Effect of Process Variables During The Friction Stir Processing of Cast Aluminum Alloy A356

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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 alloy contains 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 processing of 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.

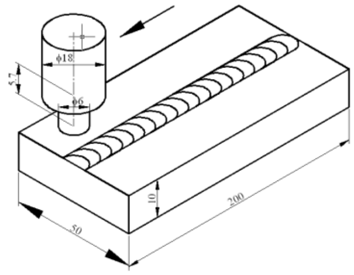

Figure 1. Friction stir processing set-up and cylindrical threaded profile tool

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 was done using different grades of emery paper and diamond paste. The etchant used was 0.5% hydrofluoric acid.

III. RESULTS AND DISCUSSION

A. Evaluation of mechanical properties

a. *Evaluation of mechanical properties*

The room temperature mechanical properties of the base and the friction stir processed material under different conditions are presented in Table 1.It is clear that for certain combinations of tool travel and rotational speeds, the friction stir processed specimens displayed superior mechanical properties compared with those of the base material. The ductility of all the FSP specimens was greater.

TABLE I. MECHANICAL PROPERTIES AT THE CENTRE OF THE NUGGET ZONE AND THE BASE MATERIAL

S. No.	Tool travel speed (mm minute^{-1})	Tool rotational speed (rpm)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Ductility (%)
1	22.2	800	100	123	4.3
		1000	99	136	7.0
		1200	103	137	5.3
		1400	102	125	3.9
		1600	64	91	3.8
2	40.2	800	103	114	4.1
		1000	165	173	8.0
		1200	86	144	5.8
		1400	90	126	3.1
		1600	85	117	3.1
3	75	800	85	120	2.1
		1000	85	145	3.0
		1200	124	144	3.3
		1400	98	99	15.5
		1600	94	96	2.2
4	Base Metal		127	132	1.9

Defects like porosity, cracks, blow holes etc. are common in cast aluminum alloys. They also display a dendritic microstructure. Due to these defects and an in homogenous microstructure, poor mechanical properties and low elongation to failure are observed. In contrast, as a result of friction stir processing, the dendritic microstructure is broken up by the mechanical stirring action of the tool pin and the defects in the castings are eliminated also by the frictional heat. As a result, the mechanical properties of the processed specimens are superior to those of the base material. But accprding to Elangovan and Balasubramanian [9] defects like piping defect, tunnel defect, pinholes etc. are present even after FSP, due to insufficient heat input, improper plastic flow and/or material consolidation. Therefore, it is important to understand the effects of the process parameters and the range over which a defect-free friction stir processed specimen can be obtained.

The true stress- true strain response of the friction stir processed A356 material at different tool travel and rotational speeds is presented and compared with that of the base material in Figures 2 (a) – (d). Both these variables are found to affect the properties strongly. At any tool travel speed, a lower tool rotational speed gives rise to a lower temperature rise. This results in poor stirring action and consolidation of material. As a result, the strength and ductility properties are rather low. With increasing tool rotational speed, a higher increase in temperature is present in the nugget zone and this causes a greater refinement of grains and leads to enhanced properties. A monotonic increase in mechanical properties with tool rotational speed is not expected. A very high tool rotational speed decreases both strength and ductility because in that case, higher temperatures and lower cooling rates are encountered. This leads to an excess release into the stirred zone of material containing microvoids [10]. The net result is that, the yield and tensile strengths and the ductility properties go through a maximum with increasing tool rotational speed. Evidently the tool rotational speed is an important variable in producing a defect-free stirred zone. In the present investigation materials processed at tool rotational speeds of 1000 and 1200 rpm displayed increased tensile strengths and ductility properties at all tool travel speeds.

Tool travel speed also affects the strength and ductility of friction stir processed A356 samples significantly. An increase in tool travel speed, at a given tool rotational speed, reduces the time of exposure of the material to frictional heatconsiderably. At high tool travel speeds heat produced by friction may be insufficient to plastically deform the materialand then the processed zone will contain defects. In contrast, at low tool travel speeds, grain growth and as a consequence, inferior mechanical properties result. Therefore, it is equally important to determine the optimal tool travel speed that produces a defect-free nugget zone. In this study, specimens processed at a tool travel speed of 40.2 mm min-1 displayed good mechanical properties and the nugget zone was defect-free.

