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Surface Modification of Cast Al-17%Si Alloys using Friction Stir Processing

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Abstract

The scope of this investigation is to evaluate the effect of input process parameters of friction stir processing to enhance the mechanical and tribological performance of the cast hypereutectic Al-17%Si alloy. Towards this end, the workpiece material of Al-17% Si alloy was cast to friction stir processing and the effect of process parameter such as tool transverse speed (26, 40, and 60) mm/min, at fixed tool rotational speed 664 rpm on the surface characteristics of the cast Al-Si alloy was studied. The results were compiled by using optical microscope, FESEM, hardness, tensile and EDX analysis. The results shows at the optimal input conditions of friction stir processing, the microstructure of cast alloy has been improved in terms of refinement of eutectic and primary Si particles, uniform distribution of Si and the reduction in porosity. In addition, the hardness and tensile properties were improved, the tensile elongation has been increased from < 2 % to about 9 %.

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Keywords: friction stir processing; Al-17%Si alloy; hardness, microstructure; tensile strength

1. Introduction

Now-a-day's aluminium-silicon alloys are in great demand in the field of defense, automobile, and aerospace industries. These alloys are known for its light weight, high thermal conductivity, and low coefficient of thermal expansion, high wear resistance, and high strength [1-3]. They are commonly used in engine components like

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connecting rod, pistons, housings, marine fittings and water manifolds[4]. Unfortunately, porosity, unfavourable shrinkage behaviour, segregation of the massive primary Si particles and coarse eutectic structure are considered as the main disadvantages of such alloys when used in conventional casting methods. These microstructural defects significantly deteriorate the mechanical properties of hypereutectic Al–Si alloys. Mechanical properties can be improved by breaking the coarse primary silicon into fine particles and eliminating the porosities using friction stir processing process[5]. Composites materials are the multi-functional materials that are having unprecedented properties. They can be utilized for the requirements of any application. The mechanical properties mainly ductility and toughness deteriorates with increase in the silicon content. Further, the reason behind limitation in applicability of composites in machinablity is the coarse primary Si particles [6].

Surface modification is the act of enhancing the surface properties by modifying chemical and physical properties, which was the different from the ones originally from material surface. Surface modification techniques can be classified as: first, surface modification by adding new material onto the surface such as welding (gas, arc, plasma etc.), thermal spraying (flame, arc, plasma, detonation etc.), cladding (brazing, explosion bonding, diffusion bonding etc.) and vapour deposition (chemical and physical). Second, surface modification by changing surface chemically such as Thermo chemical diffusion process, Electrochemical process, and Chemical conversion coatings (carburizing, nitriding, sulphurising etc.) and third, surface modification without changing the material chemically such as mechanical treatment (shot peening, deep rolling, shot blasting and friction stir processing) and thermal treatment (ion implantation, laser beam treatment and electron beam process).

Aluminium alloys are distinguished according to their major alloying elements. Si is really good in metallic alloys, because decreases the melting temperature and shrinkage during solidification, enhances the fluidity of the melt and is very cheap as a raw material. Due to these properties there has been a quick enhance in the demand of Al-Si alloys in the last few years, mainly in the automobile industries, because it has light weight, high strength, lesser wear rate and lesser density as compare to other metallic alloys [7]. The improvements in the area of automobile, military and other engineering industries create the requirement of study of their tribological and mechanical performance, because, use of Aluminum-Silicon alloys in recent years as a tribological parts. Based on Si wt percentage, the Aluminum-Silicon alloys are divided into three categories:- Hypoeutectic (<12 wt % Si), Eutectic (12-13 wt % Si), Hypereutectic (14-25 wt % Si) as shown in Fig.1.

