ANALYSIS OF MICROSTRUCTURE, MICROHARDNESS, TENSILE STRENGTH AND WEAR PROPERTIES OF AL 6082/SIC COMPOSITE 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, Aluminium 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 analysing the microstructure, microhardness, 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 - Friction Stir Processing, Aluminium 6082/SiC Composite, Tensile Strength, Pin-on-Disc Wear Analysis, Scanning Electron Microscopy, Vickers Hardness

I. 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.

Aluminium matrix composites (AMCs) are light weight high performance aluminium centric material systems which consist of a discrete constituent (the reinforcement) which is distributed in a continuous phase (the matrix). According to the different industrial demands, properties of AMCs can be tailored by appropriate fusion of matrix, reinforcement and processing route.

The major advantages of AMCs in comparison to unreinforced materials are as follows:

- Increase in hardness
- Reduced weight density
- Improved high temperature properties
- Increase in wear resistance
- Enhanced and tailored electrical performance
- Fine and equiaxed grains of the microstructure

Superior combination of properties of AMC material systems makes them unparallel in such a way that no existing monolithic material can rival. AMCs have been used many structural, non-structural and functional applications in different engineering sectors. Better performance, economic and environmental benefits are the factors due to which AMCs are gaining popularity and replacing aluminium alloys. AMCs are currently substituting monolithic materials including aluminium alloys, ferrous alloys, titanium alloys and polymer based composites in several applications worldwide. Friction stir processing is a short route-solid state processing technique which includes one processing step that achieves microstructural refinement densification and homogeneity. From the operational viewpoint, a friction stir processing run can be divided into three sub-procedures or phases:

- Plunge and Dwell
- Traverse
- Retract

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 displacement controlled mode (where tool position with respect to the workpiece surface is held constant) or 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.

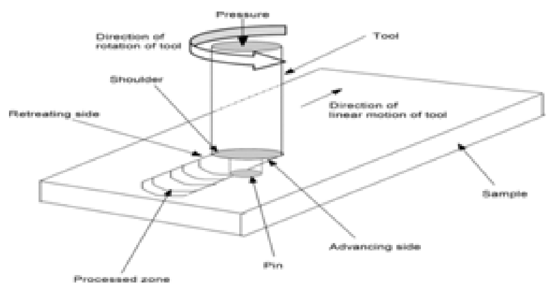


Fig. 1 Motion of Tool in Friction Stir Processing [1]

II. EXPERIMENTAL SETUP

2.1 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.

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 1: Chemical Composition of Aluminium 6082

Physical Property	Value
Density	Density 2.70 g/cm³
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 2: Physical Properties of Aluminium 6082

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

Table 3: Mechanical Properties of Aluminium 6082

2.2 Workpiece Details

Fig. 2 Single pass on the first Al workpiece without SiC

- Dimension: 200mm X 75mm X 6mm
- Number of workpieces: 5
- Composite: Aluminium 6082 + SiC particles
- Number of grooves per workpiece: 1
- Passes:
- Parent Aluminium workpiece without any processing on the first aluminium workpiece

- Single pass on the second Aluminium workpiece without SiC
- Single pass on the third Aluminium workpiece with SiC
- Double pass on the fourth Aluminium workpiece with SiC
- Triple pass on the fifth Aluminium workpiece with SiC

Fig. 3 Single pass on the second Al workpiece with SiC

Fig. 4 Double pass on the third Al workpiece with SiC

Fig. 5 Triple pass on the fourth Al workpiece with SiC

2.3 Procedure Details

The materials used were Aluminium 6082 and Silicon Carbide particles to fabricate Al-SiC composites. The specimen size of the plate was 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 in the middle of the plate. The tool Material used was H13 steel. The tool profile was Cylindrical threaded with shoulder diameter 15mm, threaded pin diameter 5 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 lay just above the centre of the groove cut. First Pass was made along the length of the job. The remaining passes were made along the length of the job after cooling the plate for 5-10 minutes. First workpiece was not processed as base metal was required for comparing results. Single pass was made on the second workpiece without SiC. SiC particles were inserted in the groove of the third workpiece and were processed once (single pass). Again, SiC particles were inserted in the groove of the fourth workpiece and were processed twice (double pass). Lastly, SiC particles were inserted in the groove of the fifth workpiece and were processed thrice (triple pass).

Fig. 6 Friction stir welding / processing machine (Central workshop, DTU)

2.4 Parameters Used During FSP

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

Table 4: Parameters used in Friction Stir Processing

2.5 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.

