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Fabrication of al 6082/SiC composite for microstructure, micro-hardness, tensile strength and wear properties using multi-pass friction stir processing

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Abstract

High strength-to-weight ratio, light weight and various thermal, mechanical and recycling properties makes aluminium alloys an ideal choice for various industrial applications in sectors as varied as aeronautics, automotive, beverage containers, construction and energy transportation. Due to the rapid injection of molten aluminium into metal moulds under high pressure, casting defects and an abnormal structure, such as cold flake, are easily formed in the base metal. These defects significantly degrade the mechanical properties of the base metal. In order to satisfy the recent demands of advanced engineering applications, Aluminum matrix composites (AMCs) have emerged as a promising alternative. Among the various metal matrix composites manufacturing and forming methods, Friction Stir Processing (FSP) has gained recent attention. This work aims at analyzing the microstructure, micro-hardness, tensile strength and wear properties of Al 6082/SiC composites fabricated by single, double and triple passes via FSP. The ultimate tensile strength of the processed material came out to be less than the parent material and the results showed that with the increase in the number of passes, the tensile properties of composites including ultimate tensile strength (UTS) and yield strength (YS) improved. The wear rate decreased with the increase in the number of passes. The hardness results showed that the specimen with maximum number of passes showed maximum hardness with the average value of 100HV whereas the parent material without any processing had an average of 60HV hardness value. Microstructure analysis revealed that as the number of passes increased, it produced a more homogeneous composition of the specimen due the presence of fine and equi-axed grains.

Keywords Composite Fabrication, Multi-pass Friction stir Processing, Microstructure improvement

1. Introduction

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid state joining technique and it was initially employed for aluminum alloys. Friction stir processing (FSP) is a new solid state technique which uses the principles of friction stir welding. It locally eliminates casting defects and refines microstructures resulting in improved strength and ductility, increase resistance to corrosion and fatigue, increase in hardness and formability. Metal matrix composites of base various base metals like aluminium, copper, iron and nickel have been fabricated using friction stir processing (FSP). It is a promising process for the automotive and aerospace industries where new materials are developed to improve resistance to wear, creep, and fatigue. Using this process, microstructural properties of powder metal objects can be improved and wrought microstructure can be introduced into a cast component.

From the operational viewpoint, a friction stir processing run can be divided into three sub-procedures or phases:

- Plunge and Dwell
- Traverse
- Retract

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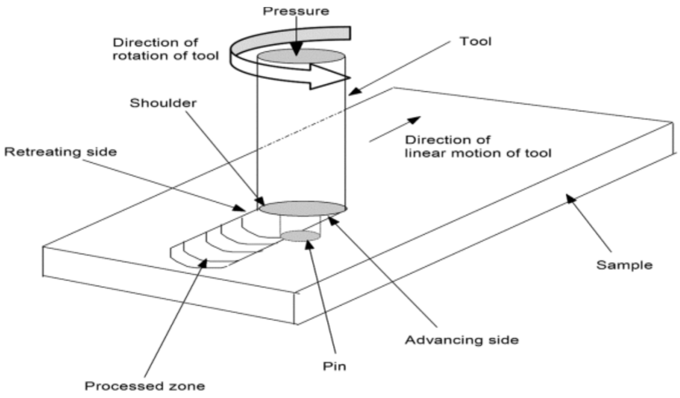

Figure 1: Motion of Tool in Friction Stir Processing. [38]

At the beginning of the plunge phase, both the tool and the workpiece are at ambient temperature. Initially, the workpiece material is too cold to flow and the rubbing action creates chipping as the tool is gradually inserted. Insertion rate determines the rate of temperature rise and extent of plasticity. The process of tool insertion continues until the tool shoulder is in intimate contact with the workpiece surface. At this stage, the entire tool shoulder and pin surface contribute to the frictional heating and the force starts to drop as the metallic workpiece reaches critical temperature for plastic flow. The rotating tool is sometimes intentionally retained at the same position for short durations in the case of metals with higher melting point so as to reach the desired temperature required for plastic flow. This is known as the dwell phase and is typically a fraction of the time required for plunge phase. Typically, the plunge stage is programmed for controlled plunge rate but it can be also done by controlling the force applied on the tool along its rotation axis (i.e. force controlled FSW). Different combinations of displacement and force controlled approach are possible. For a typical FSW run, the vertical force reaches a maximum value in this part of the run and this tends to be critical phase for the tool. Once the workpiece/tool interface is sufficiently heated up, the tool is traversed along the desired direction to accomplish joining. This is the actual processing phase and can be performed under (a) displacement controlled mode (where tool position with respect to the workpiece surface is held constant) or (b) force controlled mode (normal force applied by the tool to the workpiece is held constant). There are other modes such as power control, torque control, temperature control, etc., on advanced FSW machines available these days. The tool is finally retracted from the workpiece on the completion of the process.

2. Literature Review

H. R. Akramifard et al. [3] studied the microstructure and mechanical properties of the Cu/SiC composites fabricated using the technique of FSP. Optical microscope (OM) and scanning electron microscope (SEM) were put into use for the study of microstructure Hamid Pashadeh et al. [4] carried out a research on the investigation of the mechanical, thermal and metallurgical and material flow characteristics from friction stir processing welding of copper sheets with experimental verification. Hamad Pashazadeh et al. [5] carried out numerical modeling for evaluating hardness in friction stir welding of copper sheets. Hardness measurements and microstructural evaluations were performed on the welded specimens. Galvao et al. [6] conducted the research on influence of parameters on mechanical enhancement of copper-DHP by FSP. Mohsen Barmouz et al. [7] evaluated the microstructure, porosity, mechanical and electrical behaviour of Cu/SiC composites fabricated by multiple passes of friction stir processing. Mohsen Barmouz et al. [8] on the role of processing Cu/SiC metal matrix composites. Cu/SiC metal matrix composites, because of their excellent electrical and thermal conductivity, enhanced hardness values, wear and frictional properties have been the subject of extensive research P. Xue et al. [9] achieved bulk ultrafine grained Cu via friction stir processing R.Sathishkumar et al. [10] on role of friction stir processing on microstructure and microhardness of Boron Carbide particulate reinforced copper surface composites and found that the typical crown appearance of friction stir processed copper with B4C particles. Sathis kumar et al.[12] studied the mechanical and wears properties of copper surface composites fabricated using friction stir processing regarding characterization of boron carbide particulate reinforced in situ copper surface composites synthesized using friction stir processing. S.Mukherjee et al [13], carried out experiment on friction stir processing of direct metal deposited copper-nickel 70/30.DMD (Direct Metal Deposited) has wide applications in complex and expensive components such as navy weapon systems and equipment. Salar Sarahi et al. [14] studied fracture mechanism in friction stir processed annealed pure copper samples. Khiyavi et al [15], studied effects on friction stir processing on mechanical properties of surface composite of Cu reinforced with Cr particles. V. Jeganathan Arulmoni et al. [16] investigated parameters affecting friction stir processed copper and enhancement of mechanical properties of composite material. The machine used for Friction stir processing was a vertical milling machine in which necessary adjustments were made to make it suitable for use in friction stir processing. V. Jeganathan Arulmoni et al. [17], investigated experimentally friction stir processed copper and enhancement of mechanical properties of composite material graphite. Effect of friction stir processing (FSP) parameters such as tool rotational speed, processing speed, axial load, groove width and depth, investigated change in microstructure, micro hardness, tensile strength and wear resistance. The results showed that the grain size of fabricated composite reduce, also it is indicated that in comparison to base copper micro hardness of FSPed composites in stir zone (SZ) increase significantly. V. Jeganathan et al [18] studied the processing parameters such as tool geometry, tool rotational speed, tool tilt angle, processing speed, axial load and groove width & depth were studied. Strength of Friction Stir Processed material improved significantly and at same time ductility retained as well as hardness also improved substantially. L.B. Johannes et al [19] discusses the use of friction stir processing (FSP) in order to enhance the super plasticity property for use in aerospace and automotive panels. A. Scialpi et al [20] studied the grade of aluminum AA6082. Plates of 1.5mm thickness were welded using different types of tool shoulder geometries K. Elangovan et al [21] discusses the effect of both tool pin profile and tool shoulder diameter on the friction stir welded Aluminum. 6mm thick Aluminum of grade AA6061. Z.Y. Ma et al [22] studied the Number of passes is an important parameter in FSP on sand cast A356 plates of thickness 15mm. He find out the effect of multi passes up to five-pass FSP with a tool rotation rate of 700 rpm and a traverse speed of 203 mm/ min using a tri-flute pin. Khodaverdizadeh, H., Mahmoudi, A., Heidarzadeh, A., & Nazari, E. (23), studied the strain hardening behavior of pure copper joints which highlighting the influences of rotational and welding speeds on microstructures and mechanical properties of friction welded Al5083 . Dhayalan, R., Kalaiselvan, K., & Sathiskumar, R. [24] studied effect of FSW parameters on strain hardening behavior of pure Cu joints. Bisadi, H., Tavakoli, H., & Sangsaraki, M. [25] studied the microstructure and mechanical properties in dissimilar butt FSW of severely plastic deformed Aluminum AA 1050 and commercially pure Cu sheets Barekatain, H., Kazeminezhad, M., Kokabi, A.H. [26] studied the wear properties of copper-coated short steel fiber reinforced stir cast Al-2Mg alloy composites.

