Effect of Friction Stir Processing on Mechanical Properties and Microstructure of the Sand Casting Eutectic Al-12wt%Si Alloy

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Abstract: ***Friction stir processing (FSP) has the potential for locally enhancing the properties of eutectic Al-12wt%Si alloy. A cylindrical tool with threaded pin was used. The effect of FSP has been examined on sand casting eutectic Al-12wt %Si alloy .The influence of different processing parameters has been investigated at a fundamental level. Effect of (FSP) parameters such as transverse speed (189) mm/min, rotational speed (560,710, 900) rpm on microstructure and mechanical properties were studied. Different mechanical tests were conducted such as (tensile, micro hardness and impact tests). Image analysis of particle size distributions were used to quantify the level of particle refinement and the homogeneity of the second phase distribution. Hardness and impact measurements were taken across the process zone (PZ), and tensile testing was carried out at room temperatures. After FSP, the microstructure of these alloys was greatly refined. However, differences in microstructure have been observed throughout the process zone (PZ), which tended to be better refined and distributed on the advancing side than the retreating side of the PZ. FSP caused very little changes to the hardness of the material, while tensile and impact properties were greatly improved.***

Keywords: Friction stir processing, (FSP), Microstructure, Mechanical Properties.

1. Introduction

Recently a new processing technique, friction stir processing (FSP), was developed by Mishra et al, Friction stir processing (FSP) is based on the basic principles of friction stir welding developed by the Welding Institute (TWI) of United Kingdom in 1991 to develop local and surface properties at selected locations**[1]**,and the following unique features of friction stir welding can be used to develop new processes based on the concept of friction stirring, low amount of heat generated, extensive plastic flow of material, very fine grain size in stirred region, healing of flaws and casting porosity, random misorientation of grain boundaries in the stirred region, mechanical mixing of the surface and subsurface layers . In this case, a rotating tool with pin and shoulder is inserted in a single piece of material, for localized micro structural modification for specific property enhancement [1, 2]. Furthermore, the FSP technique has been used for the fabrication of a surface composite on aluminum substrate [3], and the homogenization of powder metallurgy (PM) aluminum alloys, metal matrix composites, and cast aluminum alloys [4,5].

2. Experiment Work

In this study includes the experimental work used for this research to assess the effect of FSP on the microstructure and mechanical properties of eutectic Al-12%Si alloy. The mechanical properties of the material, before and after FSP, were measured via hardness, impact and tensile testing. The material used for friction stir processing experiment was eutectic Al-12wt%Si alloy throughout this investigation .The chemical analysis of this alloy, as following(Al-99.7%,Si-99.9588%),shown in Table(1). .

Table 1: Composition of eutectic wt%Si alloy used in the experiments

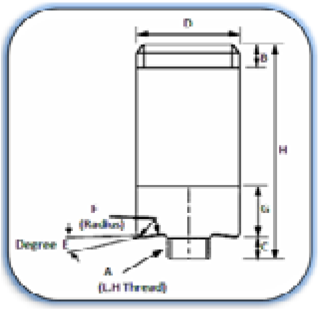
Alloy	*Si*	*Cu*	*Ni*	*Mg*	*Fe*	*Mn*	*Zn*	*Ti*	*Zr*	*V*	*Pb*	*Sn*	*AL*
AL-12wt%Si	12	0.0117	0.001	0.0003	0.23	0.0006	0.008	0.001	0.0003	0.004	0.0005	0.001	Bal

The casting process include sand mould casting for this alloy, were prepared separately by melting, pure aluminum (99.7%) with pure silicon (Si-99.9588%), in clay bonded graphite crucible using gas furnace and the melts were held at 900 ˚C with the continuous mixing by graphite mixer until all the silicon quantity are dissolved in the aluminium melt. Mould as size (200mm x 130 mm) plate, with a thickness of 15mm. The material was then air cooled back down to room temperature, therefore due to non-uniform cooling and shrinkage from casting, the surfaces of the plates were rough and uneven. Therefore, in order to generate flat surface for FSP, 2mm of material was milled away from the top and bottom surface of each plate before FSP. The friction stir processing experiment has been carried out using tool made from alloy steel (X12)which is tool, bearing and die steel, with chemical composition listed in Table(2) .

Table 2: Chemical Composition (weight %) of the FSP tool

C	*Cr*	*Mn*	*Si*	*Fe*
2.00-2.30	11.5- 13.00	.30-.35	.34-.40	Rem.

FSP tool is designed and machined as shown in Fig. (1).