Fig. 7 Machine used for tensile testing of specimens, Metal Forming Laboratory, Delhi Technological University

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

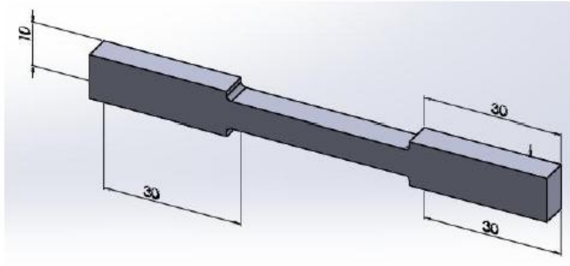


Fig. 8 Ultimate tensile testing specimen

The following graphs shows the relation between stress V/s strain and load force V/s elongation for the all the tested specimens

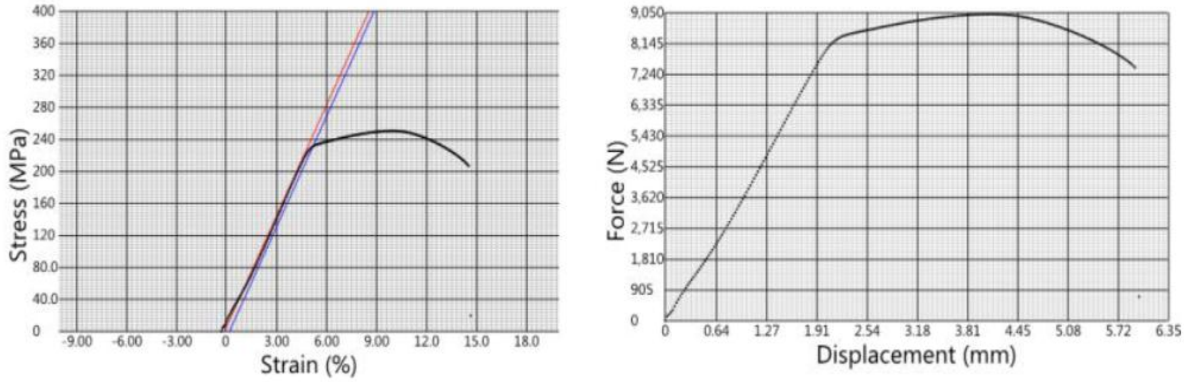


Fig. 9 Stress-Strain and Force-Displacement curves for specimen without processing

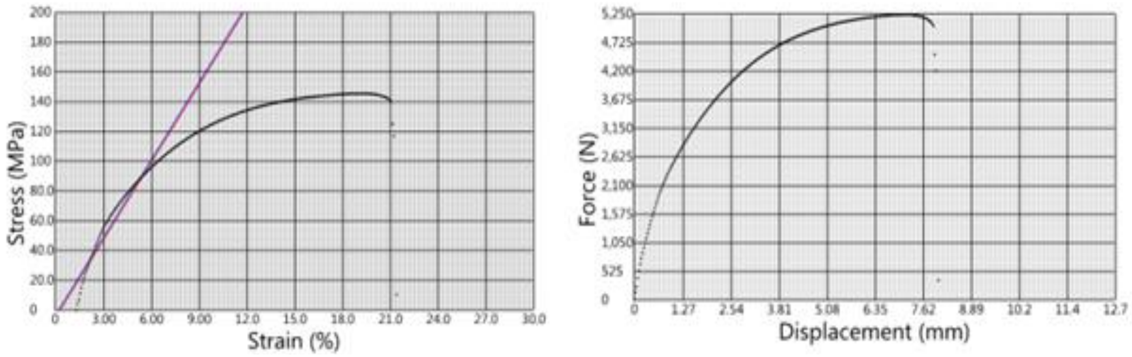


Fig. 10 Stress-Strain and Force-Displacement curves for specimen with SiC double pass processing

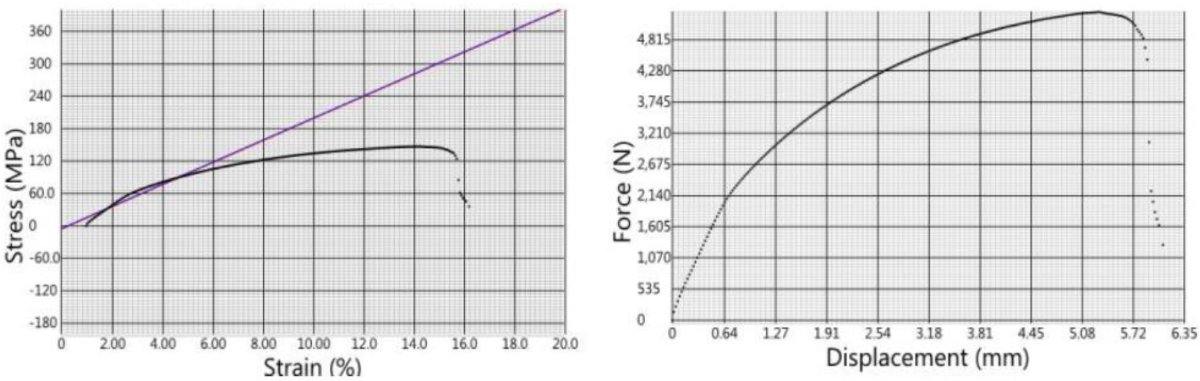


Fig. 11 Stress-Strain and Force-Displacement curves for specimen with SiC triple pass processing