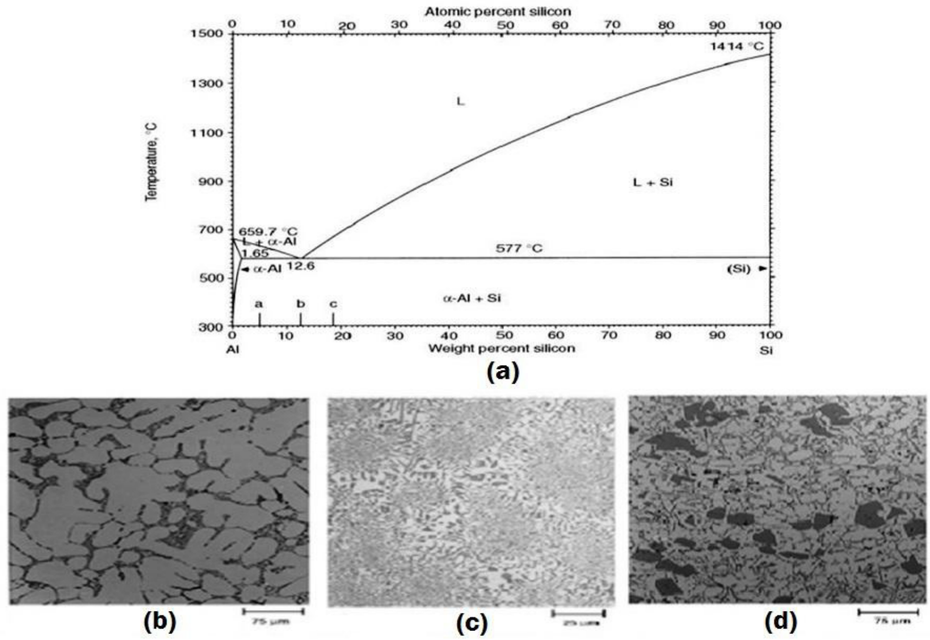

Fig. 1. (a) Al-Si equilibrium diagram of Al-Si alloy; (b) Microstructure of hypoeutectic alloy (1.65-12.6 wt% Si); (c) Microstructure of eutectic alloys (12.6% Si); (d) Microstructure of hypereutectic alloy (>12.6% Si) [7].

2. Friction Stir Processing

Friction stir processing (FSP) is a modification of friction stir welding (FSW) process. In 1991, a joining process invented by Wayne Thomas at TWI is known as the Friction stir welding process. It is a widely used technique for joining of Al alloys, because Al alloys are very poor to fusion weld. The main difference between those processes that FSP does not join materials, but can locally enhances the mechanical and tribological properties of materials like reducing casting defects, improve ductility and strength, refine microstructure, superior wear resistance and improve fatigue and resistance to corrosion. The basic principle of FSP is similar to FSW. Friction stir processing technique is widely used as solid state processing process and a surface-engineering technology. Furthermore, the FSP technique has been utilized as surface composite fabrication on Al alloy substrate, MMC's, and cast Al alloys [7-8]. A schematic diagram of FSP is shown in Fig. 2. The tool plays critical role during FSP, because the selection and the designing of tool material is critically important to process.

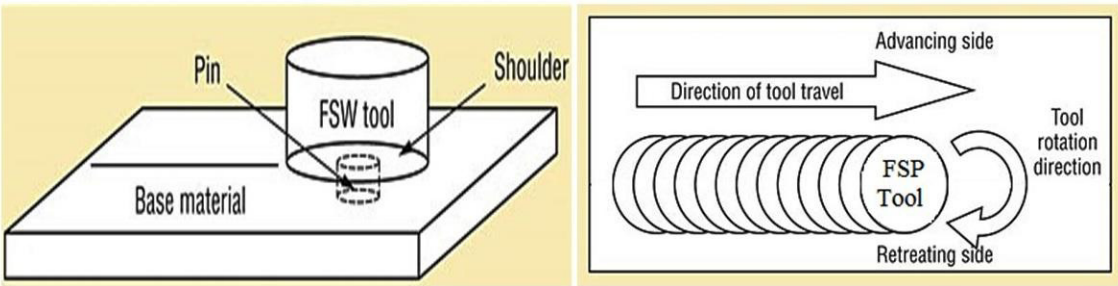

Fig. 2. A schematic diagram of friction stir processing.

A rotating piece is defined as the tool, which designed and manufactured to plastically deforming the processed zone and produce heat due to stirring action between work piece and the tool pin. The tool consists mainly three parts such as tool pin, shoulder and the shank. The angle of the tool as compare to the vertical direction is known as tilt angle. The trailing and leading edge will be used to differentiate between the rear and front limb of the tool as the front is described as the direction of travel. Hence to enhance the mechanical and tribological properties locally, Friction stir processing shows the great route to get desired properties. Friction stir processing can be applied variably up to the depth of in the range of 0.5 to 50 mm.

