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Effect of Process Variables on Microstructure of Cast Aluminum Alloy A356 during the Friction Stir Processing

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Abstract— **The surfaces of cast A356 plates of nominal composition (wt. %): Al-7.3 Si-0.6 Mg were subjected to Friction stir processing (FSP) to decrease the porosity level and the size of second phase particles which, in turn,will improve mechanical properties. Three tool travel and five tool rotational speeds were employed.Forthe best combinations of the process variables the alloy displayed an increase of about 31% in tensile strength and 29 % in yield strength compared with the cast alloy. The ductility increase ranged between 1.2 and 8 times the value for the cast alloy. Microscopy revealed that in the processed alloy the size of the second phase particles had decreased and this contributed to improvements in properties.**

Keywords: *Friction stir processing, Grain refinement, Tool rotational speed, Tool travel speed, Cast aluminum alloy A356.*

I. INTRODUCTION

Cast A356 aluminum alloy is used in the automotive industry for the manufacture of cylinder heads and blocks. The alloy is also used for making other engine and body parts, in which high strength is required. But, the cast alloycontains defects like porosity, formation of aluminum-silicon inter-dendritic regions etc. Therefore, their mechanical properties are poor.Friction stir processing (FSP), which is based on the same principles as Friction Stir Welding (FSW), modifies the microstructure in selective locations (usually at surfaces) by the combined effects of stirring action, frictional heat and pressure. The resulting local defect-free microstructures improve the mechanical properties and the magnitude of the change is influenced by the process and tool parameters [1]. This process is illustrated in Figure 1.It has been successfully used with different cast alloys, e.g., Mg –Al –Zn [2], Al 2285[3],NiAl Bronze [4]. In some alloys processed by FSP superplasticity have been observed, e.g., aluminum- alloys A356 [5], Al-Mg-Zr [6] Al 7075 [7, 8].However, the effects of the different process variables on friction stir processingof cast A356 aluminum alloy are not fully understood.

II. EXPERIMENTAL

Ingots of aluminum alloy A356, of composition (wt. %): Al – 0.09 Cu – 0.58 Mg – 7.36 Si – 0.42 Fe - 0.211 Mn – 0.09 Ni – 0.02 Zn – 0.09 Ti – 0.01 Pb – 0.01 Sn, were sand cast and cut into rectangular specimens of size 200 × 50 × 10 mm. A special purpose friction stir welding machine with a maximum force of 25 kN, power of 15 HP and spindle speed of 3000 rpm was used. A high carbon steel cylindrical threaded tool (British standard right handed threads with 1 mm pitch) of dimensions as given in Figure 1 was used. The work material was fixed while the FSPtool moved. Processing was completed at three different tool travel speeds (22.2 mm min^{-1}, 40.2 mm min^{-1} and 75 mm min^{-1}) and five tool rotational speeds (800 rpm, 1000 rpm, 1200 rpm, 1400 rpm and 1600 rpm). Single stir pass was used. The yield strength, ultimate tensile strength and percentage elongation were evaluated for the base and the processed material.

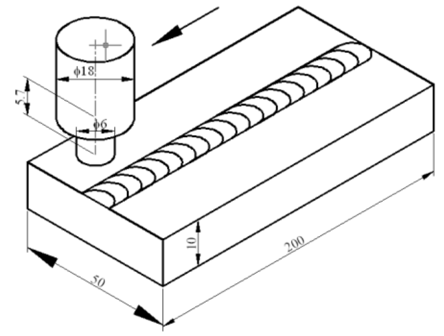
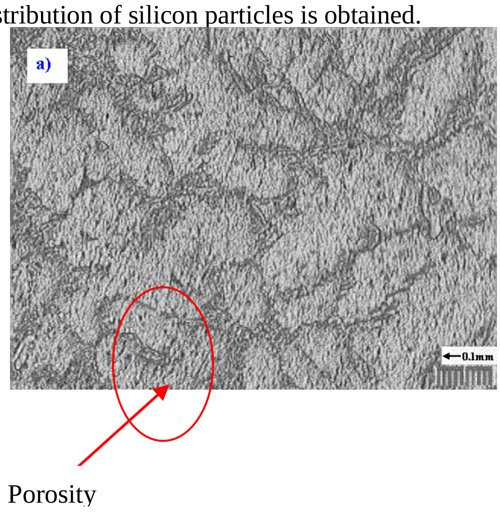