Santella et al. [11] have reported that in cast aluminum alloy A356, due to microstructural refinement and reduced porosity, FSP led to an increase in ductility ranging from 3% to 12%. It is seen in Table 1 that for many combinations of tool travel and rotational speeds moderate to high ductility increases from 1.2 to 8 times the value for the cast alloy are obtained. The FSP specimens also displayed an increase of 31% in tensile strength and 29% in yield strength. Similar increases in the values of mechanical properties for cast A319 aluminum alloy, subjected to friction stir processing has been reported [12]. Figure 2 (d) presents the true stress - true strain curve of a specimen friction stir processed at a tool travel speed of 75 mm min-1 and rotational speed of 1400 rpm. In this case a high elongation to failure is obtained even though a large tunnel defect is present. The tunnel defect, marked in the scanning electron micrograph of the processed specimen corresponding to the above tool travel and rotational speeds, is marked in Table 2. In addition, Fig. 2(d) displays a stress- strain plot which is suggestive of rigid, ideally plastic behavior (no work hardening). This might have been due to (a) the specimen temperature nearing 300°C, which is well into the hot working range for this alloy, but sufficiently low to avoid grain growth, and/or (b) work hardening cancelling the material softening resulting from the presence of the tunnel defect.

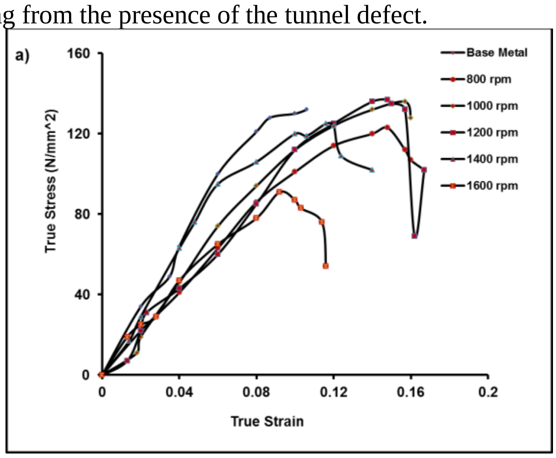

Figure 2. True stress – true strain curves for material processed at different tool travel and tool rotational speeds

a) at a tool travel speed of 22.2 mm min^{-1} and tool rotational speeds of 800, 1000, 1200, 1400, 1600 rpm

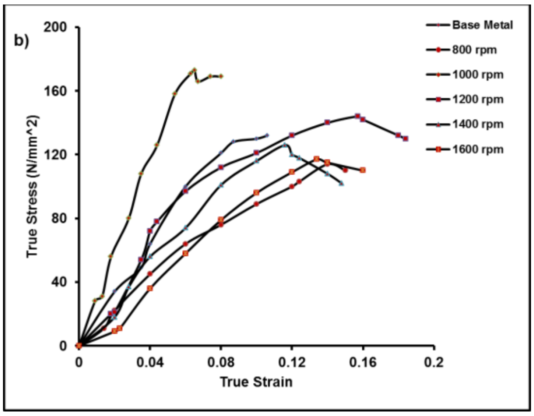

Figure 3. True stress – true strain curves for material processed at different tool travel and tool rotational speeds

b) at a tool travel speed of 40.2 mm min^{-1} and tool rotational speeds of 800, 1000, 1200, 1400, 1600 rpm

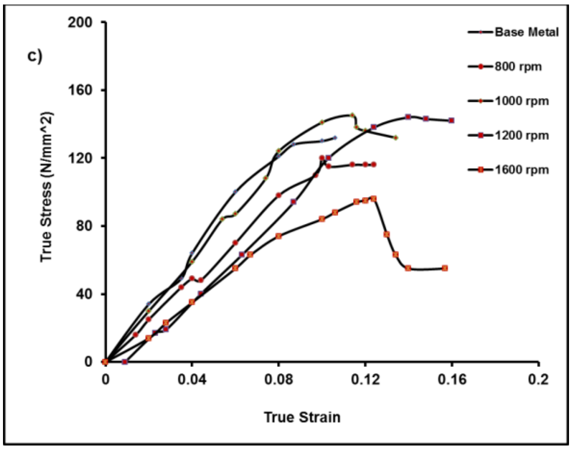

Figure 4. True stress – true strain curves for material processed at different tool travel and tool rotational speeds

c) at a tool travel speed of 75 mm min^{-1} and tool rotational speeds of 800, 1000, 1200, 1600 rpm