FSP has several advantages over other metal working process. First, Friction stir processing achieves refined microstructure, homogeneity and densification because it is a solid-state processing process. Second, In the Processed zone mechanical and tribological properties can be greatly controlled by adjusting the tool pin and shoulder diameter or length or both and by changing the tool rotation speed, tool transverse speed, tilt angle, and vertical force etc. [9]. Third, as compared to other metal working process it is very difficult to find an adjustable processed depth, but it is possible in FSP by adjusting the length of the tool pin. Fourth, FSP is a environment friendly and energy-efficient process, because the heat input comes from the stirring action between work piece and the tool pin. And the other benefits of FSP like lower distortion, good dimensional stability, no shielding gas required etc[10-12].

3. Problem Formulation

The past work reveals that existing scenario have number of gaps in era of friction stir processing of cast Al-17% Si alloy, which includes (a) Tool design has not been investigated for hypereutectic Al-17% Si alloy; (b) The study of mechanical properties of hypereutectic Al-17% Si alloy has not been done. Thus, keeping in view of the above research gaps, it was planned to investigate the effect of friction stir processing parameters on mechanical and metallurgical properties of friction stir processed of cast Al-17%Si alloys.

4. Experimental Methodology

The objectives were achieved through a selection of the experimental matrix including all material selection, friction stir processing process parameters, conducting a thorough microstructure analysis, and performing representative mechanical and tribological performance tests. Based on the demand in the field of automobile, aerospace and other application it is pertinent to study mechanical and wear behaviour. In this present study, Al based alloys with 17% wt of Si were synthesized using die casting method and then processed by FSP to enhance mechanical and tribological performance.

4.1 Material selection

After doing detailed study of the research papers in the relevant field, the gaps were found that the work on Friction stir processing of hypereutectic Al-Si alloys to enhance the mechanical and tribological performance is very limited. Hypereutectic Al-Si alloy is in much more in demand due to their high wear resistance, low strength to weight ratio and not much work done on the hypereutectic Al-Si alloys. As received material pure Al and Al-24% Si, were utilized in the formation of Al-17% Si alloy using die casting method.

4.2 Experimental Setup

The experiments have been carried out on the Friction stir welding machine with necessary equipment details such as tool, process parameter and safety precautions. Process parameter involved are the tool rotation speed, welding speed, tilt angle and tool geometry. The process of FSP begins with the tool design and fabrication. The main and the crucial thing of this project were the tool design for friction stir processing process, which would fix in the available Friction stir welding machine shank. Initially FSP tool designed in such a way that the tool geometry

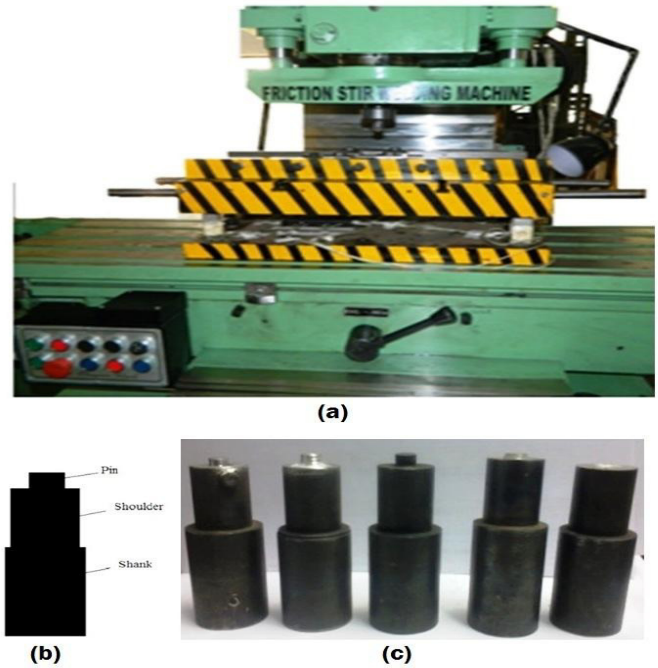

Fig. 3. (a) Photograph of Friction stir welding machine; (b) Designed tool geometry; (c) Various tool made for friction stir processing for Al-17%Si cast alloy .