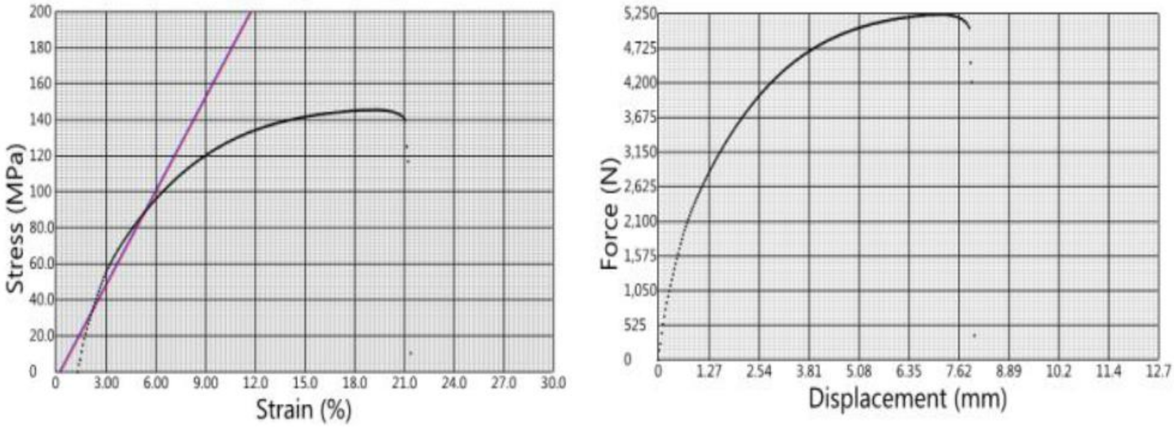


Fig. 12 Stress-Strain and Force-Displacement curves for specimen with SiC single pass processing

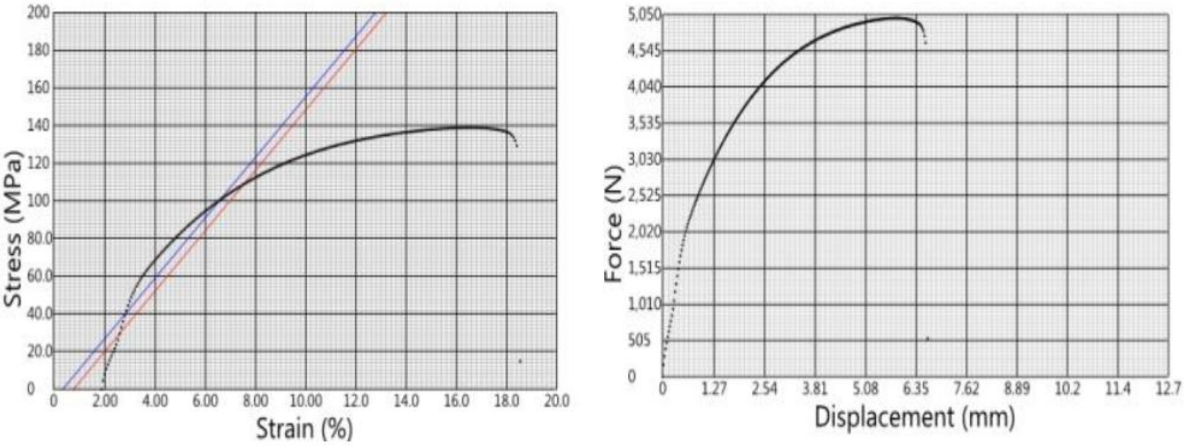


Fig. 13 Stress-Strain and Force-Displacement curves for specimen without SiC single pass processing