Mandal, D., Dutta, B.K., Panigrahi, S.C. [27] carried out FSP using friction stir welding machine, with and characterization of AA6063/SiC-Gr surface composites produced by FSP technique was studied. The surface matrix composite (SMC) was fabricated on the surface of aluminum alloy (6063) with ceramic reinforcement using friction stir processing technique. SiC and Gr was used as reinforcement. FSP parameters such as traverse speed of 30 mm/min, tool rotational speed of 1000 rpm and 10 KN of axial load. The FSP tool made of HcHCr with cylindrical threaded profile pin having shoulder diameter of 18 mm, pin length of 5.8 mm and pin diameter of 6 mm was used. Three combinations of surface composites (Al/0.8Vol.%SiC, Al/0.8Vol.%Gr and Al/0.4Vol.%SiC-0.4Vol.%Gr) were fabricated and found the grain size of the surface composite layer fabricated with SiC and Gr ceramic particulates were refined. The microstructural study showed the homogenous distribution of the ceramic particulates in the SZ and good bonding with matrix material.

Amal Ebrahim NASSAR [28] et.al discusses the design and fabrication of Wear Testing Machine and found the wear rate decreases as the load decreases from 29.4-49 N also, the wear rate decreases as the time increases from 240 to 120 second. R.S. Mishra et al, observed that the mechanical properties of welded joint by friction stir welding are largely dependent on the combined effect of both the composition of alloying element and processing parameter. Welding parameter such as tool rotation, transverse speed and axial force have a significant effect on the amount of heat generated and strength of FSW joints. Microstructure evaluation of FSW joints clearly shows the formation of new fine grains and refinement of reinforcement particles in the weld zone with different amount of heat input by controlling the welding parameter [29-30].

Sreenivasa Rao M [31] et.al carried out a review of Wire Cut EDM process and mentioned various optimization methods in WEDM research E. Huerta [32] et.al studied the UTM (Universal Testing Machine) for mechanical properties of thin metals & used new methodologies to measure the physical properties of thin films are currently required Masoud Jabbari et al. [33] developed a thermal model on Elucidating of rotation speed in friction stir welding of pure copper**.** Which was used to simulate the friction stir welding of pure copper plates with the parameters as follows, thickness of 4 mm at the constant traverse speed of 25 mm/min and five different rotation speeds M. Sarvghad Moghaddam et al. [34] studied Microstructural and mechanical properties of friction stir welded Cu–30Zn brass alloy at various feed speeds and found that influence of stir bands on various mechanical properties is done. In this study, the effect of 190–375 mm/min feed speeds on the microstructure and mechanical properties of friction stir welded Cu–30Zn alloy was investigated. M. Guerra et al. [35] studied flow patterns during friction stir welding and observed that the material is transported by two processes. In the first process, the wiping of material from the advancing front side of the nib onto a zone of material that rotates and advances with the nib. The material undergoes a helical motion within the rotational zone that both rotates, advances, and descends in the wash of the threads on the nib and rises on the outer part of the rotational zone. In the second process is an entrainment of material from the front retreating side of the nib that fills in between the sloughed off pieces from the advancing side. LI Xia-wei et al. [36] studied Microstructure and mechanical properties of dissimilar pure copper/1350 aluminium alloy butt joints by friction stir welding and found complex vortex-like and swirl patterns are formed in the dissimilar FSW joint using the XRD results.

A. Shafiei-Zarghani et al. [37] studied Microstructures and mechanical properties of Al/Al_2O_3 surface nano-composite layer produced by friction stir processing and observed that the increasing in number of FSP passes causes a more uniform in distribution of nano-sized alumina particles. The micro hardness of the surface improves by three times as compared to that of the as-received Al alloy.

3. Experimental Setup

3.1 Al 6082 properties and composition

Aluminium alloy 6082 is a medium strength alloy with excellent corrosion resistance. It has the highest strength of the 6000 series alloys. Alloy 6082 is known as a structural alloy. In plate form, 6082 is the alloy most commonly used for machining. As a relatively new alloy, the higher strength of 6082 has seen it replace 6061 in many applications. The addition of a large amount of manganese controls the grain structure which in turn results in a stronger alloy.

Table 1: Chemical Composition of Aluminium 6082

Chemical Element	**% Present**
Manganese (Mn)	0.40 - 1.00
Iron (Fe)	0.0 - 0.50
Magnesium (Mg)	0.60 - 1.20
Silicon (Si)	0.70 - 1.30
Copper (Cu)	0.0 - 0.10
Zinc (Zn)	0.0 - 0.20
Titanium (Ti)	0.0 - 0.10
Chromium (Cr)	0.0 - 0.25
Other (Each)	0.0 - 0.05
Aluminium (Al)	Balance

Table 2: Physical Properties of Aluminium 6082

Physical Property	**Value**
Density	Density 2.70 g/cm^3
Melting Point	555 °C
Thermal Expansion	24 x10-6 /K
Modulus of Elasticity	70 GPa
Thermal Conductivity	180 W/m.K
Electrical Resistivity	0.038 x10-6 Ω .m

Table 3: Mechanical Properties of Aluminium 6082

Property	**Value**
Proof Stress	255 MPa
Tensile Strength	300 MPa
Elongation A50 mm	9 Min %
Hardness Brinell	91 HB

3.2 Workpiece Details

- Dimension : 200mm X 75mm X 6mm
- Number of workpieces : 4
- Composite : Aluminium 6082 + SiC particles
- Number of grooves per workpiece : 1
- Passes
  - Parent Aluminium workpiece without any processing.
  - Single pass on the first Aluminiumworkpiece without SiC
  - Single pass on the second Aluminium workpiece with SiC
  - Double pass on the third Aluminium workpiece with SiC
  - Triple pass on the fourth Aluminium workpiece with SiC

Figure 2(a) :Single pass on the first Al workpiece without SiC

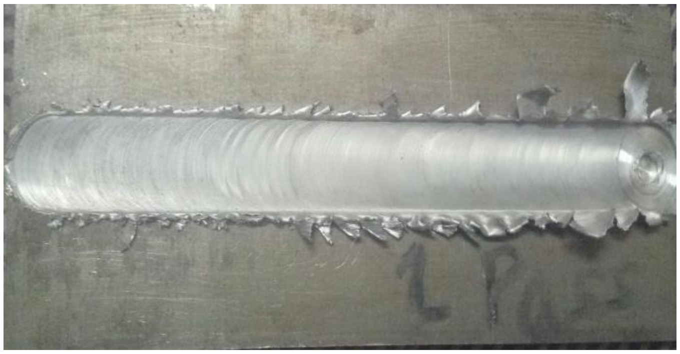

Figure 2(b) : Single pass on the second Al workpiece with SiC

Figure 2(c): Double pass on the third Al workpiece with SiC

Figure 2(d): Triple pass on the fourth Al workpiece with SiC

3.3 Friction Stir Processing

The material used is Aluminium Al6082 and Silicon Carbide particles to fabricate Al-SiC composites. The specimen size of the copper plate that is used for processing 200 mm x 75 mm x 6 mm. One groove of 1mm width and 2.5 mm deep was made on the 99.99% pure Aluminium Plates using horizontal milling machine with a 1mm (width) saw cutter was cut in the middle of the specimen plate for processing. The tool Material used is H13 steel. The Tool profile is Cylindrical threaded with shoulder diameter 15mm, threaded pin diameter 8 mm, pin length 1.5 mm with tool rotational speed 1000 rpm, tool tilt angle 2° and table traverse speed 35 mm / min with axial force 450 Kgf. The pin of the tool was brought just above the plate in such a way such that the centre of the pin lies just above the centre of the groove cut. First Pass is made along the length of the job. Second Pass, after cooling the plate for 5-10 minutes is made along the length of the job. The job was allowed to cool for some time and then taken out from the fixtures. Initially without Silicon Carbide Particles one specimen plate was processed with single pass. Then second specimen plate was processed after filling Silicon Carbide Particles in the groove cut (single pass). Then third specimen plate was processed after filling Silicon Carbide Particles in the groove cut (double pass). Finally the fourth specimen plate was processed after filling Silicon Carbide Particles in the groove cut (triple pass). The Silicon Carbide powder was filled into the grooves of second and third plate and process is repeated as per the following table. Process Parameters for first, second, third plate are mentioned in the table.

Figure 3.1: Friction stir welding / processing machine (DTU)

Table 4: Parameters used in Friction Stir Processing

Workpiece	Tool shape and size	Feed	rpm of Spindle	Axial Force
99% pure Aluminium Al6082 plates	H13 steel tool cylindrical Pin Shoulder Diameter-15mm Pin diameter-5mm Pin length-1.5mm Pin shape- straight cylindrical threaded	35 mm/ min	1000 rev/min	450 kgf

3.4 Tensile test

The processed pieces were taken for the Tensile testing using Universal testing machine. Five specimens were chosen marked with marker on their ends. After the FSP the specimen for tensile testing were cut from the job.