was very simple with cylindrical tool i.e. shank diameter 25 mm, shoulder diameter 20 mm, pin diameter 9 mm, pin length 4 mm. By using this tool geometry, generated forces during penetration of tool or processing were huge in the magnitude. Then we go for modification in tool geometry to reduce the huge forces at the time of penetration by using threaded pin. This led to the tunnel formation in the processed region in the form of defect and it was the observed that the heat generated was very high and in order to reduce this frictional heat the shoulder diameter was reduced to18 mm and pin diameter reduced to 8 mm. Hence, we finally came up with a design that resulted in good processed zone at reduced forces. The designed and fabricated tool for Al-17Si cast alloy had shank diameter 25 mm, shoulder diameter 18 mm, pin diameter 8 mm, pin length 3.5 mm.

FSP was applied to specimen of 150 mm x 100 mm x 6mm, sand casting Al-17wt% Si alloy work piece under different processing parameters. Optical microscope, SEM and EDX measurements have been performed to reveal and study microstructure before/after FSP. A range of material properties, including hardness and tensile properties of Al-17wt% Si alloy, were examined before and after FSP. A tool made of H-13 tool steel with a shoulder of 19 mm diameter, a threaded pin of diameter 8 mm and 3.5 mm height with a tilt angle of 1^o was used to perform the FSP. After designed and fabrication of tool fixed on the friction stir welding machine and the work piece was clamped to a worktable. The input process parameters used for FSP were selected by number of pilot experiments i.e. fixed tool rotation speed of 664 rpm and variable welding speed of 26, 40 and 60 mm/min.

Finally start the lowering down the machine head and tool is plunged in the work piece slowly. The rotating pin is forced into the work piece and moved along the desired direction with a specific combination of rotational and translation speeds Frictional heat is produced from the relative motion of the rotating shoulder with respect to the sheet being processed, while the rotating pin deforms rather generates a ‘stirring’ action which locally heats up and creates severe plastic deformation in the material. After plunging to the required depth the feed is giving to the setup in terms of welding speed.

4.3 Material characteristics

Material characterization was done to check the soundness of modified surfaces by using various tests such as visual examination, optical microscopy, EDX, FESEM and tensile test.

5. Results of Experiments

The experimental results have been carried out to obtain the effect of FSP on the mechanical and tribological properties of Al-17%Si alloy. The following tests have been done by preparing the workpiece sample as per the requirements of the process.

5.1 Macroscopy test

Fig. 4 shows the micrographs of successfully modified surfaces of FSP using different rotational speeds and welding speeds, i.e. (a) 664 rpm and 26 mm/ min, (b) 664 rpm and 40 mm/min and (c) 664 rpm and 60 mm/min. It

Fig. 4. Friction stir processed zone and cross sectional view of micrographs at (a) 664 rpm and 26 mm/ min; (b) 664 rpm and 40 mm/min; (c) 664 rpm and 60 mm/min.

can be observed that high tool transverse speed of 60 mm/min gives a smooth surface as compare with the other two speeds. Hence, it is cleared that with the increase of tool transverse speed surface roughness decreases at constant tool rotation.

5.2 Microscopy test

The optical micrographs of (a) cast Al-17% Si alloy, (b) FSPed at 664 rpm and 26 mm/min, (c) Alloy FSPed at 664 rpm and 40 mm/min and (d) Surface FSPed at 664 rpm and 60 mm/min as shown in fig.5. From Fig. 6 (a), it can be observe that cast Al-17% Si alloy is composed of coarse primary silicon particle in eutectic matrix with non uniform distribution of Si particles. As evident of Fig. 5 (b), (c) and (d), the FSP reducing the size of Si particles improves distribution as compare to cast Al-17% Si alloy. Si particles were found in the almost spherical shape as a result of more intense stirring effect, these fine spherical particle are expected to reduce crack sensitive zone. However, the size and distribution were not much affected by various welding speeds.