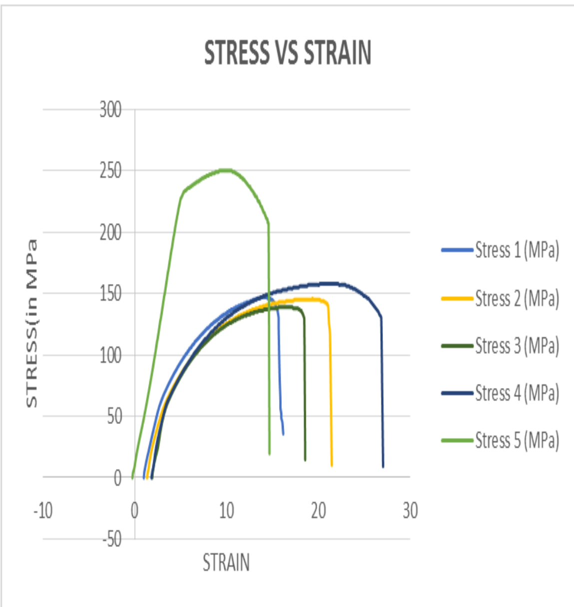


Fig. 14 Stress V/s Strain comparison for all specimens

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

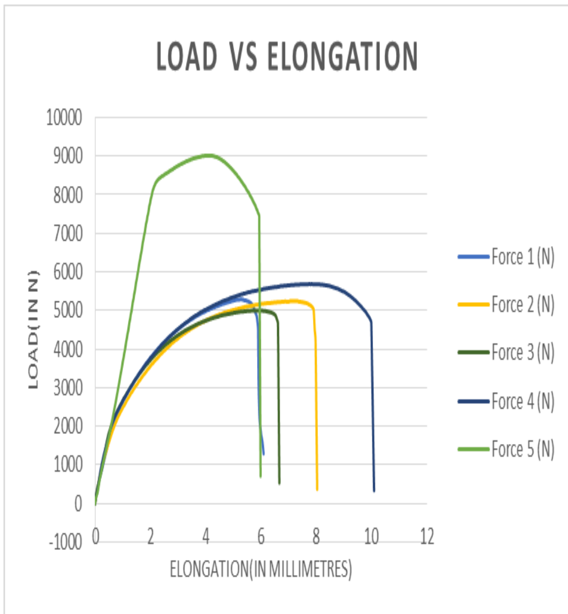


Fig.15 Load V/s Elongation comparison for all specimens

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

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	140
Offset @ 0.2% (N)	8320	3660
Offset @ 0.2% (MPa)	231	102
TE (Auto) (%)	14.6	26.8

Table 5: Specimens Details and Output Results during Tensile Tests

Output (Generic metals tensile from position)	Single Pass With SiC	Two Pass With SiC	Three 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	158
Offset @ 0.2% (N)	3190	3150	3620
Offset @ 0.2% (MPa)	88.5	87.5	101
TE (Auto) (%)	15.7	18.3	21.1

Table 6: Specimens Details and Output Results during Tensile Tests

2.6 Vickers Microhardness Test

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load of 1 to 100 kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf by the square area of indentation. Specimen dimensions:

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

The following table shows the effect on Microhardness

Specimen Designation	Specimen Description	Vickers test parameter	Observed result
5	Without Silicon Carbide and without processing	Vickers hardness number(HV1)	58-62
4	Single pass processing Without Silicon Carbide	Vickers hardness number(HV1)	59-64
1	Single pass With Silicon Carbide	Vickers hardness number(HV1)	62-66
2	Double passes With Silicon Carbide	Vickers hardness number(HV1)	64-67
3	Triple passes With Silicon Carbide	Vickers hardness number(HV1)	98-102

Table 7: Vickers Hardness Observation Table

2.7 Microstructure Test

Scanning Electron Microscopy Test was conducted at the SEM Facility of IIT Delhi to determine the microstructure of the specimens. The instrument used was ZEISS EVO Series Scanning Electron Microscope EVO 18.

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

Fig. 16 Scanning electron microscopy facility, Department of Textile Technology Indian Institute of Technology, Delhi

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.

The following images show the effect on microstructure with the change in the number of passes:

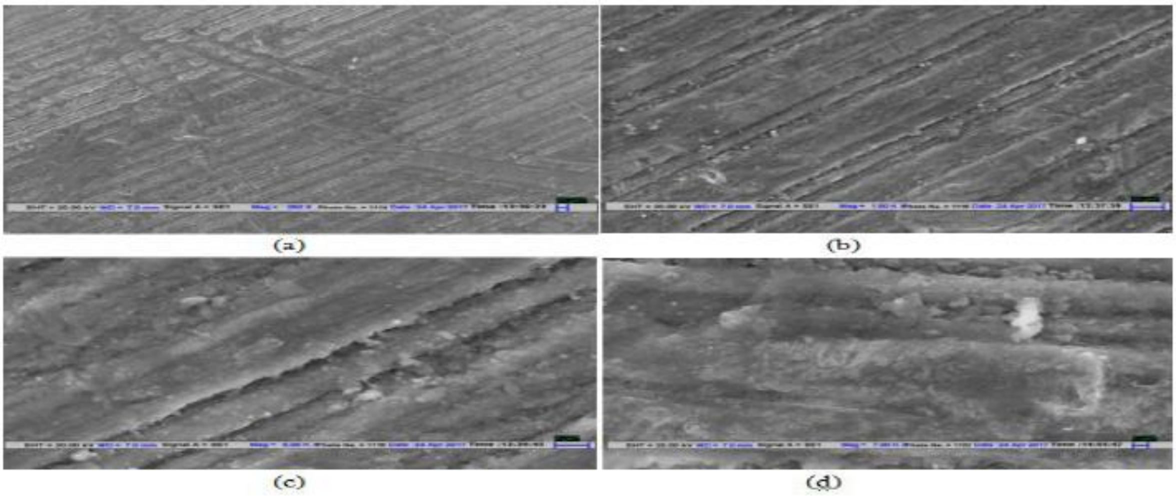
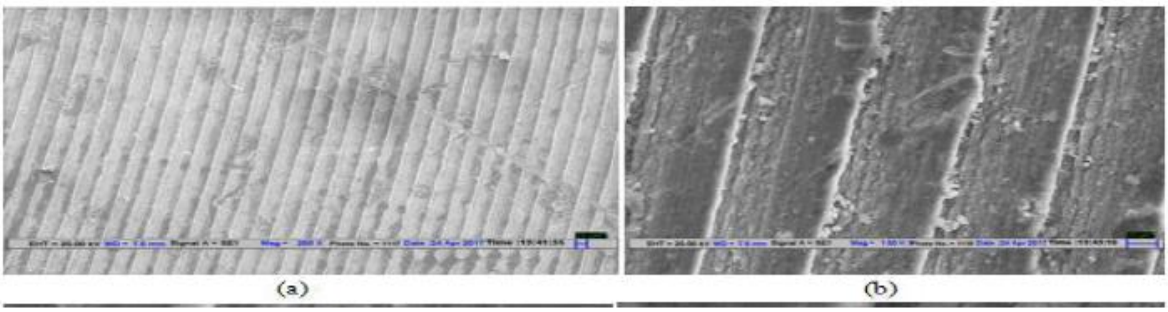