Figure 3.2: Machine used for tensile testing of specimens, Metal Forming Laboratory, D T U, Delhi

3.4.1 Tensile test specimen

- Length of specimen- 100 mm
- Gauge Length – 40 mm
- Gauge width- 6 mm
- Gauge thickness- 6 mm

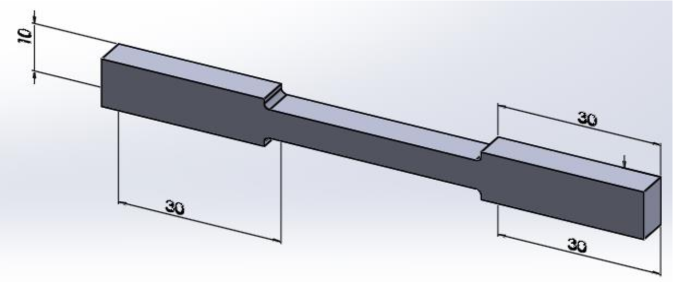

Figure 3.3: Ultimate tensile testing specimen

3.4.2 Tensile Test Observations

The stress strain graphs and load elongations graph are shown for the ultimate strength of the specimen. The ultimate tensile strength of the processed material came out to be lesser than the parent material.

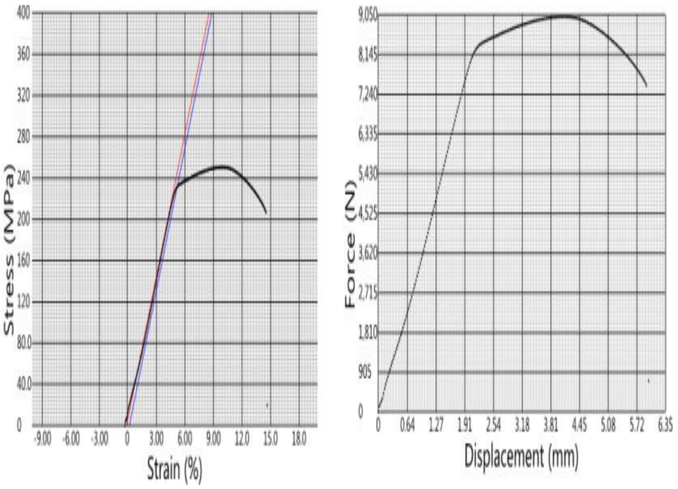

Figure 3.4 (a) : Stress-Strain and Force-Displacement curves for specimen without processing

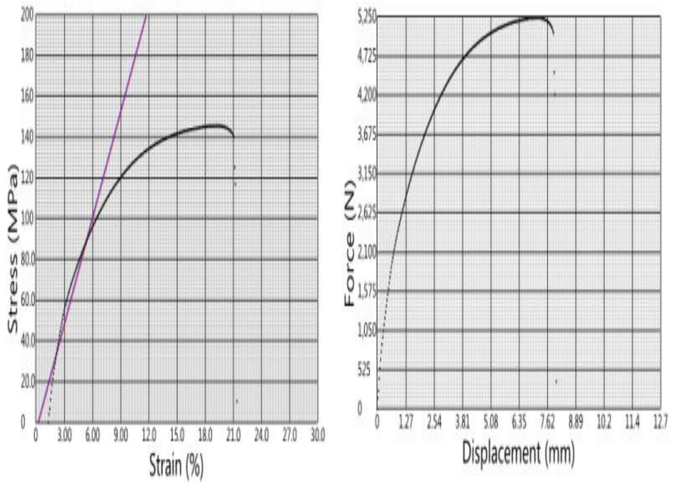

Figure 3.4 (b): Stress-Strain and Force-Displacement curves for specimen without SiC single pass processing

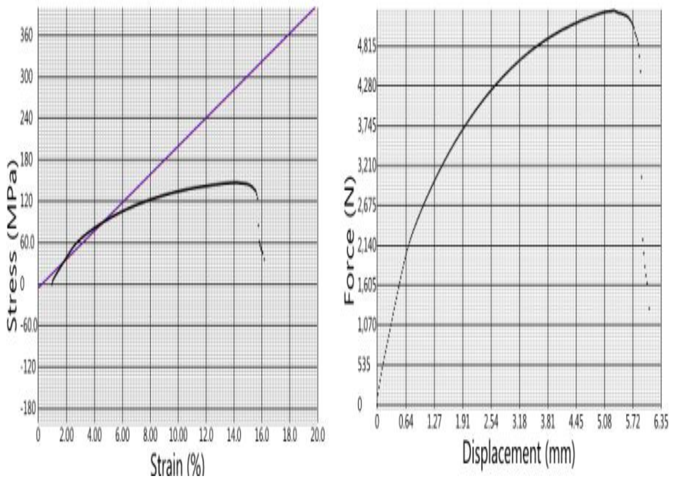

Figure 3.4(c): Stress-Strain and Force-Displacement curves for specimen with SiC single pass processing

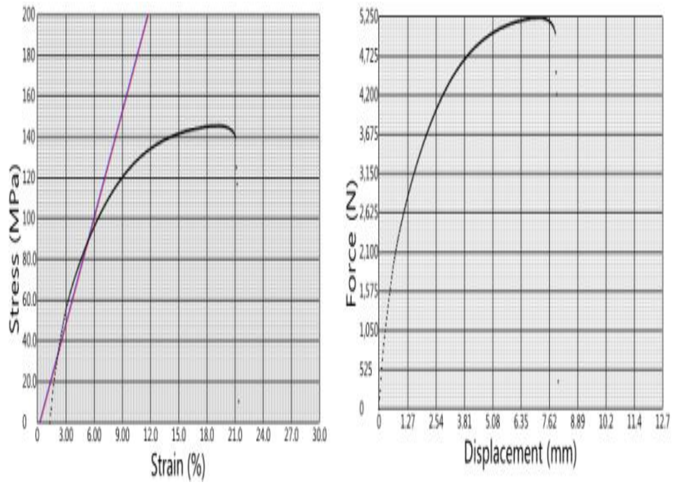

Figure 3.4 (d): Stress-Strain and Force-Displacement curves for specimen with SiC double pass processing

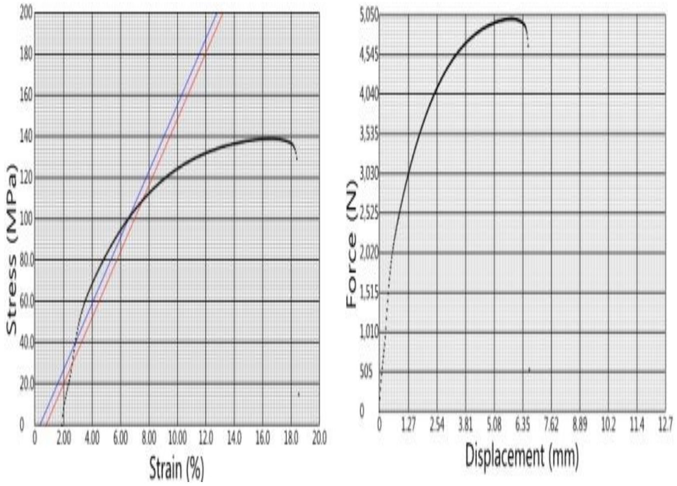

Figure 3.4 (e): Stress-Strain and Force-Displacement curves for specimen with SiC triple pass processing

Table 5: Specimens Details and Output Results during Tensile Tests

Output (Generic metals tensile from position)	Without processing	Single Pass Without SiC
Width(mm)	6.00	6.00
Thickness(mm)	6.00	6.00
Gauge Length (Initial) mm	40.00	40.00
Gauge Length (Final) (mm)	46.0	50.1
Area (mm^2)	36.0	36.0
Ultimate Force (N)	9010	5690
Ultimate Stress (MPa)	250	158
Offset @ 0.2% (N)	8320	3660
Offset @ 0.2% (MPa)	231	102
TE (Auto) (%)	14.6	26.8

Table 6: Specimens Details and Output Results during Tensile Tests

Output (Generic metals tensile from position)	Single Pass with SiC	2 Pass with SiC	3 Pass with SiC
Width(mm)	6.00	6.00	6.00
Thickness(mm)	6.00	6.00	6.00
Gauge Length (Initial) (mm)	40.0	40.0	40
Gauge Length (Final) (mm)	46.1	48.1	46.7
Area (mm^2)	36.0	36.0	36.0
Ultimate Force (N)	5210	5250	5310
Ultimate Stress (MPa)	144	146	148
Offset @ 0.2% (N)	3190	3150	3620
Offset @ 0.2% (MPa)	88.5	87.5	101
TE (Auto) (%)	15.7	18.3	21.1

3.5 *Vickers Micro hardness Test*

3.5.1 *Specimen dimensions*

- Number of specimens: 5
- Cross-section: Square
- Side length: 10mm
- Height / Depth: 6mm

(a)

3.6 *Microstructure Test*

For microstructure test the five specimens were tested on SEM at IIT Delhi. The instrument used was ZEISS EVO Series Scanning Electron Microscope EVO 18.

