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Effect of friction stir processing on fatigue behavior of A356 alloy

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Abstract

Cast A356 alloys prepared by friction stir processing (FSP) were subjected to fatigue investigation. FSP resulted in a significant improvement in fatigue life of A356. Fatigue life improvement was attributed to significant grain refinement, homogenization of the microstructure, and the elimination of porosity.

Keywords: Fatigue; Friction stir processing; Cast A356

1. Introduction

Aluminum alloys constitute a significant proportion of lightweight metals used in industry. Among commercial cast aluminum alloys, Al–7Si–Mg alloys are the most widely used because of their excellent castability, corrosion resistance, and good mechanical properties. The mechanical properties are influenced by composition, solidification conditions, modifiers added, and the heat treatment [1]. The above processing parameters influence microstructural features such as secondary dendrite arm spacing, interdendritic porosities, silicon particle size, and the size of other intermetallic inclusions [1–3]. A356 is a hypoeutectic aluminum alloy wherein the aluminum solid solution precipitates from the liquid as the primary phase in the form of a dendritic network followed by a eutectic reaction. Unmodified eutectic silicon is present as coarse polyhedral particles and consequently the casting exhibits poor mechanical properties [1]. Although chemical modifiers such as sodium and strontium significantly improve certain casting characteristics, they have other undesirable effects. Various thermal treatments are also used to modify the eutectic morphology of the alloy hence improving its mechanical properties [4]. Fatigue properties of aluminum castings depend on the microstructure. For example, failure of cast aluminum alloys under a fatigue load is caused by cracks initiated from prominent casting defects. If these defects are minimized or eliminated, the fatigue performance is significantly improved [1–8].

Friction stir processing (FSP) is related to the friction stir welding (FSW) technique developed at TWI [9]. FSW is a solid state joining process, combining frictional and deformation heating, used to obtain high quality defect free joints. In this technique, a non-consumable rotating tool is introduced between two adjoining plates and welding is achieved via material transport around a rotating pin. The pin tool promotes severe plastic deformation along the joint line and the shoulder provides forging action thus forcing the material down. FSP has shown significant microstructural refinement and improved mechanical properties for both wrought aluminum alloys and cast microstructures [10–15]. The enhanced fatigue life results reported in this document for A356 take advantage of the microstructural refinement, elimination of casting defects, and homogenization of the cast microstructure attainable by friction stir processing.

2. Experimental procedure

A356 plates with dimensions 30.48 cm × 7.62 cm × 1.52 cm were sand cast. The alloy composition is shown in Table 1. To study the influence of processing conditions on the microstructure, the plates were friction stir processed using different processing conditions i.e., varying tool rotation rate and traverse speed, and with

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Table 1
Chemical composition (wt.%) of A356 alloy

Al	Si	Mg	Fe	Mn	Cu	Zn	Ti	Cr	Ni
Bal	7.20	0.36	0.13	0.007	0.014	0.018	0.16	0.003	0.007

different pin geometries. Mini tensile tests were conducted using a custom built desktop machine to study mechanical properties from the nugget (stir) region. Mechanical property results from the above study are reported elsewhere [12]. Based on optimum mechanical properties, obtained by the mini tensile tests, two plates were processed for fatigue testing. One plate was processed using a standard FSW pin at 900 rpm (revolution per minute) and a traverse speed of 203.2 mm per minute and the other plate was processed using a triflute pin at 700 rpm and 203.2 mm per minute. The microstructure of the processed samples was examined both in an optical microscope and in a scanning electron microscope (SEM). Fatigue tests were conducted at Metcut Research Inc. on a closed loop servo controlled hydraulic system under axial load control with a load ratio of $R = 0.1$ at a sinusoidal frequency of 80 Hz. Fatigue samples were prepared using ASTM E-466-96 standards with a low stress ground and polished 8 Ra longitudinal surface finish. A total of 24 specimens were tested with different microstructures and different loading conditions. Failed samples were mounted, polished and examined under an optical microscope as well as an SEM. Further, fracture surfaces were subjected to SEM examination.

3. Results

3.1. Microstructure evolution

Fig. 1 shows the macrostructure of A356 after FSP. Two distinct regions are marked including the thermo mechanically affected zone (TMAZ), and the stir zone (SZ). These regions are formed due to intense plastic deformation at high temperature leading to dynamic recrystallization [13] and complex material mixing during FSP.