Fig. 17 SEM microstructures of specimen of single pass FSPed with SiC particles under magnifications of (a) 250X (b) 1.50KX (c) 5.00KX (d) 7.00KX



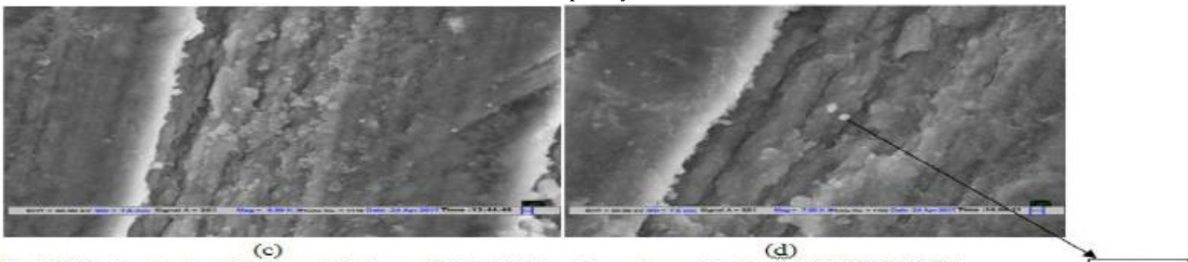


Fig. 18 SEM microstructures of specimen of double pass FSPed with SiC particles under magnifications of (a)250X(b)1.50KX(c) 5.00KX(d)7.00KX

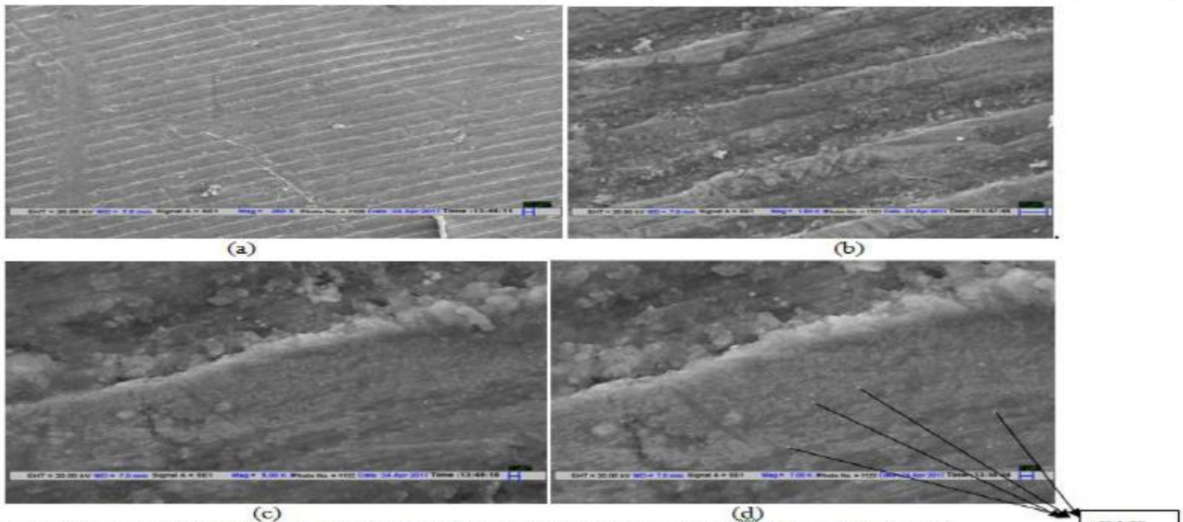


Fig. 19 SEM microstructures of specimen of triple pass FSPed with SiC particles under magnifications of (a) 250X (b)1.50KX(c) 5.00KX(d)7.00KX