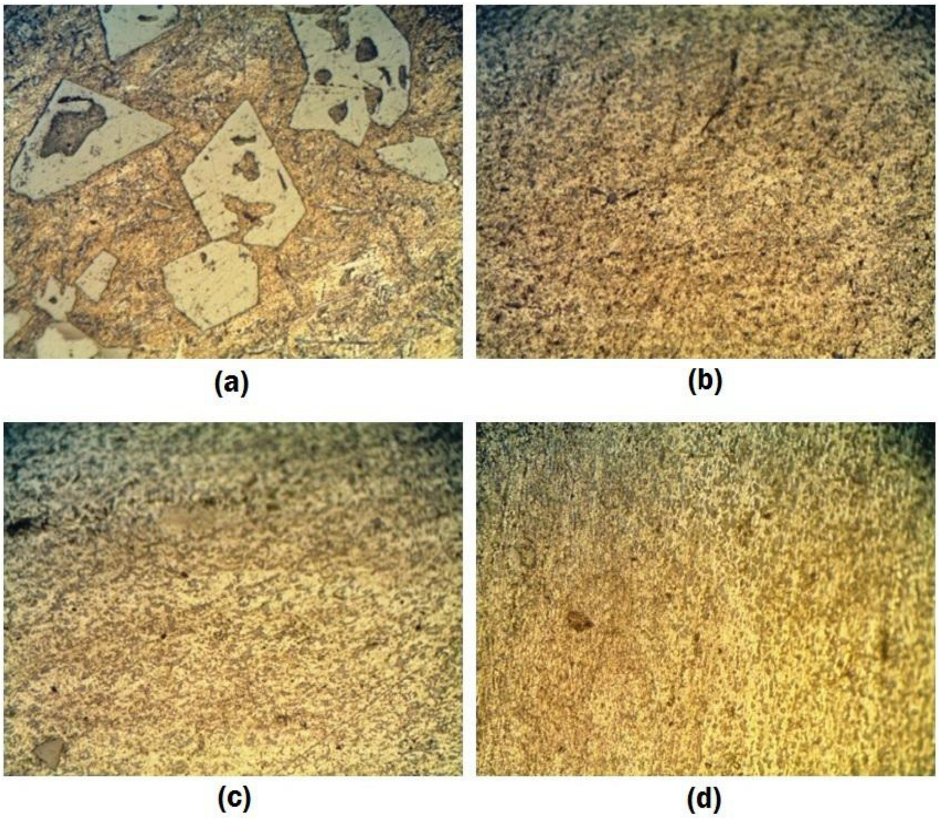

Fig. 5. Friction stir processed zone and cross sectional view of micrographs at (a) 664 rpm and 26 mm/ min; (b) 664 rpm and 40 mm/min; (c) 664 rpm and 60 mm/min.

5.3 Optical emission spectroscopy test

The chemical compositions of the cast alloys were found by Optical emission spectroscopy (OES) test (in wt. %) of Al- 81.4%, Si-16.58% and the rest impurities. The base was found as Al and matrix was true global. Table 1 shows the compositional weight of various elements present in the cast alloy. The presence of porosity in the samples is expected to affect the results of OES test, and the same may be attributed to marginal variation in composition as compare to nominal composition.

Table 1 Composition of cast Al-Si alloy.

Elements	Si	Fe	Mg	Al
Wt %	16.5278	1.6842	0.3161	Rest

5.4 Scanning electron microscope test

After performing FSP on the Cast Al-Si alloys successfully the micrographs of different process parameters samples were taken from various regions. Fig. 6 shows the effect of various process parameters on structure of FSPed surface. The Si present in the needle shape in cast Al-17%Si alloy results in the higher crack growth regions and poor mechanical as well as wear resistance. FSPed surface show almost spherical shape and the fine Si particle, which is expected to improved mechanical and wear performance as compare to cast Al-Si alloy. From the micrograph at 664 rpm with 60 mm/min welding speed at 500X, the size and the distribution of Si particles were more uniform as compare to other two welding speeds of cast Al-17Si alloy.

