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Influence of friction stir processing on the room temperature fatigue cracking mechanisms of A356 aluminum alloy

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ABSTRACT

Failure by fatigue is a common problem associated with cast aluminum alloys due to defects like shrinkage porosities, non-metallic inclusions, etc. Friction stir processing (FSP) has recently emerged as an effective technique for local modification of microstructure. This study investigates the fatigue crack initiation and growth mechanisms in cast and FSPed A356 aluminum alloy. Two sets of parameters were used to friction stir the cast alloy resulting in the complete modification of the cast microstructure to a wrought microstructure. Both the FSPed microstructures exhibited severe abnormal grain growth (AGG) after heat treatment leading to a multimodal grain size distribution – the grain sizes ranging from a few microns to a few millimeters. One of the FSP conditions displayed an excellent improvement in fatigue life by an order of magnitude, while the other condition displayed an unexpectedly large scatter in fatigue lives. Detailed study of the fractured fatigue specimens by electron back scattered diffraction (EBSD) revealed that both, fatigue crack initiation and propagation, were intimately tied to the grain size as well as the grain misorientations in the microstructure.

1. Introduction

In the past few decades the automobile industry has transitioned from ferrous alloys to cast aluminum alloys to build a majority of engine components like pistons, engine blocks, and cylinder heads [1–3]. Engine pistons and cylinder heads are constantly subjected to rapid cyclic loading and fluctuations of temperature in the combustion chamber. Hence, these components are prone to fatigue failure [4].

The A356 Al alloy has become the most commonly used cast aluminum alloy, due to advantages like high strength-to-weight ratio, excellent castability to near-net shapes, and wear resistance [5]. However, despite enjoying diverse applications, the A356 alloy suffers from poor fatigue performance. The cast microstructure consists of mainly coarse, primary α-aluminum dendrites and interdendritic irregular Al–Si eutectic regions. The distribution of Si particles is not uniform throughout the aluminum matrix and is restricted to the interdendritic regions [6–8]. Many researchers have extensively assessed the fatigue behavior of cast A356 alloy, and have concluded that the low fatigue life of the cast A356 alloy is due to the presence of microstructural defects such as casting porosities, non-metallic inclusions, non-uniform distribution of secondary phases, and the shape and morphology of particles [9–22]. These defects act as sites of stress concentration leading to early failure. Current attempts to improve mechanical properties of these alloys mainly focus on modifying the microstructure by:

- Adding alloying elements, for example, Sr to modify the morphology of Si particles [23,24]
- Heat treating to improve strength and spheroidize Si particles [25]
- Changing cooling rates during solidification to control dendrite arm spacing [26,27]

Though effective, these techniques have not been able to eliminate the main sources of crack initiation - casting porosities, intermetallic particles, and other microstructural stress raisers. The above techniques do have a significant effect on the shape and morphology of the Si particles but do not have the ability to modify the non-uniform Si particle distribution and their segregation in the interdendritic regions of the cast microstructure. This non-uniform distribution of Si particles results in non-uniform distribution of strain, which in turn results in localized regions of stress concentrations.

Therefore, to improve the fatigue performance of engine components, we are left with two alternatives. The first is to change the material itself to higher strength alloys like nickel-based alloys, titanium alloys, or micro-alloyed steels. However, these often tend to be very

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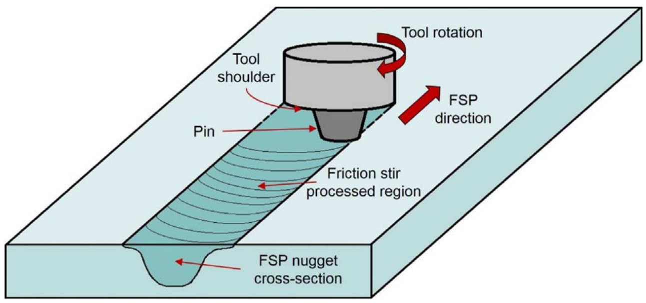

Fig. 1. Schematic of the friction stir process.

expensive, heavy, or both. The second alternative is to locally modify the cast microstructure of the existing alloy to improve strength and fatigue resistance.

Friction stir processing (FSP) is emerging as an effective technique to achieve microstructural modification in a variety of metals and alloy systems [28,29]. Fig. 1 shows a schematic of the friction stir process. A spinning pin tool (usually made of high strength tool steel) is plunged into the work piece and moved along the desired path. As the rotating tool comes in contact with the work piece, the friction between the rotating tool and the workpiece generates heat, and softens the material. This plasticized material flows around the tool and cools down in the wake of the moving tool [30,31]. Refinement of grain structure and modification of texture in the material are achieved through severe plastic deformation [32–37].