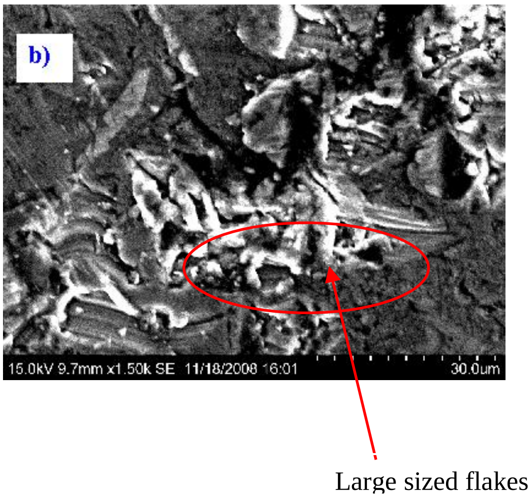
Figure 1. Friction stir processing set-up and cylindrical threaded profile tool

Specimens for tensile testing of gauge length 28 mm, gauge thickness 6 mm, fillet radius 6.5 mm, grip length 45 mm and grip width 24 mm were cut from the centre of the processing zone along the direction of processing, as per ASTM (American Society for Testing of Materials) B557M specifications. The tests were carried out on a 50 kN, electro-mechanical controlled table top tensometer. The specimens were loaded at a rate of 15 kN min^{-1} and the stress - strain curves for each combination of tool travel and tool rotational speed were recorded. Temperatures reached in the nugget zone were recorded with K type thermocouples. The microstructures of the base and the processed material were examined using optical and scanning electron microscopy. The grain morphology and size were determined. Polishing of specimens for microscopy wasdone using different grades of emery paper and diamond paste. The etchant used was 0.5% hydrofluoric acid.

III. RESULTS AND DISCUSSION

The microstructure of the parent material is shown in Figures 1 (a) – (c). The alloy consists mainly of primary aluminum and irregular interdendritic regions of aluminum-silicon eutectic. The presence of porosity, other casting defects and a non-uniform distribution of silicon particles is the reason for the poor ductility /strength of cast A356 aluminum alloy. During friction stir processing these defects are eliminated and a uniform distribution of silicon particles is obtained.





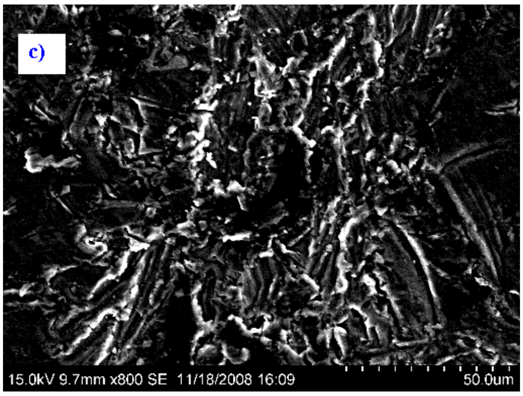


Figure 2. 1 Parent Material

a) Optical micrograph showing casting defects (the defects are indicated)

b) Defects in parent material (large sized flakes)

c) Aluminum silicon interdendritic region

A fully recrystallized microstructure containing refined aluminum-silicon eutectic grains evolves in cast A356 as a result of FSP [13, 14]. Severe plastic deformation and material flow due to the stirring action of the pin and the high temperatures to which the material is exposed during FSP (due to adiabatic heating) lead to the recrystallization of grains.The refined microstructure contributes to improvements in mechanical properties. This has been confirmed in earlier studies on different aluminum alloys also [15,16]. FSP results in significant microstructural evolution within and around the stirred zone. Tables 1-3 display the microstructures of the nugget zone obtained under different tool travel and tool rotational speeds. In most of the processed specimens higher tool rotational speed resulted in a more uniform distribution of, what appear to be, particles of aluminum silicates and globular magnesium silicideparticles (length /width ratio ~ 1). The specimens processed at 1000 rpm and 1200 rpm tool rotational speeds did not reveal the presence of defects.