Figure 4.1: Scanning electron microscopy facility, Room No. TX - 118 Department of Textile Technology Indian Institute of Technology, Delhi

3.7 *Specimen dimension and testing parameters*

- Sample cross-section: circular
- Sample diameter: 10mm
- Sample height / thickness: 6mm
- Magnification Levels: 250X, 1.50KX, 5.00 KX and 7.00 KX

Sample 1-Single pass specimen with Silicon Carbide particles
Sample 2-Double pass specimen with Silicon Carbide particles
Sample 3-Triple pass specimen with Silicon Carbide Particles
Sample 4-Single pass specimen without Silicon Carbide particles
Sample 5-Parent Material Aluminium specimen without any processing

3.8 *Microstructure Test Observation*

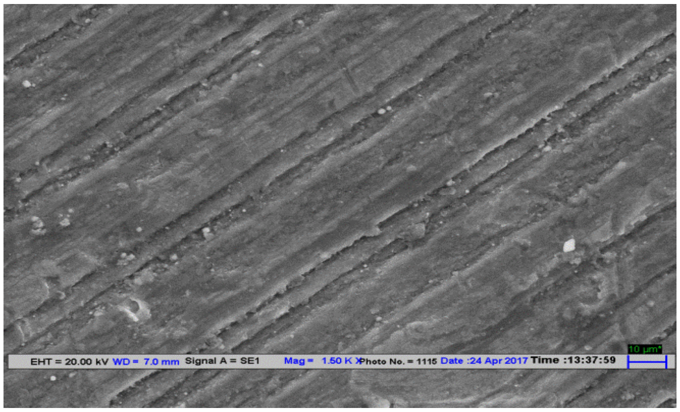

Figure 4(a) *SEM microstructures of specimen of single pass FSPed with SiC particles under magnifications of 250X*

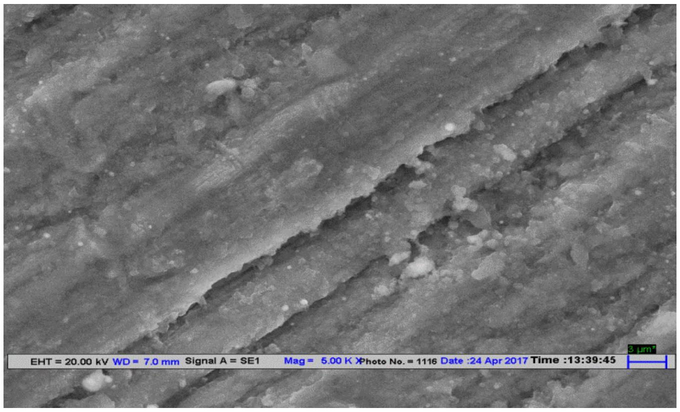

Figure 4(b) *SEM microstructures of specimen of single pass FSPed with SiC particles under magnifications of 1.50KX*

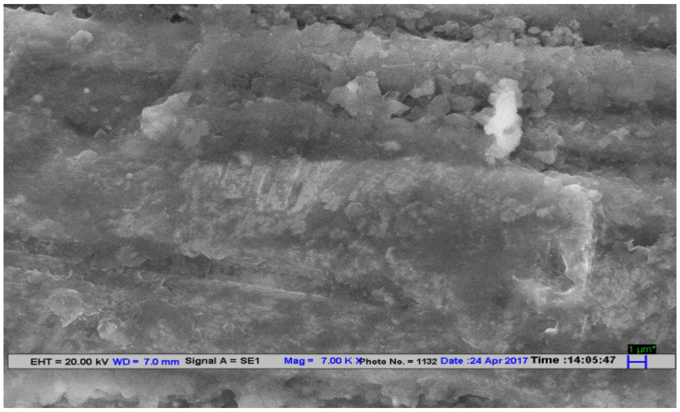

Figure 4(c) SEM microstructures of specimen of single pass FSPed with SiC particles under magnifications of 5.0KX

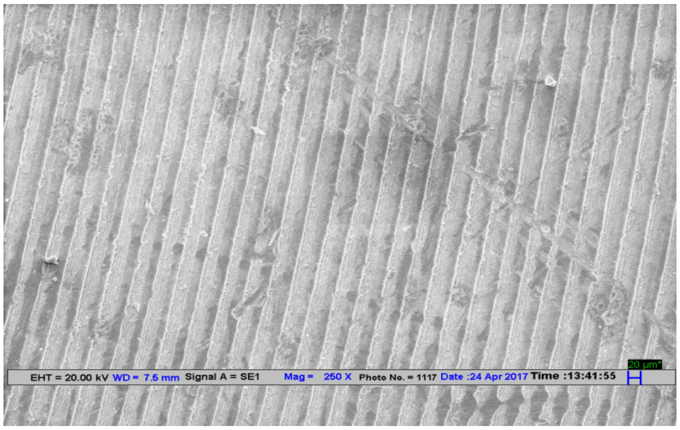

Figure 4 (d) *SEM microstructures of specimen of single pass FSPed with SiC particles under magnifications of 7.0KX*

The SEM microstructures of specimen of double pass FSPed with SiC particles under magnifications is explained in Fig-5 respectively.

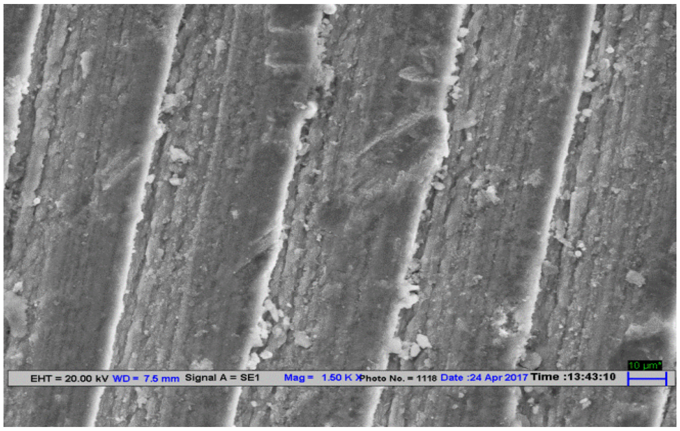

Figure 5(a) : SEM microstructures of specimen of double pass FSPed with SiC particles under magnifications of 250X

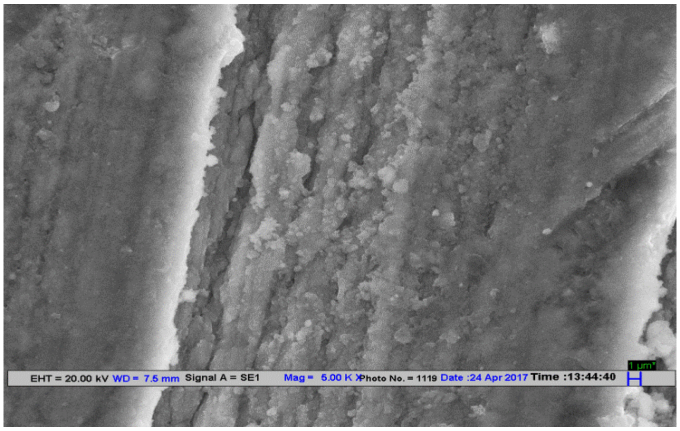

Figure 5(b): SEM microstructures of specimen of double pass FSPed with SiC particles under magnifications of 1.50KX

(b)

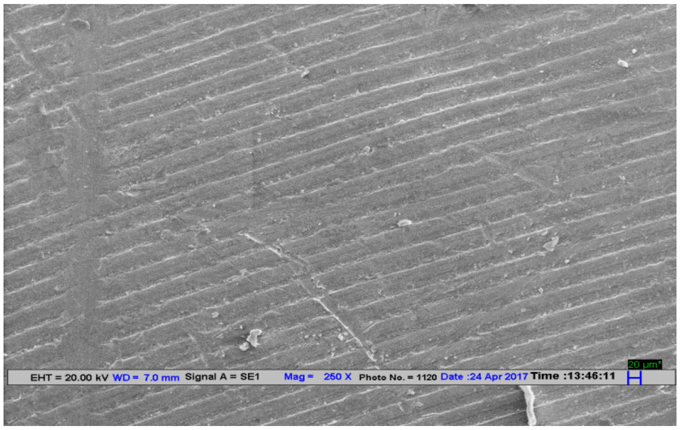

Figure 5(c).: SEM microstructures of specimen of double pass FSPed with SiC particles under magnifications of 5.0KX

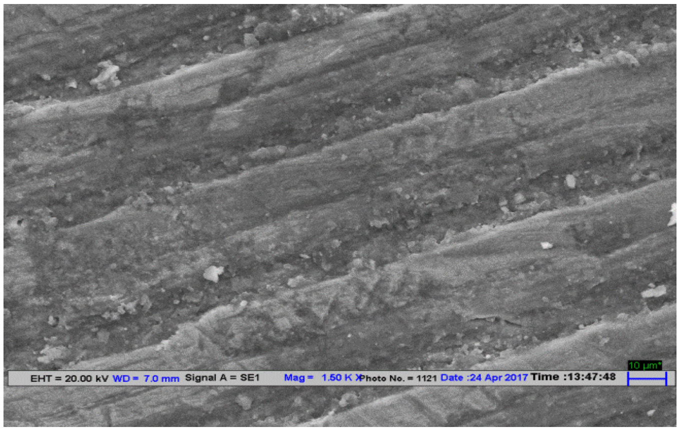

Figure 5(d) .: SEM microstructures of specimen of double pass FSPed with SiC particles under magnifications of 7.00KX

The SEM microstructures of specimen of triple pass FSPed with SiC particles under different magnifications of (a) 250X (b) 1.50KX(c) 5.0 KX, (d) 7.00KX are given in Fig-6 respectively.