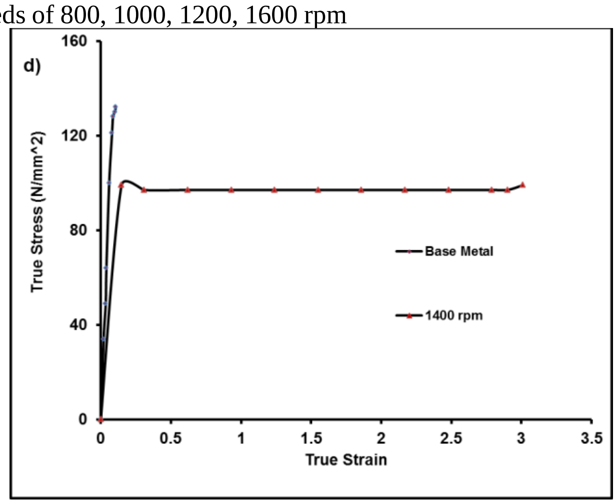

Figure 5. True stress – true strain curves for material processed at different tool travel and tool rotational speeds

d) at a tool travel speed of 75 mm min-1 and tool rotational speed of 1400 rpm

Figure 6 is a record of the temperatures present in the nugget zone corresponding to various tool rotational and travel speeds. In FSP, heat is generated by a combination of friction and plastic dissipation during deformation. The maximum temperature in the nugget zone rises initially with tool rotational speed but falls slightly at the higher speeds. In contrast, with increasing travel speed the temperature in the stir zone falls. Generally, a combination of a high tool rotational speed with a low travel speed results in a hotter specimen and a combination of a low tool rotational speed with a high tool travel speed gives rise to a colder specimen. This is because with increasing tool travel speed, less heat generation and faster heat dissipation are present and hence the decrease in temperature.

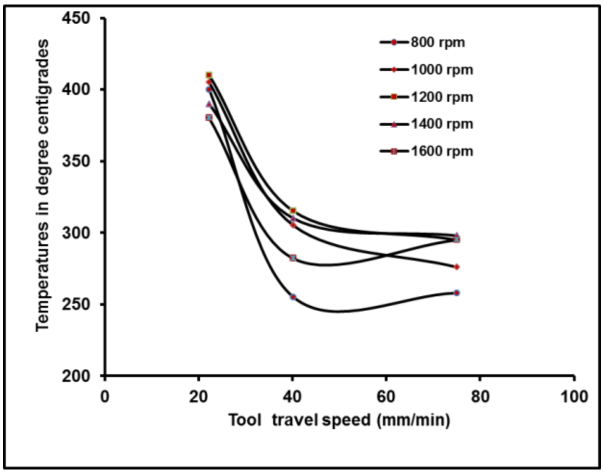

Figure 6. Temperatures at the center of the nugget zone for various tool travel and rotational speeds

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 variables tool travel and rotational speeds influence the properties resulting from friction stir processing significantly.
ii. Ductility increases ranging from 1.2 to 8 times the value for the cast alloy were recorded in the FSP specimens.
iii. Increases of around 31% in tensile strength and 29% in yield strength could be obtained.

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REFERENCES

[1] K. Elangovan, V. Balasubramanian, S. Babu, J. Mater. Des. 30 (2009) 188-193.
[2] A.H. Feng, , Z.Y.Ma, Scr. Mater. 56 (2007) 397-400.
[3] L.Karthikeyan, V.S.Senthilkumar, D.Viswanathan, S.Natarajan,J. Mater. Sci. Technol. 23 (2007) 614-618.
[4] Keichirro oh-Ishi, Terry R.Mcnelley, Metall. Mater. Trans. A36 (2005) 1575-1585.
[5] Z.Y.Ma,R.S.Mishra, M.W.Mahoney, Scr. Mater. 50 (2004) 931-935.
[6] Z.Y.Ma, R.S.Mishra, M.W.Mahoney, R.Grimes,Mater. Sci. Eng.,A351 (2003) 148-153.
[7] A.Dutta, I.Charit,L.B. Johannes, R.S.Mishra,Mater. Sci. Eng., A 395 (2005) 173–179.
[8] P.Cavaliere, A.Squillace, Mater.Charact. 55 (2005) 136-142.
[9] K.Elangovan,V.Balasubramanian, J. Mater. Des.29 (2008) Pages 362-373.
[10] K.Elangovan,V.Balasubramanian,Mater. Sci. Eng., A 459 (2007) Pages 7-18.
[11] M.L.Santella,T.Engstrom, D.Storjohann, Pan.T.Y., Scr. Mater. 53 (2005) 201-206.
[12] L. Karthikeyan, V.S. Senthilkumar, K.A. Padmanabhan, J. Mater. Des. (2009), doi:10.1016/j.matdes.2009.08.001.
[13] Z.Y.Ma,S.R.Sharma,R.S.Mishra,Mater. Sci. Eng.,A 433 (2006) 269-278.
[14] S.R.Sharma,Z.Y.Ma, R.S.Mishra,Scr. Mater.51 (2004) 237-241.
[15] L.Karthikeyan, V.S.Senthilkumar, V.Balasubramanian, S.Natarajan, Mater. Des. 30 (2009) 2237-2242.
[16] M.D. Fuller, S. Swaminathan, A.P. Zhilyaev,T.R.McNelley,Mater. Sci. Eng.,A 463 (2007) 131.