TABLE I. EFFECTS OF ROTATIONAL SPEED ON MICROSTRUCTURE OF FSP SPECIMENS (AT A TOOL TRAVEL SPEED OF 75 MM MIN^{-1})

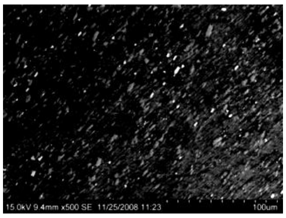
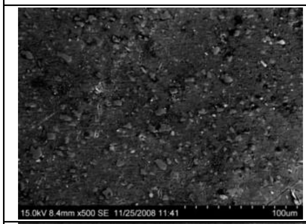
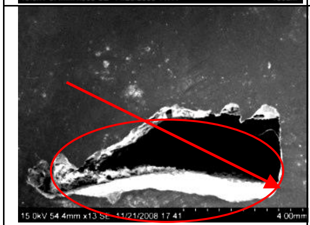
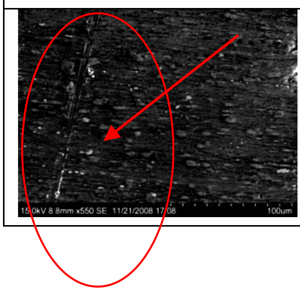
SEM Micrograph	Speed (rpm)	Observations	Possible Reasons
	800	Tunnel defects and pinhole defects are observed.	A high tool travel speed might have been the reason for the low strength.
	1000	Very fine particles, with flow oriented towards the advancing side of the tool, are observed.	The fine particles might have been the result of an optimal temperature generated by this combination of tool travel and rotational speeds.
	1200	Good consolidation and fine breaking of the particles are observed.	The recrystallized and refined equiaxed particles might have contributed to the superior mechanical properties.
	1400	A big tunnel defect is observed in the FSP specimen.	This defect might have been the result of high temperature at this tool rotational speed and poor cooling rate due to the high travel speed. However, the specimen might have had some high strength particles in a fairly ductile matrix which held together in spite of the defect and led to very high ductility but poor strength.
	1600	Lengthy cracks are observed in addition to the good distribution of particles are observed	The high tool travel speed may have been the cause of poor consolidation of material and the defect. Hence the low strength observed in this specimen

TABLE II. EFFECTS OF ROTATIONAL SPEED ON MICROSTRUCTURE OF FSP SPECIMENS
(AT A TOOL TRAVEL SPEED OF 40.2 MM MIN^{-1})

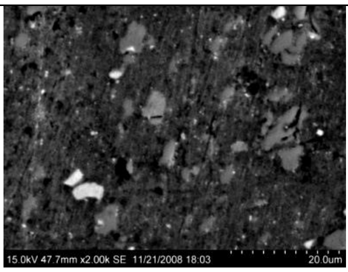
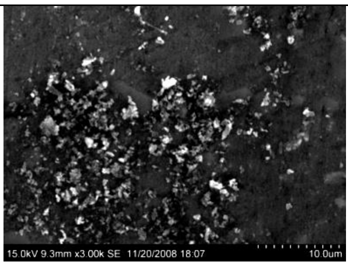
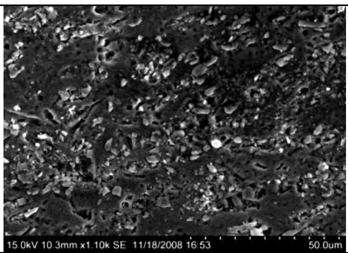
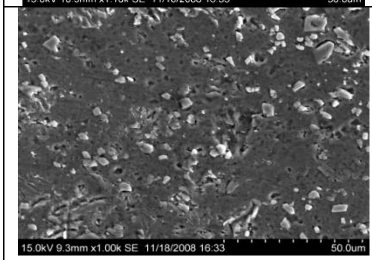
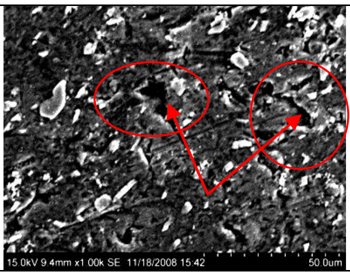
SEM Micrograph	Speed (rpm)	Observations	Possible Reasons
	800	Poor breaking and distribution of particles is observed. Concentration of particles is observed in certain places.	A low heat generated with a higher tool travel speed may have resulted in the defects and the inhomogeneous redistribution of particles.
	1000	A uniform size and distribution of aluminum silicates [12, 13] and magnesium silicides are observed.	The near-globular, extremely refined and recrystallized particles may have contributed to the increase in strength.
	1200	Very fine particles with scattered and highly precipitated magnesium silicides are observed. Along with varied sizes, a major fraction of globular particles is observed.	The tool travel and rotational speeds might have contributed to a sufficient and optimal temperature so that the strength is high. Even so, a few minor defects present might have been a factor in the fall in strength compared with the FSP specimen of same tool travel and 1000 rpm rotational speeds.
	1400	Very fine, recrystallized particles are observed. In addition, a number of pores and voids are present.	The presence of a number of defects contributes to the loss in strength.
	1600	Break up of the lamellar aluminum silicate is observed, along with a number of pores, voids and scratches.	A very high temperature might have led to an excessive release of stirred material and hence the defects and the low strength.