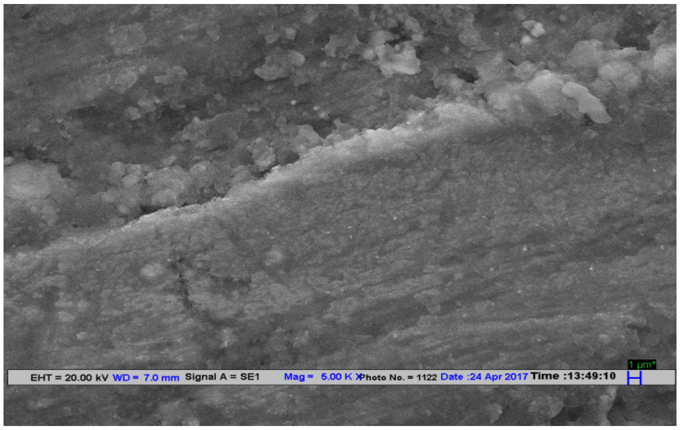

Figure-6(a): SEM microstructures of specimen of triple pass FSPed with SiC particles under magnifications of 250X

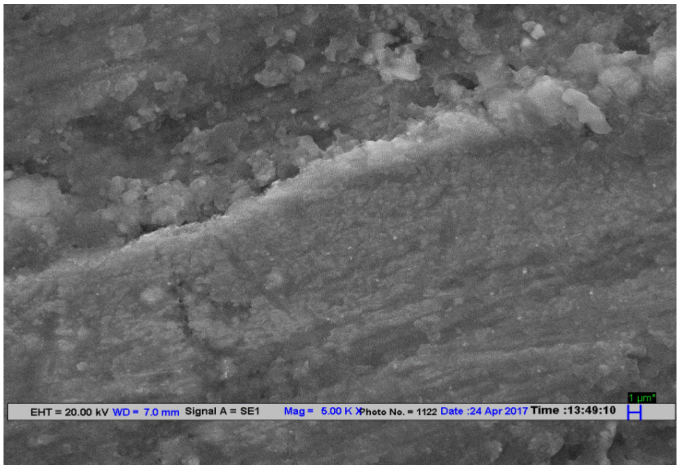

Figure-6(b): SEM microstructures of specimen of triple pass FSPed with SiC particles under magnifications of 1.5KX

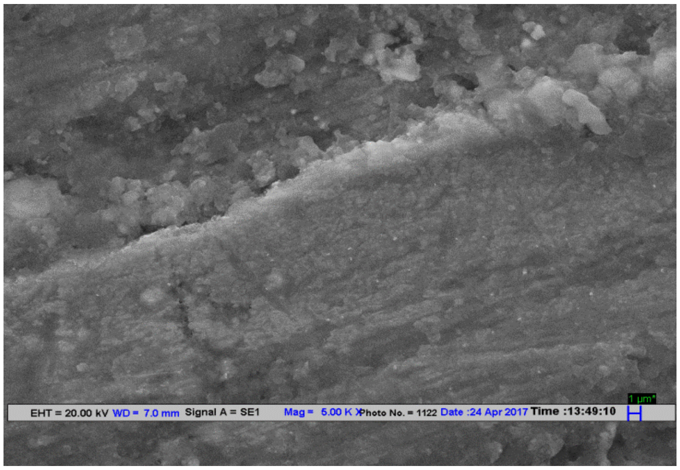

Figure-6(c): SEM microstructures of specimen of triple pass FSPed with SiC particles under magnifications of 5.0KX

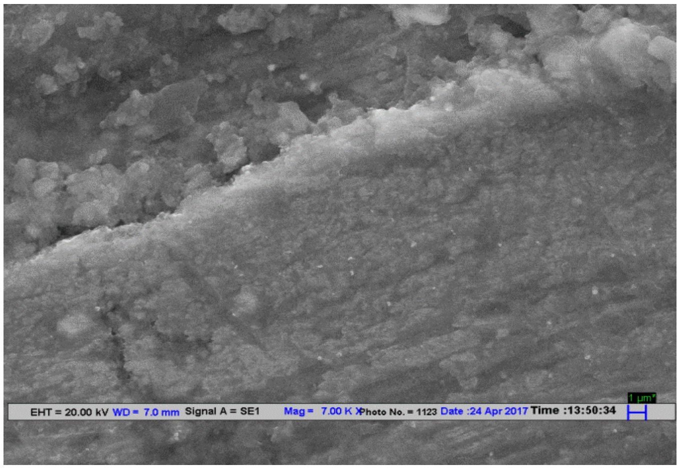

Figure -6(d) SEM microstructures of specimen of triple pass FSPed with SiC particles under magnifications of 7.00KX

The SEM microstructures of specimen of single pass FSPed without SiC particles under magnifications of (a)250X (b)1.50KX(c) 5.00KX(d)7.00KX is given in Fig-7 respectively

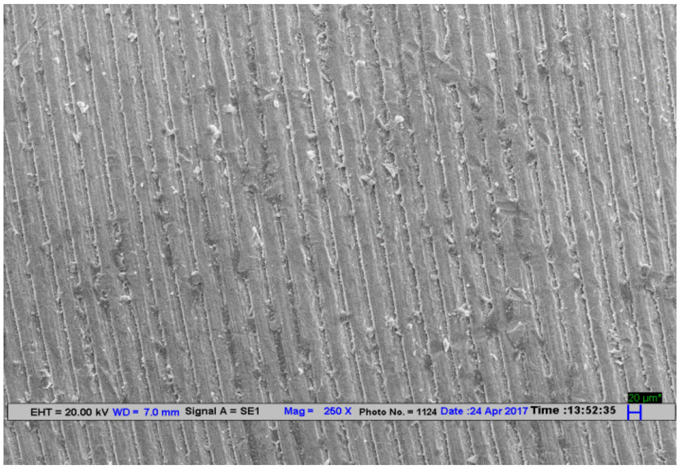

Figure 7 (a): SEM microstructures of specimen of single pass FSPed without SiC particles under magnifications of 250X

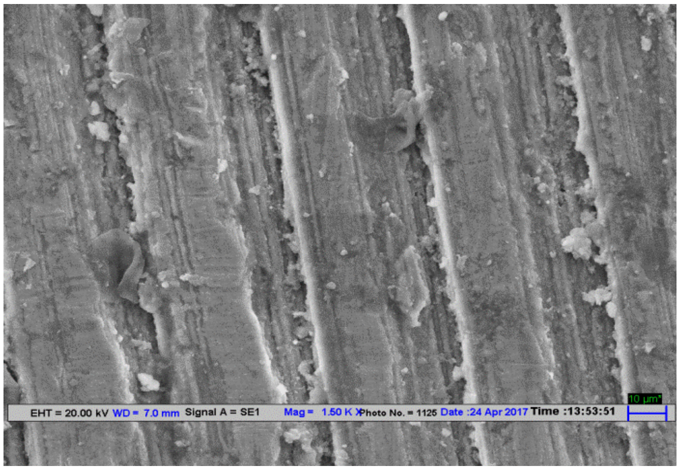

Figure 7 (b): SEM microstructures of specimen of single pass FSPed without SiC particles under magnifications of 1.50KX

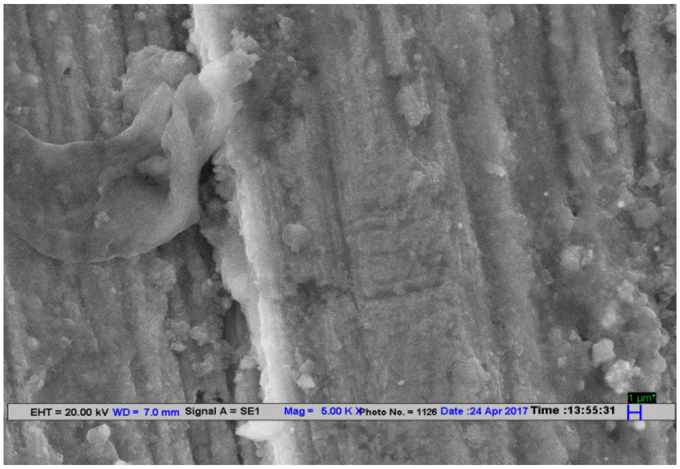

Figure 7(c): SEM microstructures of specimen of single pass FSPed without SiC particles under magnifications of 5.00KX

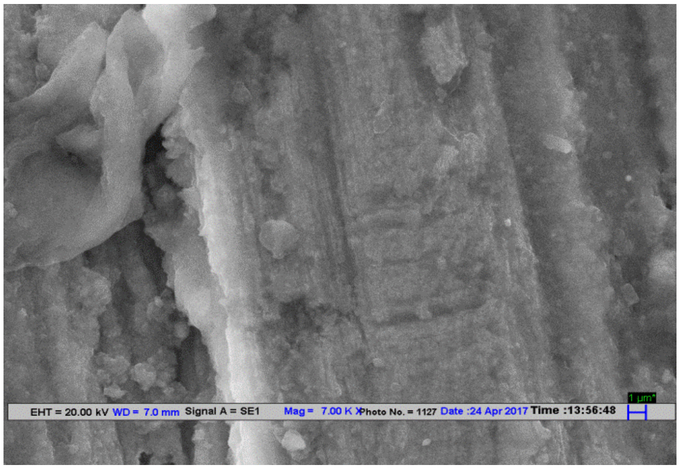

Figure 7(d): SEM microstructures of specimen of single pass FSPed without SiC particles under magnifications of 7.00KX