Fig. 2 compares microstructures of A356 plates before and after FSP. The base metal microstructure

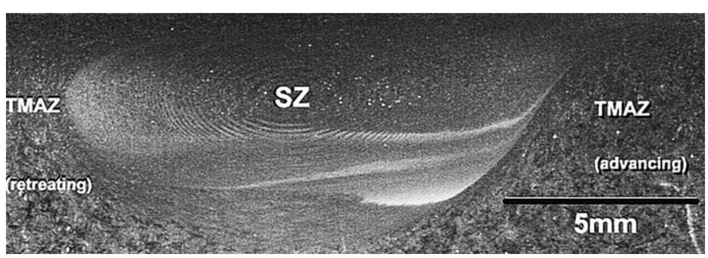

Fig. 1. Optical macrograph of a FSP A356 showing the three regions.

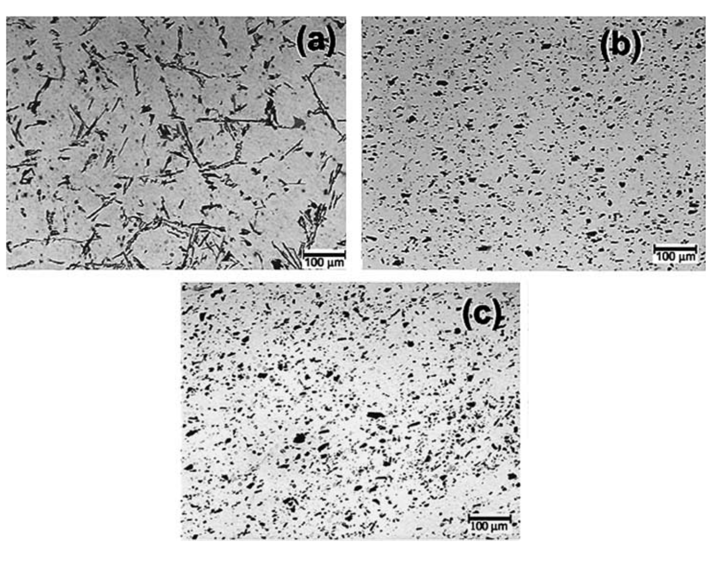

Fig. 2. Optical micrographs of (a) as-cast plate, (b) plate processed using a standard pin at 900 rpm and 203.2 mm per minute, and (c) plate processed using a triflute pin at 700 rpm and 203.2 mm per minute.

Table 2
Influence of FSP on particle size and porosity volume fraction in cast A356

Material	Particle Area (μm^2)	Porosity volume fraction (%)
As-cast 3/5"	69 ± 152	0.95
900 rpm and 203.2 mm per minute (standard-pin)	20 ± 26	0.027
700 rpm and 203.2 mm per minute (triflute-pin)	16.5 ± 26.5	0.024

consists of primary α and an Al–Si eutectic structure with a dendrite arm spacing (DAS) of ≈80 μm. The microstructure of the SZ consists of homogeneously dispersed Si particles in the α matrix. Also, the number of pores in the SZ is greatly diminished when compared to the base metal (BM) because of the stirring and forging action of the FSP tools. No porosity greater than 10 μm in diameter was observed in the SZ.

Table 2 shows the average silicon particle size and their standard deviation before and after FSP. Not only is the particle size reduced significantly due to material flow during the process and shearing action generated by a rotating pin, but the standard deviation is also greatly minimized.

3.2. Fatigue properties

Fig. 3 illustrates fatigue results for A356 plates before and after FSP. For processed plates, the samples were machined completely from the SZ. The arrows in the figure indicate specimens that did not fail. As shown, the fatigue strength threshold stress increased by >80% after FSP. This fatigue strength improvement is attributed to both a reduction in silicon particle size and reduced porosity volume fraction.