For over a decade, FSP has been used as a tool for localized microstructure modification, to obtain tailored properties in aluminum and magnesium alloys [38–44]. FSP is one of the most effective routes to overcome the limitations associated with a cast microstructure, and improve the fatigue performance of A356 alloy beyond the best possible performance achievable with a dendritic microstructure. During FSP, the tool interacts directly with the cast microstructure and breaks down the dendrites. Ma et al. [45–47] reported that after FSP of an A356 alloy, the microstructure was refined with a random, homogeneous distribution of second phase particles. Most of the Si particles were very fine and equiaxed, and the casting porosities were completely eliminated. Sharma et al. [48,49] investigated the fatigue response of A356 alloy after FSP and showed that the improved microstructure resulted in enhanced fatigue behavior in the alloy. Fatigue strength threshold in FSP material increased by more than 80% due to the elimination of porosities as well as reduction in Si particle size and aspect ratio. Jana et al. also researched the effect of FSP on microstructure and mechanical properties of A356 alloy [50–53]. Their extensive study on crack growth characteristics in cast and FSP A356 alloy details several important findings [51]. They concluded that resistance to crack growth increased after FSP, and could be attributed to a more ductile aluminum matrix that exhibited more uniform plastic deformation. When the fatigue crack encountered Si particles, it deflected to follow the particle–matrix interface. This crack meandering reduced crack growth by increasing the total crack length and decreasing the effective stress intensity at the crack tip. Multi-pass FSP also has been used to homogenize microstructure over a large area, resulting in random distribution of Si particles with uniform size and aspect ratio [47,53].

The aim of the current study is to understand the effect of FSP on fatigue cracking mechanisms and how it leads to the observed fatigue behavior of the current A356 alloy. All the studies mentioned above used unmodified cast A356 alloys that contained large Si particles with a plate-like morphology and very high aspect ratios. This morphology did not change significantly even after heat treatment. In this study, we used a Sr-modified A356 alloy in which the Si particles were very fine with a fibrous, broom-like morphology in the as-cast condition. After T6 heat treatment, the particles became almost fully spheroidized. The current alloy also had very small secondary dendritic arm spacing (SDAS) compared to the alloys used in the previous studies. In terms of mechanical properties, the current cast alloy was vastly superior to those used in previous studies.

Another difference in this study compared to previous studies is that we used mini-fatigue specimens based on the sub-sized specimen geometry developed by De et al. [54], instead of standard-sized specimens. The advantage of using mini samples versus standard-sized samples was that we could obtain samples from within the narrow, locally modified region that consisted only of FSP material. This would not be possible on a standard specimen whose gauge dimensions are greater than the FSP region width. However, a disadvantage with using sub-sized specimens is that these specimens are so small that they may not be representative of the bulk properties of the cast A356 alloy. Microscopic defects like an inhomogeneous microstructure, casting porosities, or second phase particles will have a bigger negative impact on macroscopic properties of mini or sub-sized specimens, resulting in large scatter in fatigue-life data. A standard-sized specimen would be big enough to average out these effects.

2. Experimental procedure

We friction stir processed a cast A356 Al alloy, with the chemical composition shown in Table 1, using a conical, step-spiral tool in position control mode.

We used two different processing conditions, FSP 1 and FSP 2, to obtain different microstructures and mechanical responses. FSP 1 was performed at a tool rotation rate of 1500 RPM and tool traverse speed of 102 mm/min, while FSP 2 was performed at 300 RPM and 102 mm/min. Table 2 summarizes the friction stir parameters used in the two conditions. Both FSP conditions had a plunge depth of the tool of 5.6 mm.

The temperature of the weld was recorded by means of a thermocouple embedded in the tool. Fig. 2 plots the tool temperature data as a function of weld time. It can be seen that the weld temperature stayed fairly constant for the most part of the weld. The average weld temperature increased, with an increase in the tool RPM. For the most part of the welds, the tool temperature was ~ 475 °C for FSP1, and ~ 350 °C for FSP2.

The as-cast A356 material was subjected to T6 heat treatment – solutionizing the material at 535 °C for 5 h, quenching in water, and then aging at 160 °C for 5 h. We shall henceforth refer to the as-cast and T6 treated alloy as "Cast". The post weld heat treatment (PWHT) of the two FSP conditions involved solutionizing at 535 °C for only 2.5 h. The materials were then water quenched and aged at 160 °C for 5 h. The heat treatment process generated three unique microstructural conditions - Cast, FSP-AGG (from the heat treatment of FSP1), and FSP-fine (from the heat treatment of FSP2). FSP-AGG is so called because abnormal grain growth (AGG) during the heat treatment resulted in a very large volume fraction of its microstructure (~ 74%) consisting of grains larger than 100 μm, and up to a few millimeters in diameter. AGG occurred in the FSP-fine microstructure too, but not to the same extent as in FSP-AGG. The majority of the volume fraction (~ 70%) consisted of grains of diameter less than 100 μm – hence, the name, FSP-fine. A more detailed description of the microstructures is given below in Section 3.

Following the heat treatment, we milled multiple samples for mini-tensile and mini-fatigue tests using a CNC machine. For the Cast condition, we obtained the samples from a surface 2 mm below the top

Table 1
Chemical composition of A356 Al alloy used in this work.

Element	Al	Si	Mg	Fe	Sr	Ti
wt%	92.34	7.1	0.35	0.08	0.02	0.106
at%	92.68	6.78	0.39	0.038	0.006	0.06