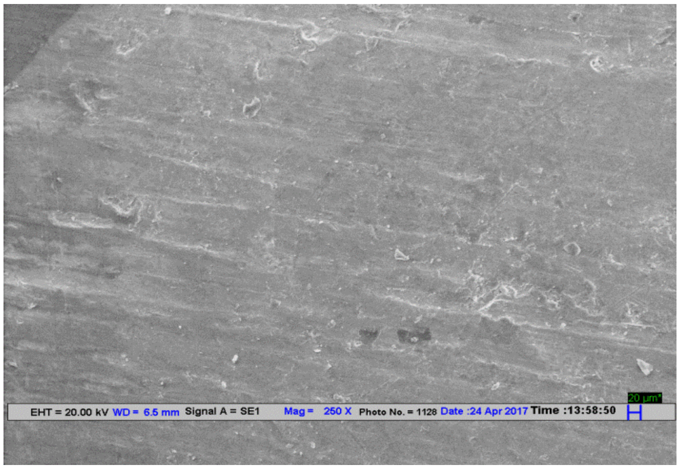

Figure 8(a): SEM microstructures of parent aluminium specimen under magnifications of 250X

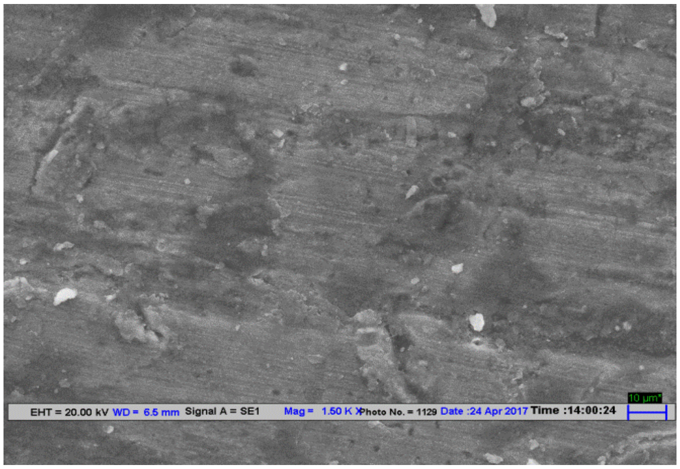

Figure 8(b): SEM microstructures of parent aluminium specimen under magnifications of 1.50KX

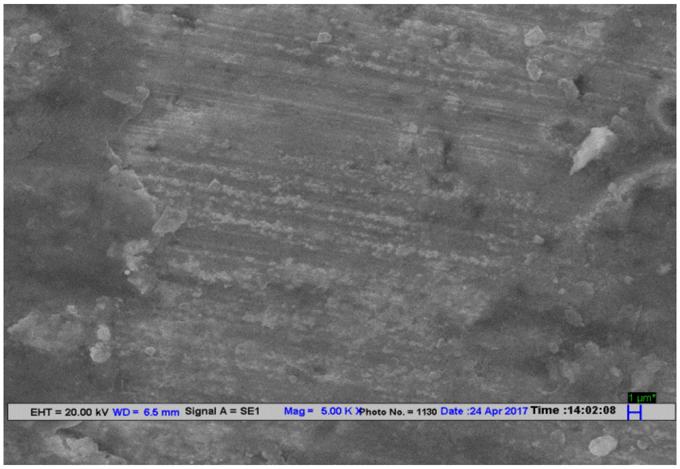

Figure 8 (c): SEM microstructures of parent aluminium specimen under magnifications of 5.00KX

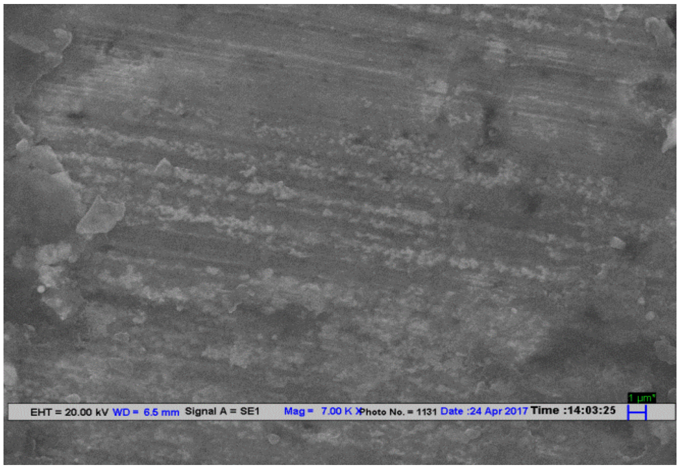

Figure 8(d): SEM microstructures of parent aluminum specimen under magnifications of 7.00KX

3.9 Pin On Disc Wear Testing

The wear test was conducted on Pin-on-Disc Wear Testing Machine available in the Dynamics of Machine (DOM) Laboratory in Delhi Technological University.

Figure 9: Pin on Disc Wear Testing Machine in DOM Laboratory, DTU

3.10 Wear Test Procedure

- Connect the power input cable to 230V, 50Hz and 15 Amps supply. Switch ON controller, allow 5 minutes for normalizing all electronic items. Thoroughly clean specimen pin with emery paper to remove burs from the circumference
- Clean the wear disc thoroughly with acetone and clamp it on holder using four screws
- Clean the specimen with acetone and weigh it by using a digital balance
- Insert specimen pin inside hardened jaws and clamp to specimen holder, set the height of the specimen pin above the wear disc using adjustment block. The adjustment block ensures the loading arm is always parallel. Tighten clamping screws on jaws to clamp specimen pin firmly. Swivel off the height adjustment block away from loading arm
- Add the required load
- Set required wear track radius by removing the sliding plate over graduated scale on base plate. Tighten all 6 no's of clamping screws to ensure assembly is clamped firmly

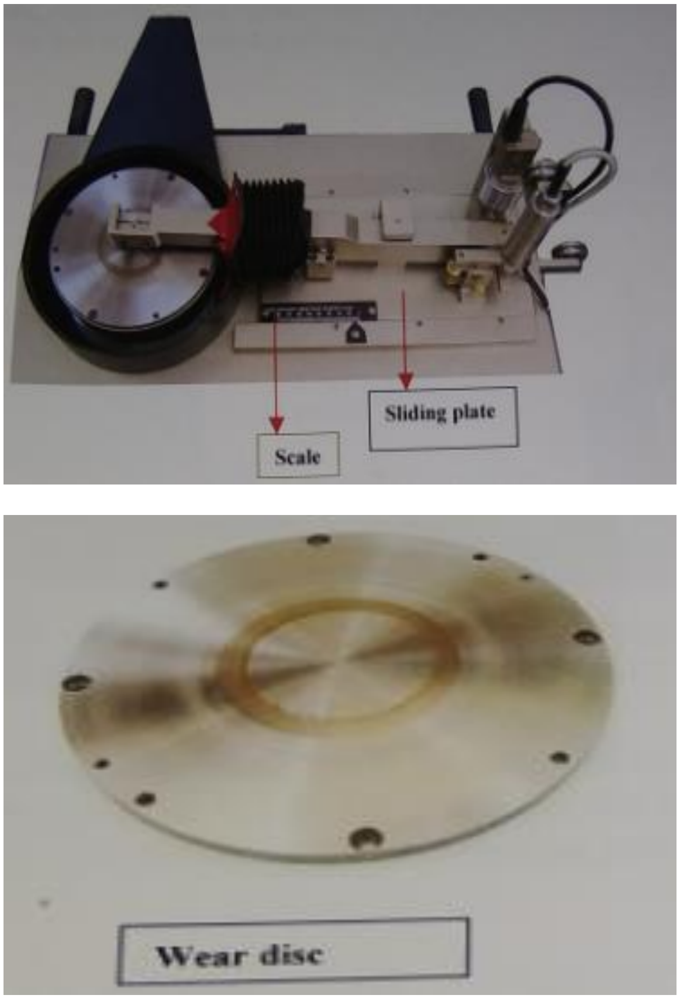

Figure 10: Disc and Specimen Mounting Location [39]

3.11 Wear Test Working Parameters

- Normal Load Applied(F) : 5kg (49.033N)
- Revolutions per minute (RPM) : 500
- Sliding Distance(L) : 3000m
- Pin Diameter : 10mm
- Pin Length : 32mm
- Disc Diameter : 165mm
- Disc material : EN31

3.12 Wear Test Observations

Table 7: Wear Amount Values

Specimen	Specimen Designation	Initial Weight (gm)	Final Weight (gm)	Weight Loss (gm)
Specimen with SiC single pass processing	1	17.1934	17.1735	0.0199
Specimen with SiC double pass processing	2	17.2813	17.2628	0.0185
Specimen with SiC triple pass processing	3	17.2513	17.2375	0.0138
Specimen without SiC single pass processing	4	17.2272	17.2057	0.0215
Specimen without processing- Base material	5	17.2993	17.2765	0.0228