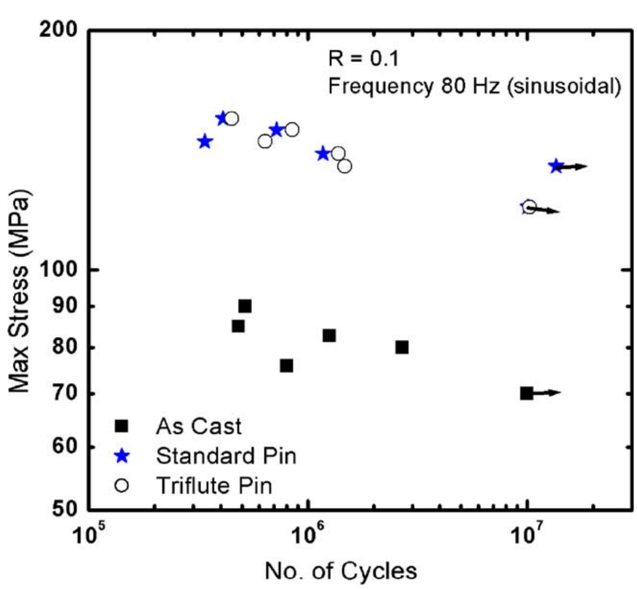

Fig. 3. Influence of FSP on fatigue properties of A356.

The influence of pore size on fatigue life has been evaluated previously [8,16,17]. The fatigue life N_f has been related to the positive component of cyclic stress, σ^*, and the pore size a_o, by

$$\sigma^* = C(a_o N_f)^{-\frac{1}{m}} \quad (1)$$

where m is the Paris exponent for fatigue crack growth and C is a constant that depends on the Paris pre-exponential constant and on the pore shape and position. From the above analysis, it was concluded that fatigue life is influenced more by the size of the largest pore rather than porosity volume fraction or mean pore size. In addition to porosity, fracture characteristics of Al–Si–Mg castings are influenced by size, orientation and local distribution of Si particles as well as by the Si-matrix interface strength. As stated by Lee et al. [6], fatigue failure in A356 occurs in four stages including (a) crack initiation at Si or second phase particles, (b) crack growth, (c) crack propagation across the Al–Si matrix via linkage of micro cracks generated as a result of decohesion and/or particle cracking, and (d) high rate of crack growth eventually leading to fracture of the aluminum matrix. Larger Si particles present in the as-cast material accelerate crack nucleation due to stress concentration effects. Murakami and Endo [16] have proposed the following equation for the fatigue limit in metals with 3-D defects:

$$\sigma_w = \frac{1.43(H_V + 120)}{(\sqrt{A})^{\frac{1}{6}}} \quad (2)$$

where σ_w is the fatigue limit (MPa), A is the area obtained by projecting a defect or a crack onto the plate perpendicular to the maximum tensile stress (mm), and H_V is Vickers hardness (kgf mm^{-2}) between 70 and 720 H_V. Based on this equation, a 30% reduction in particle size alone would contribute to a 25% improvement in fatigue limit. FSP significantly refines the microstructure leading to a homogeneous distribution of smaller Si particles with smaller aspect ratios when compared with the as-cast microstructure. This refined microstructure also leads to increased plastic deformation in the aluminum matrix during cyclic crack tip propagation resulting in a concurrent increase in crack energy dissipation and a consequent increase in crack growth resistance. Plastic deformation during fatigue leads to crack nucleation either by separation of the silicon aluminum interface or by particle cracking or both. Fig. 3 indicates that for the pin geometries tested, there was no effect on fatigue behavior of FSP A356. A similar observation was made for the tensile test results [12].

3.3. Fractography

Fracture surfaces of the fatigue samples were evaluated to determine the difference in fracture behavior of as-cast and FSP samples. For as-cast samples, crack initiation was usually associated with casting defects. The crack path was generally rough and uneven indicating that the crack followed defects in the microstructure; see Fig. 4(a) and (b). Fatigue cracks propagated with significant amounts of crack branching and deflection. Nadot et al. [18] have observed that in nodular cast iron specimens, surface defects decreased fatigue life significantly more than defects located at the core. Along with refining the core microstructure, FSP can be used as a tool to minimize surface defects and hence greatly improving fatigue life. As seen in Fig. 4(c) and (d), for FSP samples, the fracture surfaces were almost perpendicular to the longitudinal axis. The crack propagated primarily along the interface between the silicon particles and the aluminum matrix and is characterized by the formation of dimples on the fracture surface.