A	M6×1LH
B	21 mm
C	6 mm
D	Ø=31.5 , 22turn per inch
E	10°
F	2.96 mm
G	22 mm
H	120 mm

Figure 1: Dimension of the friction stir processing

The FSP conditions used with this alloy as shown in Table (3).

Table 3: The processing parameters used in the investigation

Alloy	*Travel Speed (mm/min)*	*Rotation Speed (RPM)*		
		560	710	900
AL-2 wt%Si	189	X	X	X

Experiments were limited to seven FSP passes on each plate. Each run was offset by 11mm between the next pass as shown in fig. (2) . . .

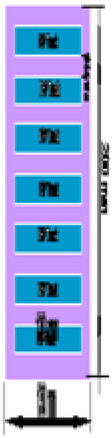


Figure 2: Schematic representation of the plates used for the experiments, showing the positions of the FSP tracks

Uniaxial tensile test was performed by gripping a specimen at both ends and subjecting it to increase axial load until it breaks. Recording of load and elongation data during the test allows the investigator to determine several characteristics about the mechanical behavior. So to perform tensile test the tensile specimens prepared as follows: 1. Cutting 10 mm width pieces from the process zone plates in, parallel to the processing direction, using horizontal milling machine. 2.Making tensile specimens using vertical milling machine according to the ASTM B 557 M-02a sub size specimen geometry shown in Fig.(3).

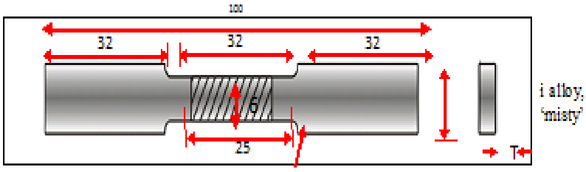


Figure 3: ASTM sub-size sample for tensile test (dimensions are in mm)

3. Removing thin layer from the top and bottom surface using vertical milling machine. 4. Smoothing the tensile specimens using abrasive paper to ensure there is no surface scratches. **Micro hardness testing** was used using a (Digital Micro hardness tester HV- 1000) TH-717 type; it is to determine the hardness over small positions on the surface of base metal, TMAZ, HAZ and process nugget to indicate the variation in hardness for each place, in accordance with ASTM E3841. A load of 200 g was employed and loading time was 20 seconds. **The specimens for microstructure test** were prepared in consistent with the standard metallographic techniques. The ultimate objective of such a process was to obtain a flat scratch free, mirror like surface. **The impact tests** were carried out on processed samples using an instrumented pendulum machine. According to ASTM E23, Sub-size charpy V specimens (10 X 5 X 55) mm^3, with 2mm deep V- notch, were used for the tests.

3. Results and Discussion

3.1 Microstructures Prior to FSP

3.1.1 Grain Structure Analysis

Before FSP, the grain structures of hypoeutectic Al-12wt%Si alloy after casting were found to be very coarse. In addition, the grains closer to the surfaces of the plates were also found to be finer than those developed at the centre of the material, due to the higher cooling rate.

3.1.2 Grain Refinement in FSP

The experiments discussed and mainly concentrate on the effect of FSP on the eutectic Al-12wt%Si alloy, with a view to first providing an overview of the general effects observed in FSP, before focusing in more depth on specific areas of interest. In general, the microstructure of the cast Al-Si alloys was found to be greatly refined by FSP, as has been reported previously by other authors **[6, 7]**. Images of a typical FSP track, processed at a transverse speed of 189 mm/ min and a rotation rate of 710 rpm, are shown in fig.(4), where the sample has been anodized, and the region indicating the processed zone (PZ) marked.

Figure 4: Images of the cross section from a friction stir processed track; produced in eutectic A1-12wt%Si alloy, using a, transverse speed of 189 mm/min and rotation rate of 710 RPM. The process zone (PZ) appears 'mistry' white in the image

Optical micrographs taken from the as-cast material are shown and compared to that of the advancing and retreating side of the PZ at the mid-plane in fig.(5).