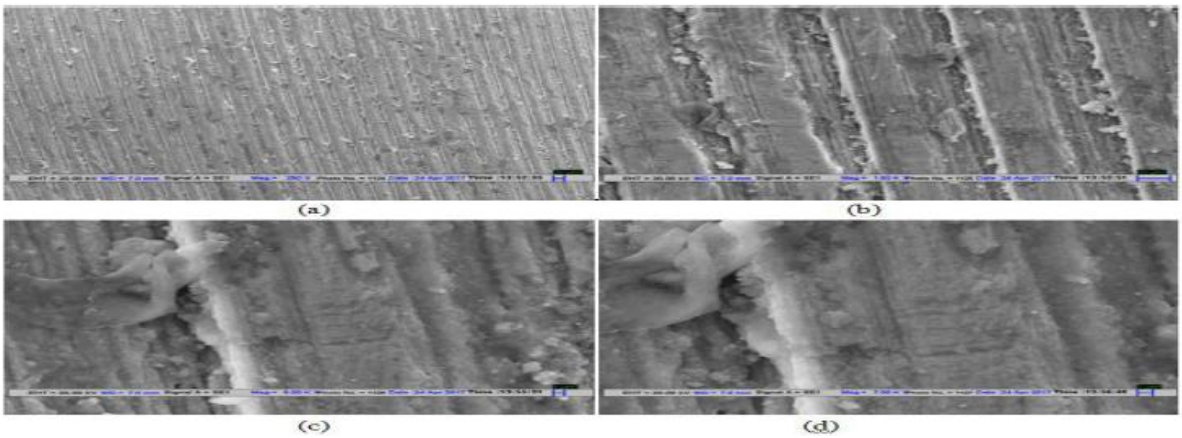


Fig. 20 SEM microstructures of specimen of single pass FSPed without SiC particles under magnifications of (a)250X (b)1.50KX(c) 5.00KX(d)7.00KX

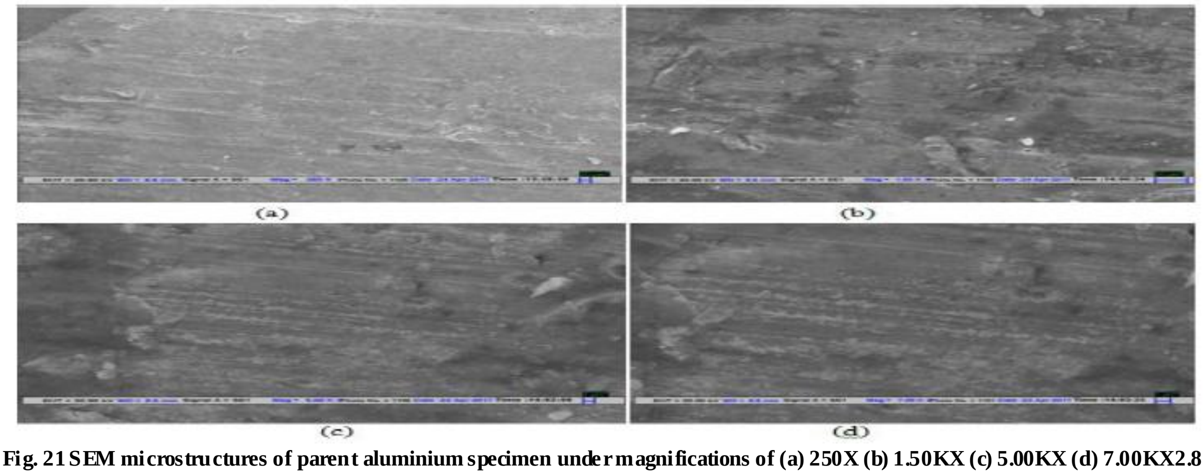


Fig. 21 SEM microstructures of parent aluminium specimen under magnifications of (a) 250X (b) 1.50KX (c) 5.00KX (d) 7.00KX2.8

Wear Test

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

Fig. 22 Pin on Disc Wear Testing Machine in DOM Laboratory, DTU

Testing 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
- The machine is now operated through a software on a PC
- Enter Load value, pin diameter value, rpm value and time duration value in the software.
- Click ACQUIRE button and set the starting values of parameters are zero
- Click RUN button to start the test. Test stops automatically after the elapse of preset time. The system can also be manually stopped by clicking on the STOP button
- Take the specimen out of the specimen holder and weigh it by using a digital balance after cleaning it with acetone
- Repeat the procedure for the remaining samples
- Study the pattern and compare graphs of all the specimens. Calculate the wear rate and coefficient of friction of each specimen

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

Test Observations of Al 6082/SiC composite using pin-on-disc wear testing machine is shown:

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

Table 8: Wear Amount Values

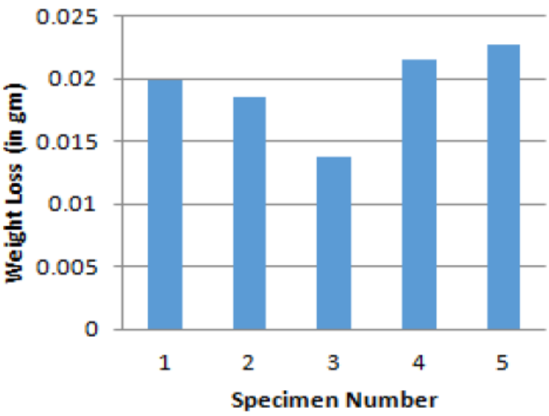


Fig. 23 Comparison of Weight Loss

Specimen Designation	Test Duration (sec)	Wear Rate (gm/sec)$\times 10^{-5}$	Specific Wear Rate (gm/N-sec)$\times 10^{-5}$
1	1023	1.808406647	0.03688141
2	1317	1.511009871	0.03081618
3	1273	1.084053417	0.02210864
4	1023	2.101661779	0.04286219
5	1000	2.280000000	0.04649929

Table 9: Wear Rate Values

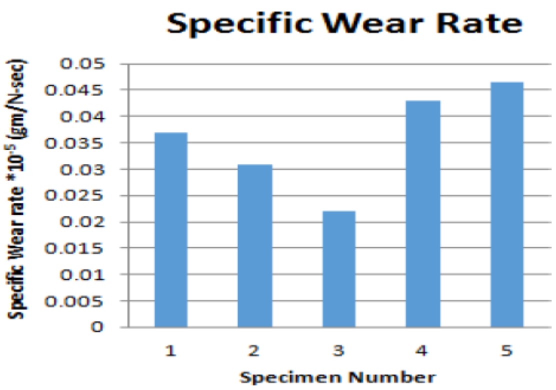


Fig. 24 Comparison of Specific wear rate

Specimen Designation	Test Duration (sec)	Sliding speed (m/s)	Average friction force (N)	Coefficient of Friction
1	1023	2.27765	15.07345	0.30741
2	1317	2.93205	12.89999	0.26308
3	1273	2.35611	14.00714	0.28566
4	1023	2.93205	11.91938	0.24308
5	1000	1.64927	16.62290	0.33901

Table 10: Coefficient of Friction Values

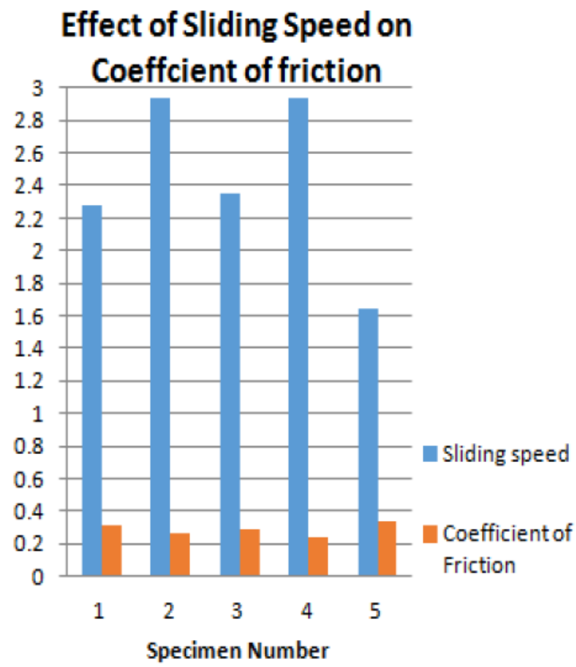


Fig. 25 Effect of sliding speed on coefficient of friction

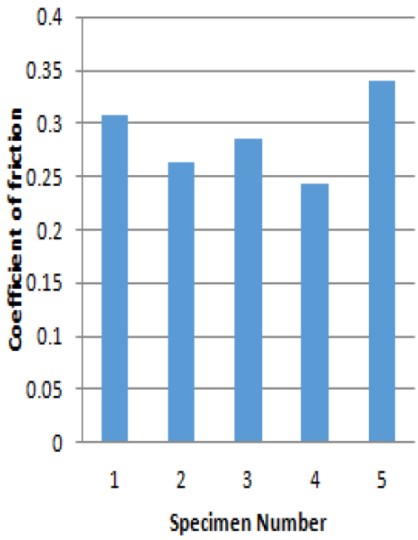


Fig. 26 Comparison of coefficient of friction

The following graphs helps in analysing the friction force and coefficient of friction for each specimen. The graphs also shows the effect on friction force with the change in the number of passes