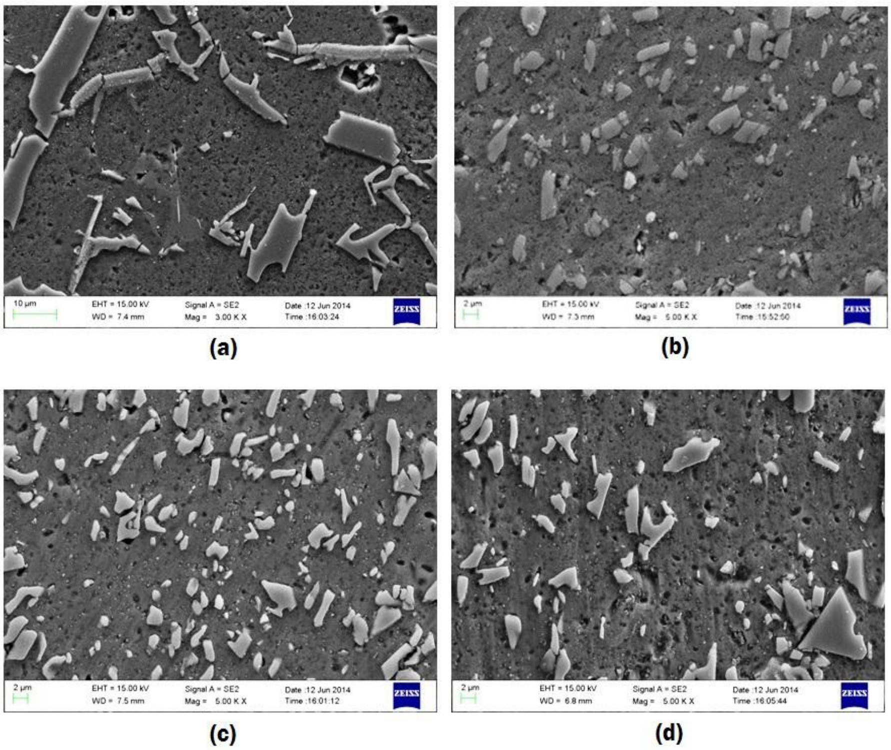

Fig. 6. SEM images (a) Base material; (b) FSPed at 26 mm/min; (c) FSPed at 40 mm/min; (d) FSPed at 60 mm/min.

5.5 Tensile test

Tensile test was performed on the Universal testing machine. The base material average yield strength was 43.025 MPa and FSPed samples show the yield strength 76.28, 59.06 and 62.65 MPa at various welding speed 26, 40 and 60 mm/min respectively. Results suggested that yield strength increases after FSP, but it is decreases with increase welding speed. The base material average Ultimate tensile stress (UTS) was 116.89 MPa and FSPed surfaces show the UTS 157.367, 147.15 and 148.54 MPa at various welding speed 26, 40 and 60 mm/min respectively. Results suggested that the UTS at constant tool rotation speed 664 rpm and tool transverse speed 26, 40, 60 mm/ min decreased by 1.35,1.25 and 1.27 times respectively as compare to cast alloy. Fig. 7 (a) shows the variation in Stress v/s strain in base and FSPed samples at various process parameters. The cast alloy shows % elongation 1.72 and FSPed surface done at 26, 40, 60 mm/min speed showed % elongation of 8.01, 6.09 and 6.1555. Hence, the tensile elongation of FSPed samples has increased from < 2 % to about 9 % at various welding speeds as compare to cast Al alloy. Fig. 7 (b) show the variation of tensile strength with various welding speeds.