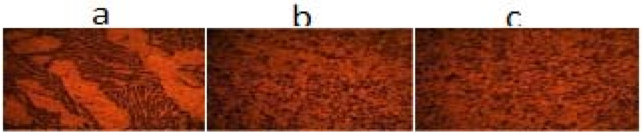


Figure 5: Optical micrographs of the (a) original cast microstructure of eutectic A1-12wt%Si alloy, and after FSP, with a 189 mm/min travel speed and 710 RPM rotation rate, from (b) the advancing edge and (c) retreating side, at mid-depth of the PZ

After FSP, all the second phase particles (Si) were greatly refined .As a result, a clear reduction in size and aspect ratio can be observed, and this was expected, since the Si flakes and coarse eutectic particles are readily broken up by the rotating tool during FSP **[6,7].** Atypical image of the PZ, with key regions highlighted, produced by FSP with a transverse speed of 189 mm/ min and a rotation rate of 710 rpm is shown in fig. (6a). In general, the PZ develops several observable features. Firstly, towards the retreating edge of the PZ, where the particles tended to be larger and less uniformly distributed. This region of the PZ is termed the ‘flow arm’ [**8**], and was generated by the trailing rear of the tool shoulder, which rotates over the material that the tool pin passed through, causing material to be dragged across the weld from the less deformed TMAZ into the PZ. It can further be seen in fig. (6b) that the boundary between the PZ and the TMAZ on the advancing edge was found to be defined by a sharp transition, from the coarser unaffected microstructure to the refined microstructure containing fine and homogeneous distributed particles. On the other hand, the transition region on the retreating edge was wider, and the particles showed a more gradual change in size (fig.6c). In general, the refined particles were found to be finer and more homogenous on the advancing side than the retreating side of the PZ. This finer distribution of particles can be observed throughout the advancing side in fig. (6). However, from the centre line to the retreating side of the PZ, the particles were coarser and less homogeneously distributed (see fig.5).Finally, moving into the process zone boundary, the particles progressively increased in size, back to that of the particles within the parent material.

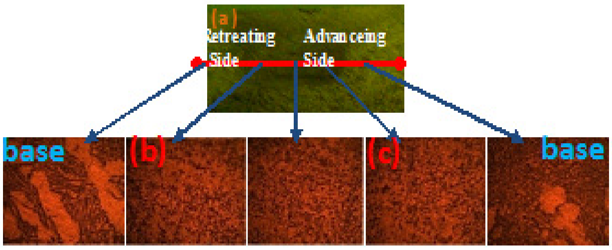


Figure 6: (a) image showing example of the main feature seen within a typical PZ, generated with a transverse speed of 189 mm/min and a rotation rate of 710 RPM of eutectic A1-12wt%Si alloy. High magnification optical show (b) the transition layer on the retreating side, (c) the traition layer on the advancing side

3.2 Impact Test Results.

The results of the charpy impact test for eutectic Al-12wt%Si alloy as show fig (7). This significant increase in the total absorbed impact energies can be related to the micro structural changes induced by the FSP, such as grain refinement and dynamics recrystallization of process zone which result in remove strain hardening effect. Another observation of impact results are transverse speed effect, where increasing transverse speed, the absorbed energy decreased due to little rate of softening of process zone and high density of dislocations. Also, increasing the rotational speed results in decreasing absorbed energy similarly as **[9].**

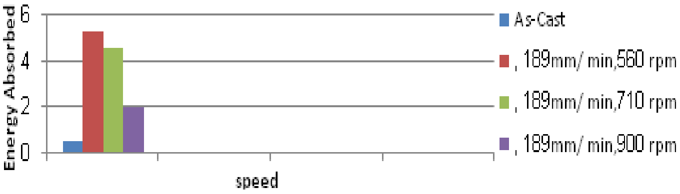


Figure 7: Interactive effect of tool rotational speed and transverse speed on energy absorbed of the PZ of eutectic A1-12wt%Si alloy after FSP

3.3 Tensile Test Results

In order to determine the tensile strength of the FSP material, tensile samples were cut from the PZ parallel to the transverse direction. The results of the tensile test listed in the Tables (4) (average values on three tests).the mechanical properties of the as-cast alloy was very poor. Typical stress strain curves shown in fig. (8). It is possible to see that the mean ultimate tensile strength (UTS) of eutectic Al-12wt%Si alloy was only 123 MPa, with total elongation of 5.8% to failure. This is mainly due to the presence of large pores and brittle Si particles, which existed within the material after casting and acted as crack nucleation and propagation sites **[10].** Directly after FSP, the alloys demonstrated significant improvements in tensile properties. The UTS of this alloy was increased to greater than 159 MPa, and ductility higher than 14%, which is mainly due to the elimination of porosities and the refinement of the microstructure. Other researchers have shown that the tensile properties of cast Al-Si alloys increased with decreasing pore size and density **[11].** It is notable that the sample processed at 710 RPM appeared to show better properties than the material processed at 560 RPM. This difference is most likely related to the processing temperature experienced by the material during FSP.