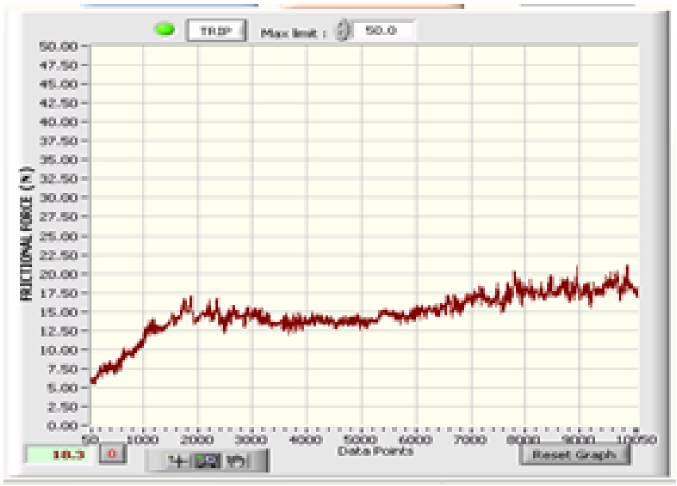

Figure 11: Specimen with SiC single pass processing

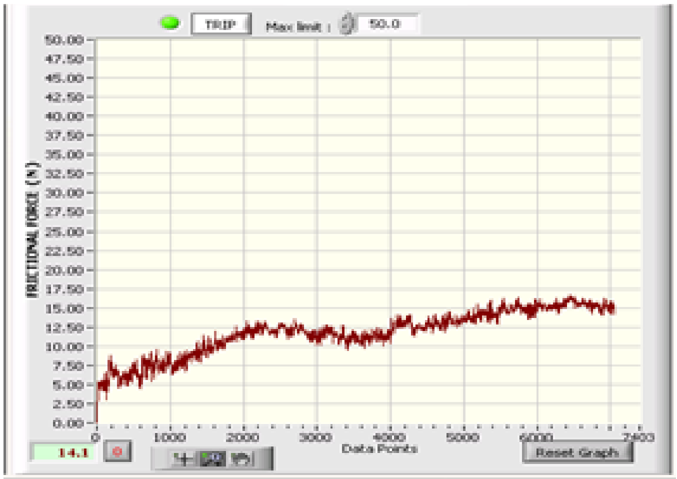

Figure 12: Specimen with SiC double pass processing

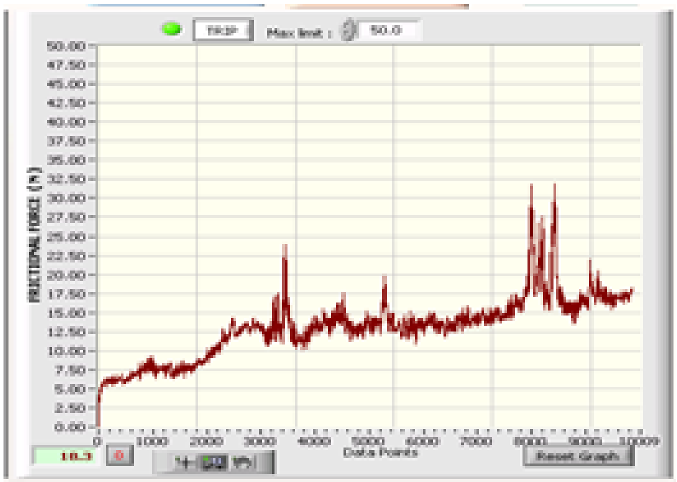

Figure 13: Specimen with SiC triple pass processing

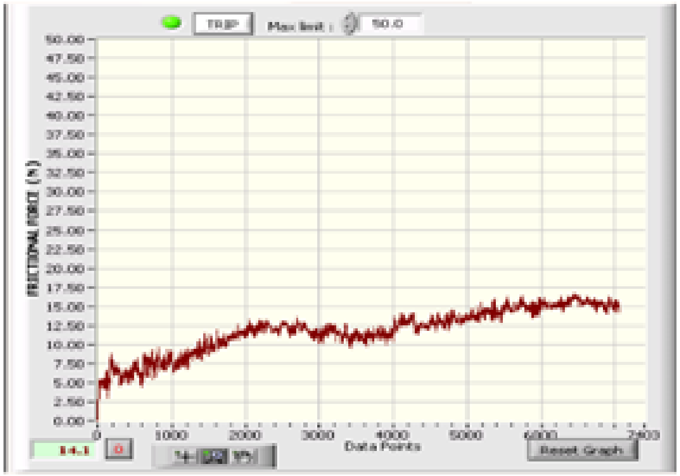

Figure 14: Specimen without SiC single pass processing

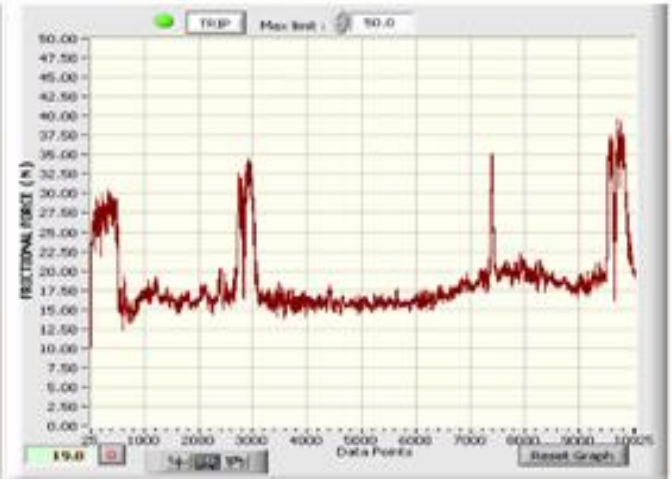

Figure 15: Specimen without processing-Base metal

4. Result and Discussion

The various tests conducted on FSW are given below.

4.1 Tensile Test

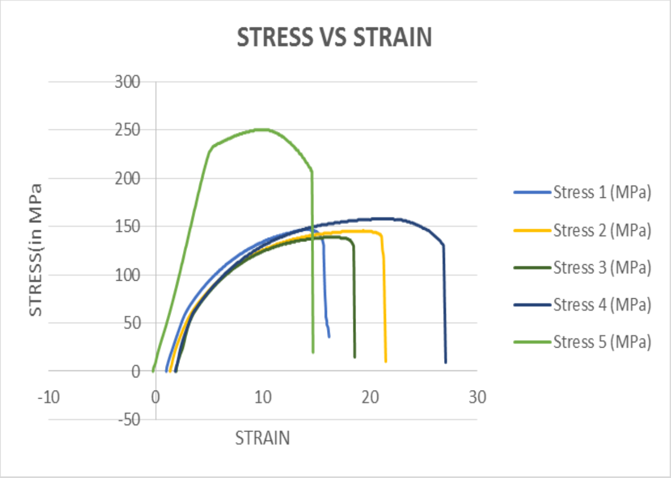

Figure 16: Stress vs Strain comparison for all specimens

1- Specimen with SiC single pass processing
2- Specimen with SiC double pass processing
3- Specimen with SiC triple pass processing
4- Specimen without SiC single pass processing
5- Specimen without processing

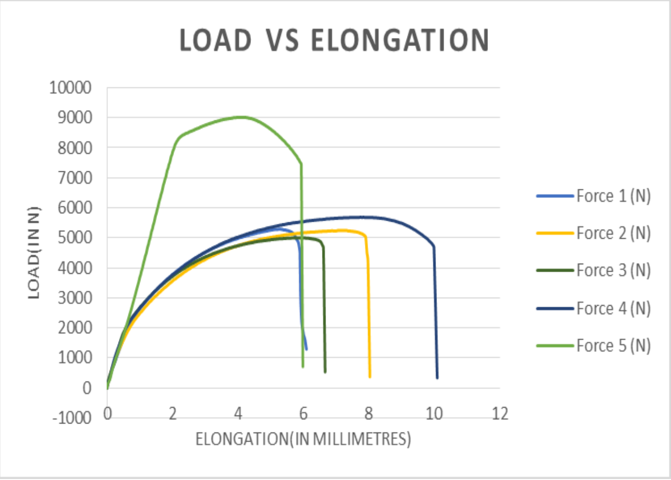

Figure 17: Load vs Elongation comparison for all specimens

1- Specimen with SiC single pass processing.
2- Specimen with SiC double pass process.
3- Specimen with SiC triple pass processing.
4- Specimen without SiC single pass processing.
5- Specimen without processing

- The ultimate tensile strength of the processed material came out to be lesser than the parent material.
- The results reported in Table showed that with the increase in the number of passes, the tensile properties of composites including ultimate tensile strength (UTS) and yield strength (YS) improved due to reduced porosity contents and improved bonding between SiC particles and copper matrix leading to elimination of interfacial de-bonding and also formation of more cohesive bonding.

4.2 Vickers Hardness Test

Table 8: Vickers Hardness Test Results

Specimen	Specimen Description	Vickers test parameter	Result	Test method
1	Without Silicon Carbide and without processing	Vickers hardness number(HV1)	58-62	IS 1501(Part-1)-2013
2	Single pass processing Without Silicon Carbide	Vickers hardness number(HV1)	59-64	IS 1501(Part-1)-2013
3	Single pass With Silicon Carbide	Vickers hardness number(HV1)	62-66	IS 1501(Part-1)-2013
4	Double passes With Silicon Carbide	Vickers hardness number(HV1)	64-67	IS 1501(Part-1)-2013
5	Triple passes With Silicon Carbide	Vickers hardness number(HV1)	98-102	IS 1501(Part-1)-2013

- We can see the Vickers hardness of the processed specimen increases as the number of passes is increased due to the more compact microstructure. The Vickers hardness number comes out to be highest for third pass in comparing with single, double passes and parent material.
- The hardness results showed that the specimen with maximum number of passes showed maximum hardness with the average value of 100HV whereas the parent material without any processing had an average of 60HV hardness value.
- The possible strengthening mechanisms which may operate in particle-reinforced metal matrix composites are:
  - ➢ Orowan strengthening.
  - ➢ Grain and substructure strengthening.
  - ➢ Quench hardening resulting from the dislocations generated to accommodate the differential thermal contraction between the reinforcing particles and the matrix.
  - ➢ Work hardening, due to the strain misfit between the elastic reinforcing particles and the plastic matrix.
- According to the characteristics of the microstructure, the major contributions to the hardness of the surface composite layers fabricated by FSP are:
  - ➢ Fine grain size of the Al matrix, and
  - ➢ Orowan strengthening due to the fine dispersion of nano-sized Al2O3 particles.
- For the 6082 Al alloy with no alumina powder, after three FSP passes, microhardness profile shows a general softening and reduction of hardness in the stirred zone in contrast to that of the as-received Al. The hardness of as-received Al has an average of 100Hv. The stirred zone has a lower hardness than that of the as-received Al in spite of smaller grain size. The result means that the hardness distribution of stirred zone was independent with grain size considering Hall–Petch relation.
- Therefore, other factors may govern the mechanical properties of stirred zone such as precipitations and dislocation density. As reported in literature studies, it seems that the softening of the stirred zone was result of coarsening (and dissolution) of strengthening precipitates during the FSP of heat-treatable (precipitation hardenable) Al alloys.