For the as-cast specimen, significant numbers of silicon particles fractured and pulled out from the aluminum matrix (Fig. 5a). Also, there was evidence of crack nucleation and growth 3 mm away from the main failure location. For the FSP sample, comparatively fewer particles cracked prematurely and no crack nucleation was observed in the material away from the failure site (Fig. 5b). The fatigue crack growth rate is significantly retarded in the case of unbroken silicon particles because the crack propagates gradually along the particle-matrix interface. This is due to an increase in effective crack length as the crack grows around a network of

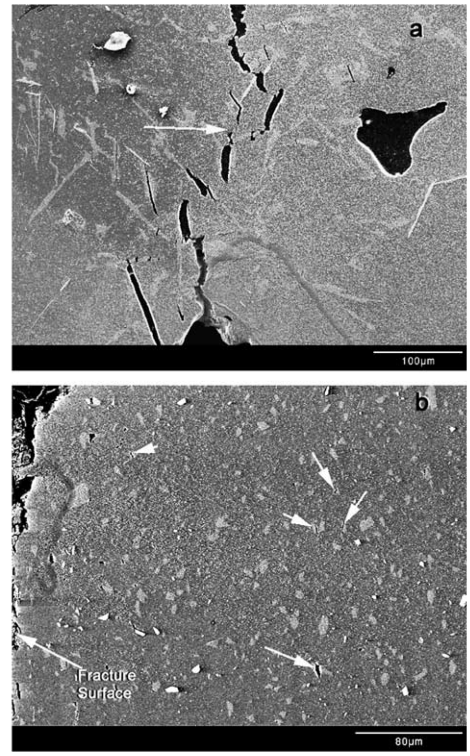

Fig. 5. Sectioned surfaces of (a) as-cast specimen, showing secondary crack nucleation 3 mm away from the main failure location and (b) FSP specimen showing particle cracking.

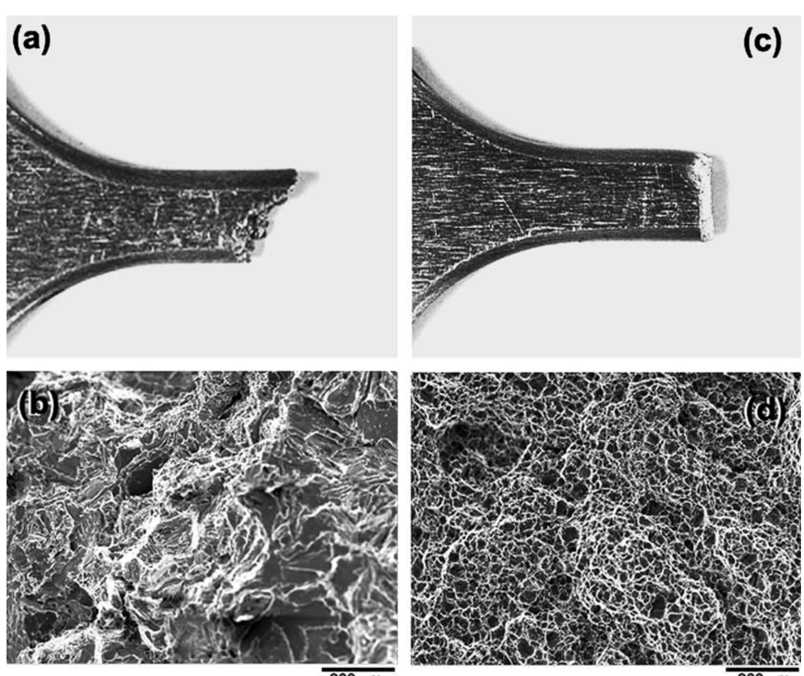

Fig. 4. Fracture surfaces of (a) and (b) as-cast specimens, (c) and (d) friction stir processed specimen.

particles within a ductile matrix [19,20]. Conversely, if the particles fracture prematurely, a weak material path is provided for the propagating crack tip hence increasing crack growth rate [20]. Crack initiation from defects and joining of adjacent micro cracks is easier for as-cast specimens.

4. Conclusions

FSP resulted in a significant breakup and uniform distribution of Si particles in the aluminum matrix as well as elimination of porosity. This leads to an improvement in fatigue stress threshold stress >80% in the stir zone of the FSP sample. This improvement in fatigue properties is attributed to an increased effective crack length and reduction in crack growth rate. FSP can be used as a tool to locally modify the microstructures in regions experiencing high fatigue loading and thus significantly improve the overall performance of aluminum castings.

Acknowledgements

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