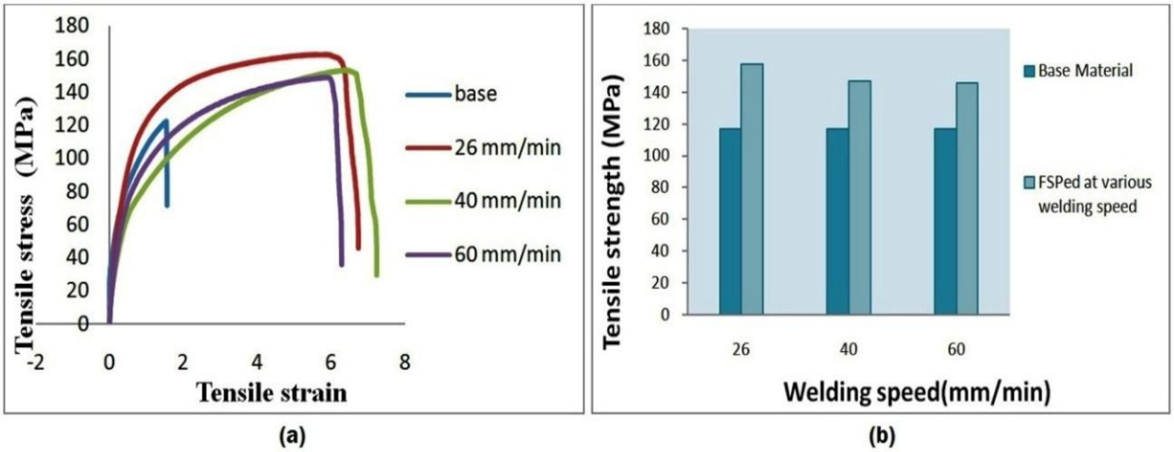

Fig. 7. (a) Stress verses strain in base and FSPed samples at various process parameters; (b) Tensile strength verses welding speed of base and various FSPed samples.

Fig.8 shows the tensile samples of FSPed cast Al-17wt% Si alloy at 664 rpm tool rotation speed and 26, 40, 60 mm/min tool transverse speed as (a) before testing and (b) after testing. The samples show the fracture point after testing. Fig. 9 shows SEM images of fracture surfaces of FSPed samples (a) base material (b) FSPed sample at 26 mm/min and 664 rpm. As seen from the fracture surface of cast Al-17% Si alloy show brittle fracture while FSPed surface show ductile fracture, an evident from presence of dimples in the fractured surface.

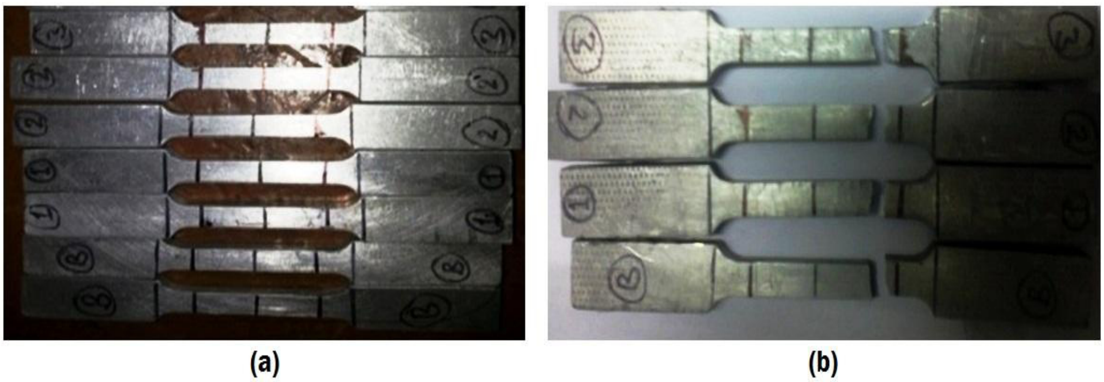

Fig. 8. Tensile samples of FSPed cast Al-17wt% Si alloy at 664 rpm tool rotation speed and 26, 40, 60 mm/min tool transverse speed.

as (a) before testing and (b) after testing

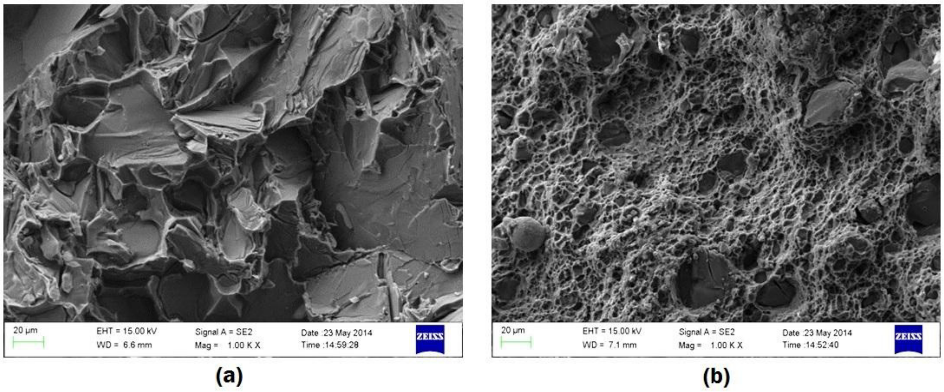

Fig. 9. Fracture surfaces of FSPed samples (a) base material and (b) FSPed sample at 26 mm/min and 664 rpm.

