several FSP aluminum alloys such as 7075Al [2,7,8], Al–Mg–Zr [9], and 2024Al [10]. However, FSP A356 did not exhibit HSRS, though it had fine-grained microstructure of ~3 μm (Fig. 1c). This is likely that the Si particles influence the superplastic deformation process. The Si particles are around 0.3 μm and diffusional accommodation around these particles might limit the optimum superplastic strain rate.

Fig. 4 shows tested specimens of the FSP A356 deformed to failure at 530 °C and two strain rates. The specimens show neck-free elongation characteristic of superplastic flow. No noticeable deformation occurred in the grip section. This is consistent with a previous investigation on FSP Al–4Mg–1Zr [9].

Fig. 5 shows the variation of flow stress with initial strain rate and temperature for both FSP and cast A356. The cast A356 exhibited a strain rate sensitivity of ~0.14 throughout the investigated strain rates of 3×10^{-4}–1×10^{-1} s^{-1}. This accounts for the absence of

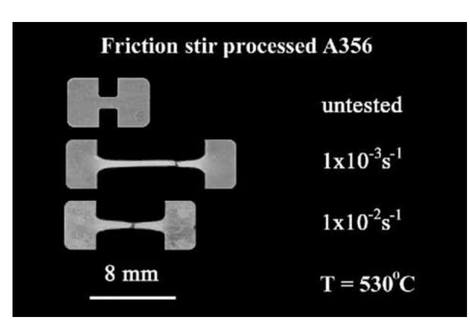

Fig. 4. Appearance of specimens before and after superplastic deformation at 530 °C.

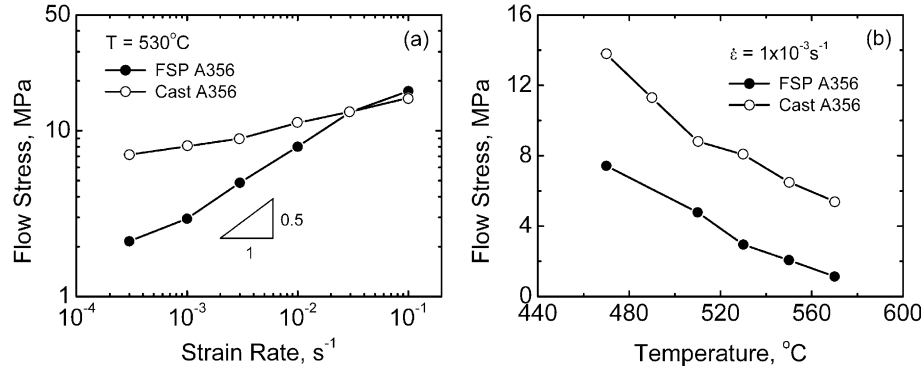

Fig. 5. Variation of flow stress with (a) initial strain rate and (b) temperature for both FSP and cast A356.

superplasticity in cast A356. By comparison, the strain rate sensitivity of the FSP sample is 0.26, 0.45, 0.43, and 0.24 in the initial strain rate ranges of 3×10^{-4}–1×10^{-3}, 1×10^{-3}–3×10^{-3}, 3×10^{-3}–3×10^{-2}, and 3×10^{-2}–1×10^{-1} s^{-1}, respectively, i.e., the FSP A356 exhibited the typical S-type stress–strain rate behavior characteristic of a superplastic material (Fig. 5a). The maximum strain rate sensitivity of 0.45 at the initial strain rate of 1×10^{-3} s^{-1} corresponds to the maximum elongation of 650%. A strain rate sensitivity close to 0.5 indicates that grain boundary sliding is the dominant deformation mechanism [25]. Furthermore, flow stress of the FSP sample is significantly lower than that of the cast sample at initial strain rates $<3\times10^{-2}$ s^{-1} for 530 °C and at temperatures of 470–570 °C for an initial strain rate of 1×10^{-3} s^{-1}. This is attributed to a significantly-refined microstructure in the FSP sample.

The overall implication of the present study is significant. It shows that the simple application of FSP can induce superplasticity in cast A356. To the best of our knowledge, this is the first result illustrating superplastic behavior in cast A356. This demonstrates that FSP is a very effective processing technique to create a thermally stable fine-grained microstructure in cast aluminum alloys resulting in significant superplasticity. The generation of superplasticity in A356 will widen its application field. Research is in progress to understand the effects of FSP parameters on the superplastic behavior and the responsible deformation mechanism in this alloy.

4. Conclusions

1. FSP created a fine and uniform microstructure in cast A356, thereby converting a non-superplastic cast A356 to superplastic. Maximum superplasticity of 650% was obtained at 530 °C and an initial strain rate of 1×10^{-3} s^{-1} in FSP A356.
2. FSP A356 exhibited an S-type stress–strain rate behavior with a maximum strain rate sensitivity of 0.45 at 530 °C for initial strain rates of 1×10^{-3}–3×10^{-3} s^{-1}. The flow stress of FSP A356 was significantly lower than that of cast A356.

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