4.3 Wear Test Conclusion

Table 9: Wear rate and Coefficient of Friction Values

Specimen Designation	Test Duration (sec)	Wear Rate (gm/sec)$\times 10^{-5}$
1	1023	1.808406647
2	1317	1.511009871
3	1273	1.084053417
4	1023	2.101661779
5	1000	2.280000000

Table 9(b): Wear rate and Coefficient of Friction Values

Specimen Designation	Specific Wear Rate (gm/N-sec)× 10^{-5}	Sliding speed (m/s)
1	0.036881419	2.27765
2	0.030816182	2.93205
3	0.022108649	2.35611
4	0.042862190	2.93205
5	0.046499296	1.64927

Table 9(c): Wear rate and Coefficient of Friction Value

Specimen Designation	Average friction Force (N)	Coefficient of Friction
1	15.07345	0.30741442
2	12.89999	0.26308812
3	14.00714	0.28566766
4	11.91938	0.24308903
5	16.62290	0.33901464

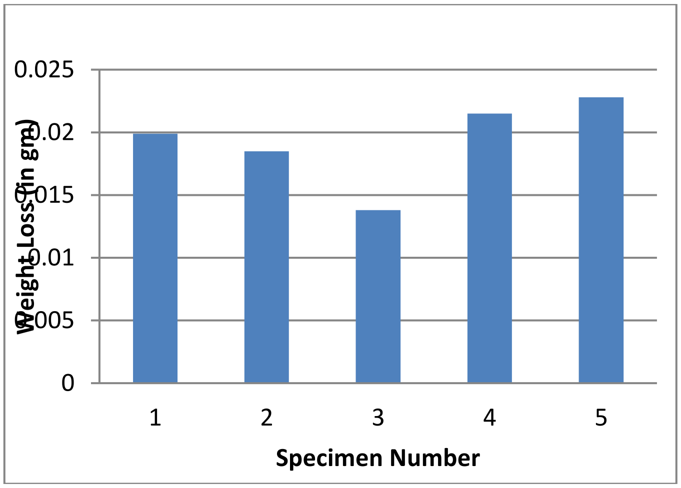

Figure 18: Comparison of Weight Loss

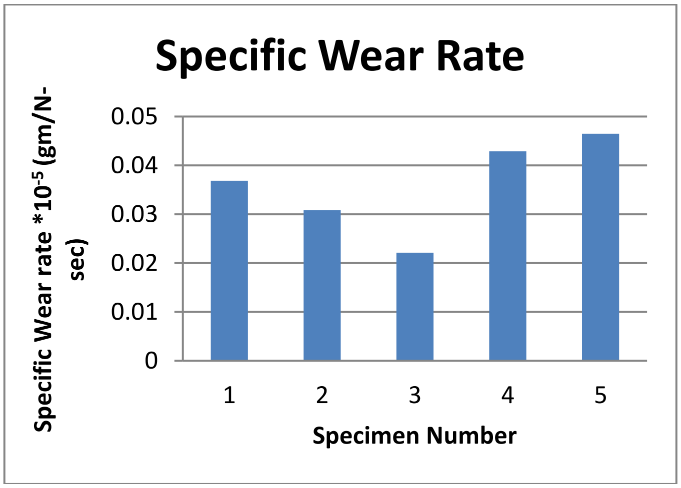

Figure 19: Comparison of Specific wear rate

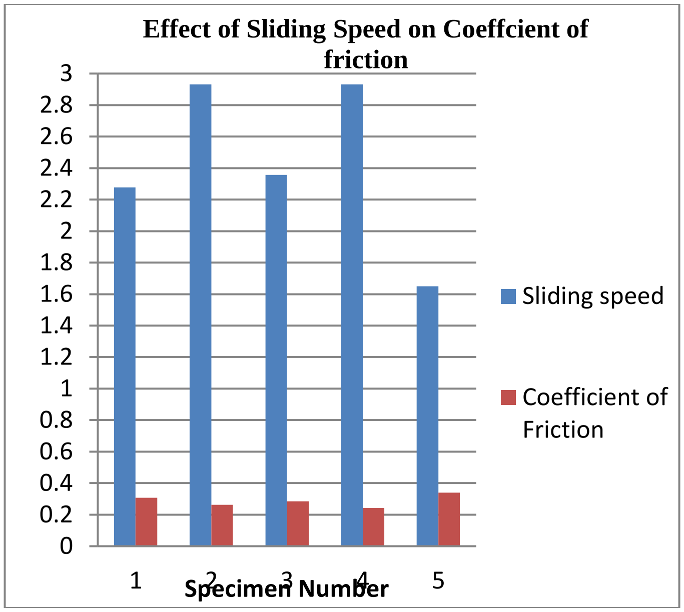

Figure 20: Effect of sliding speed on coefficient of friction

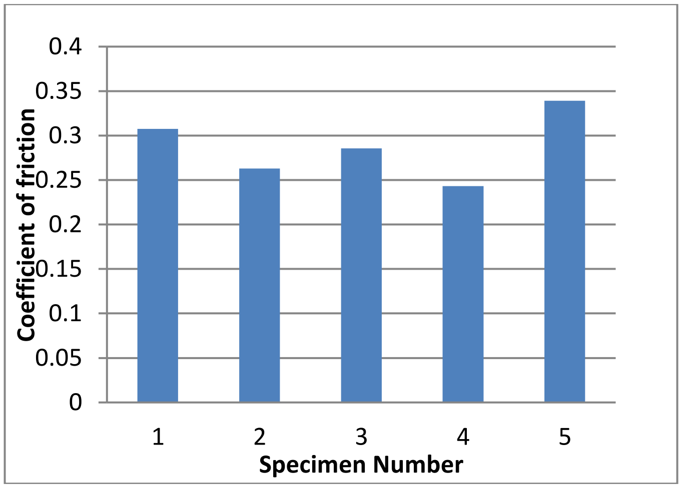

Figure 21: Comparison of coefficient of friction

5. Conclusion

- The lowest specific wear rate was observed for specimen 3 i.e. specimen with SiC triple pass processing and whereas the highest specific wear rate was observed for specimen 5 i.e. base metal. A general trend for wear rate was observed in which the wear rate decreased with the increase in the number of passes for the prepared metal matrix composite. Al-based metal matrix composite showed a decrease in wear rate with increasing content of SiC reinforcement because it acts as an obstacle to shear deformation.

Sliding speed was found to be the most influencing factor for coefficient of friction values. As the sliding speed increased, coefficient of friction decreased. The lowest coefficient of friction value was observed for specimen 4 and the highest coefficient of friction value was observed for specimen 5.

- The tribological properties of the composites exhibited better wear resistance properties. The wear resistance improved with the addition of SiC reinforcements to the base alloy. The images above shows the highly magnified SEM images of the SZ after one pass, two pass and three pass processing, respectively. After one pass, the distribution of SiC particles is not homogeneous, indicating that the materials flow is not enough and the SiC particles cannot be scattered completely into the Al matrix by the stirring of the rotation tools. It could be found that triple pass Friction stir processing leads to a higher level of dispersion of SiC particles in the Aluminium matrix which could be because of the longer stirring action and stronger mechanical stress in Stir Zone compared to single pass FSP.
- It is also seen that single-pass Friction stir processing causes partial agglomeration of SiC particles leading to weaker mechanical and microstructural behavior. On the other hand, SiC particles become smaller upon increasing the Friction stir processing passes which may most probably due to the continuous disruption of these particles within the matrix during each pass.
- From the figures Stir zone of the specimens produced by Friction stir processing was characterized by fine and equaxied grain structure which is a result of recrystallization caused by concurrent severe plastic deformation and frictional heat. There seems to be two distinct reasons for grain size variation:
  - Heat input that causes annealing which increases the grain size,
  - Continuous dynamic recrystallization due to the stirring action of the tool pin which creates new nucleation sites leading to reduction of the grain size. It is clear from these results that in the stir zone of the specimens, a fine structure is obtained implying that the second reason is predominant.
- It can be seen that in the microstructures of the specimens Friction Stir Processed with SiC particles, the pinning effect of SiC particles gives rise to impediment of grain growth and consequently the grain size becomes smaller than those Friction stir processed without SiC particles. In comparison to the surface composite layer produced by one Friction stir processing pass, the surface composite layer produced by three Friction stir processing passes showed a better dispersion of SiC particles. It is considered that the pinning effect by the SiC particles retarded the grain growth of the dynamically recrystallized grains of Al matrix.

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