TABLE III. EFFECTS OF ROTATIONAL SPEED ON MICROSTRUCTURE OF FSP SPECIMENS

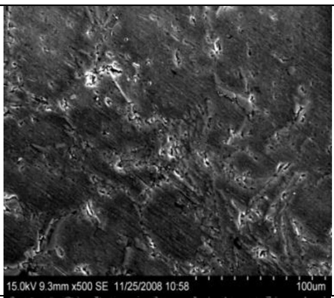
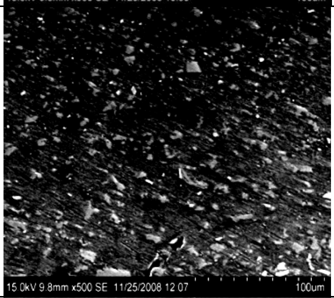
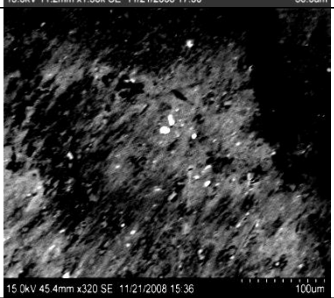
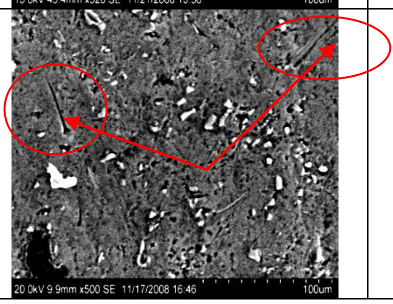
SEM Micrograph	Speed (rpm)	Observations	Possible Reasons
	800	Micropores and coagulated particles are observed. Aluminum oxide particles are seen as white particles.	The pores may be due to low temperatures generated at low tool rotational speeds.
	1000	Breaking up and uniform distribution of recrystallized (probably) aluminum silicate eutectic is observed throughout the specimen.	This speed combination may be optimal for both grain refinement and preventing grain growth. This leads to higher strength.
	1200	Very fine broken up dark particles, most probably magnesium silicides along with aluminum silicates are observed along the direction of tool travel.	This breaking up and a near- globular eutectic particles contribute to the higher strengths.
	1400	Plastic flow of grains of the eutectic material towards the advancing side of the FSP region is observed. Micropores and pinhole defects are also seen.	A higher temperature with improper material flow might have contributed to the low strength.
	1600	Defects such as cracks, scratches and pinholes are observed. Some burnt grains are also seen.	Due to very high heat input, localized melting/burning of aluminum silicate particles of low melting temperature might have led to the formation of localized voids.

Figure 2 illustrates the relation between the particle size (µm) and tool rotational speed (rpm), along with the base metal grain size. A higher tool rotational speed reduces the grain/ particle size, although a very high tool rotational speed coarsens the particles.The same reasons assigned earlier for the variations in the mechanical properties on changing the tool rotational speed are relevant here also.

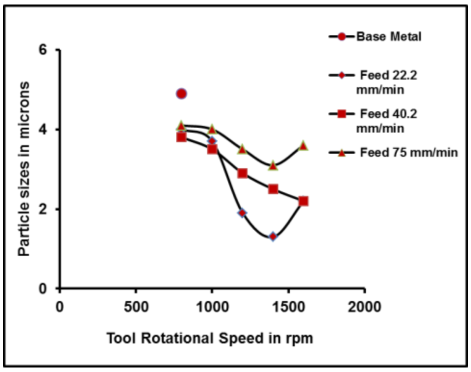


Figure 3. Influence of tool rotational speed on the particle size

IV. CONCLUSIONS

Cast A356 grade aluminum alloy was friction stir processed at different tool travel and rotational speeds. The following conclusions could be drawn.

i) The microstructure is considerably altered for all combinations of tool travel and rotational speeds.

ii) A defect-free microstructure and good mechanical properties are obtained in friction stir processed specimens at all tool travel speeds corresponding to the tool rotational speeds of 1000 rpm and 1200 rpm.

V. ACKNOWLEDGEMENTS

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