Table 4: Result of the tensile test for eutectic A-1-12wt%Si alloy

Sample Number	*Tool rotating speed (RPM)*	*Transverse Speed (mm/min)*	*Tensile Strength (MPs)*	*Yield Strength (MPs)*	*Total Elongation (%)*
AS CAST			123	105	5.8
AS FSP1	560	189	132	88	14.5
AS FSP2	710	189	160	91	14.5
AS FSP3	900	189	67	58	6.6

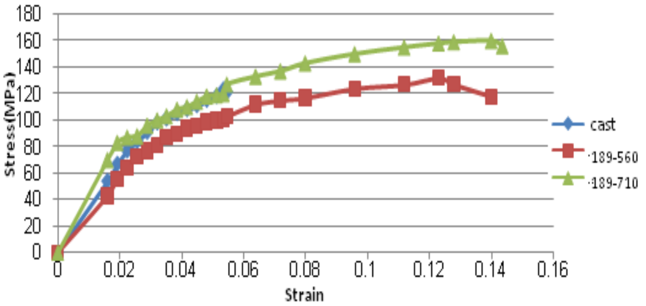


Figure 8: Typical stress strain curves tested at for eutectic Z1-12wt%Si alloy samples friction stir processed at a transverse speed of 189 mm/min, and a rotation rate of (a) 560 RPM and (b) 710 RPM

3.4 Hardness Test Results

The hardness values of the original as-eutectic Al-12wt%Si alloy had hardness (64Hv) of cast alloy. After FSP, there appeared to be only small changes in hardness for eutectic Al-12wt%Si alloy within the PZ .It has been demonstrated that refinement of the microstructure resulted in very little influence on the hardness of the material. While the high volume fraction of the second phase particles that exist within the alloy can potentially increase hardness by constraining yielding through load transfer, and enhanced work hardening, this does not appear to result in much variability in hardness across the processed tracks. The results of hardness test for alloy shown in fig (9). The hardness profiles across the PZ of Alloy after FSP at different rotation rates are summarized in fig. (17).Such a behavior has not often been observed in non-heat treatable alloys, which tend to show an improvement to the hardness due to the refinement in microstructure [12]. Finer elongated fragments. The different size and geometry of the Si particles was caused by the original difference in low aspect ratio and size between the original eutectic and primary particles.

1) Very little change in material hardness was observed after FSP. It has been shown that the refinement of the microstructure demonstrated very little influence to the hardness of the material.
2) From tensile experiments, the tensile property of the as-cast eutectic Al-12wt%Si alloy was found to be very poor. the base of the PZ. A towards the retreating edge of the PZ, where the particles tended to be larger and less uniformly distributed Failure was dominated by the link up of voids in high porosity density regions. However, the ductility of the material was greatly improved after FSP.
3) For eutectic Al-12wt%Si alloy, impact energies increased in FSP material with respect to the corresponding base metals, from (0.5 J), B.M. impact energy, to (5.3 J) for FSP1, (560 RPM, 189 mm/min) .

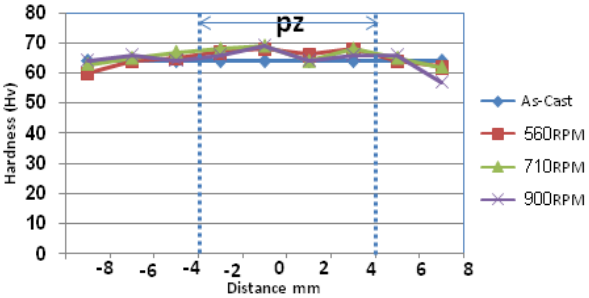


Figure 9: Hardness Profiles across the PZ of eutectic A1-12wt%Si alloy after FSP at a transverse speed of 189 mm/min and increasing rotation rate

4. Conclusions

The mechanisms of particle refinement during FSP of eutectic Al-12wt%Si alloy, and the effect of various processing parameters on particle refinement have been studied in detail. The main findings are summarized below:

1) The microstructure of eutectic Al-12wt%Si alloy was greatly refined after FSP. However, micro structural homogeneity was not necessarily achieved throughout the processed zone.
2) The PZ was found to develop a basin geometry in cross section, which was widest at the surface and shrink towards the base of the PZ. A towards the retreating edge of the PZ, where the particles tended to be larger and less uniformly distributed.
3) The affect of FSP on cast eutectic Al-12wt%Si alloy were investigated .The results showed that, after FSP, primary Si particles appeared to break up as larger fragments , with

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Author Profile

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