5.6 Micro hardness test

The micro hardness readings were taken at the room temperature. The micro hardness of cast Al-17% Si alloy was found on an average 63 HV and while surfaces shows 69, 80 and 89 HV FSPed with welding speed 26, 40 and 60 mm/min respectively. Fig. 10 shows the micro-hardness of FSPed samples developed using various welding speeds. It can be observed that an increase in welding speed increases the micro hardness of samples. In general FSPed samples show higher micro hardness as compare to cast Al-17% Si alloy.

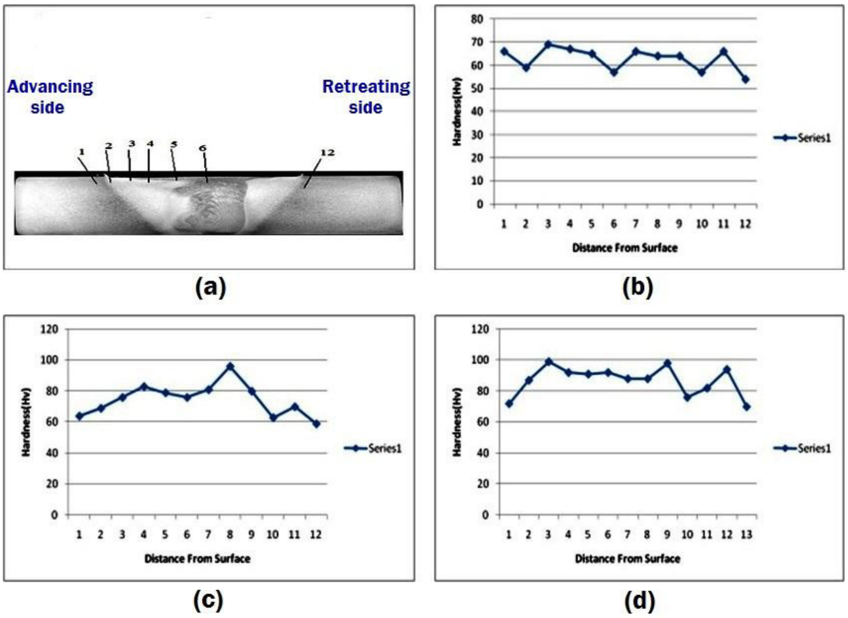

Fig. 10. (a) locations of hardness analysis; (b), (c) and (d) Microhardness of FSPed cast Al-17wt% Si alloy developed using 664 rpm tool rotation speed and 26, 40, and 60 mm/min welding speed.

Fig. 10 (b),(c), and (d) show the micro-hardness of FSPed cast Al-17wt% Si alloy developed using 664 rpm tool rotation speed and 26, 40, and 60 mm/min welding speeds. At tool rotation speed of 60 mm/min the micro-hardness variation was more uniform as compare to other two welding speeds. The micro hardness of FSPed surface is not affect much by various welding speeds. The FSPed region show the micro hardness higher than base metal.

Conclusions

Friction stir processing can play important role for designing the mechanical and tribological properties of Al-17% Si alloy. From this study, the following conclusions were drawn:

1. The FSP of cast Al-17% Si has been successfully performed with designed tool dimensions such as shank diameter 25 mm, shoulder diameter 18mm, pin diameter 8mm, pin length 3.5mm.
2. The significant refinement of eutectic and coarse primary Si particles and improved distribution of Si particles in the Al matrix takes place as a result of FSP in cast Al-17% Si alloy. FSP recorded for generating fine grains of 2–4μm approximately in cast Al-17%Si alloy samples and input process parameters of FSP did not exert a significant effect on the grain size.
3. FSP increases UTS (Ultimate tensile stress) of cast Al-17% Si alloy. FSP samples showed 1.26 to 1.35 time higher strength than base material.
4. FSP increases % elongation of cast Al-17% Si alloy from < 2 % to about 9 %.
5. FSP increases the micro-hardness of cast Al-17% Si alloy. An increase in welding speed increases the micro-hardness of cast Al-17% Si alloy.
6. Mechanical properties results the optimize parameter for FSP of cast Al-17% Si alloy were TRS of 664 rpm and welding speed of 60 mm/min.

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