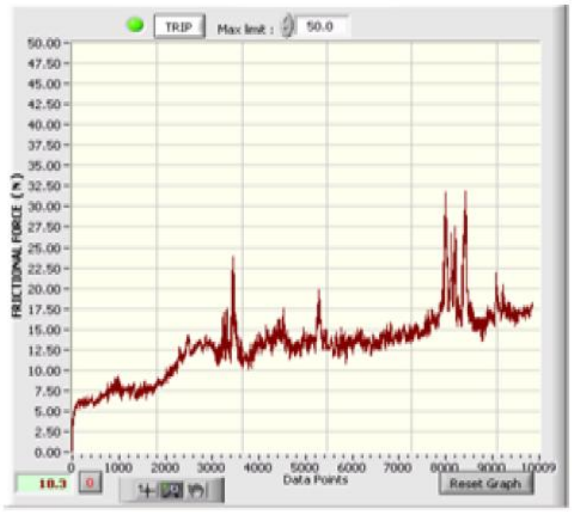


Fig. 27 Frictional force graph for specimen 3

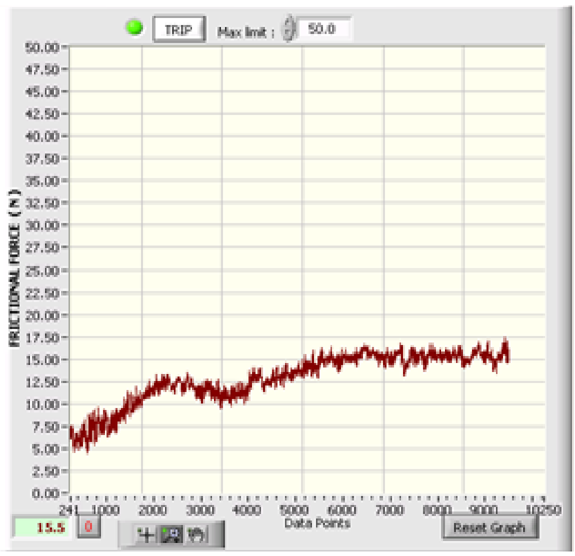


Fig. 28 Frictional force graph for specimen 2

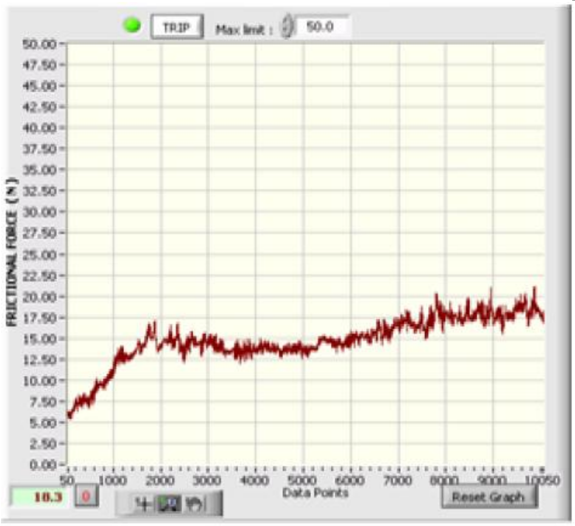


Fig. 29 Frictional force graph for specimen 1

Fig. 30 Frictional force graph for specimen 4

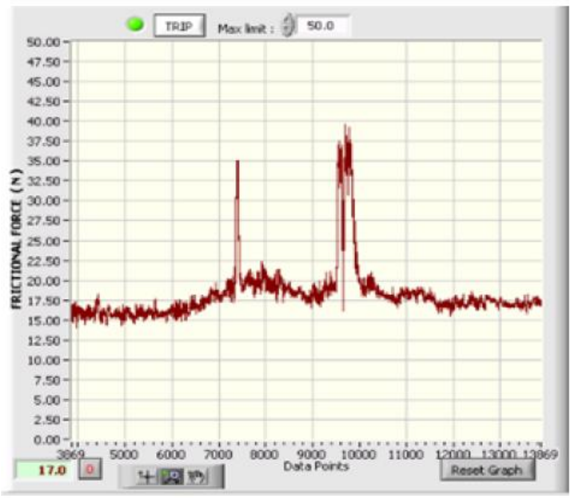


Fig. 31 Frictional force graph for specimen 5

III. RESULTS AND DISCUSSIONS

- Vickers hardness of the processed specimen increased 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 highly magnified SEM images of the SZ after one pass, two pass and three pass processing shows that 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.
- 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.

CONCLUSIONS

Effect on microstructure, microhardness, tensile strength and wear properties with the number of passes was studied and the major conclusions observed from the tests are:

- Vickers hardness of the processed specimen increased as the number of passes increased. 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 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 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.
- 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.

ACKNOWLEDGEMENTS

This complete research could not have been accomplished without the contribution of a number of people. We take it as a privilege to appreciate and acknowledge the efforts of all those who have directly or indirectly helped us in achieving our aim. We take great pride in expressing our unfeigned appreciation and gratitude to Dr R.S. Mishra, Head of Department, Department of Mechanical, Automotive, Production and Industrial Engineering, Dr. Ranganath M Singari, Associate Professor, Department of Mechanical & Production Engineering and Mr. V. Jeganathan Arulmoni, Associate Professor, Department of Mechanical & Production Engineering for their invaluable inspiration, guidance and continuous encouragement throughout this research. We would also like to acknowledge Mr. Kuldeep Sharma, Lab Incharge, SEM Laboratory, IIT Delhi for guiding us throughout the SEM test.

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