JJMIE

Volume 15, Number 5, December. 2021
ISSN 1995-6665
Pages 483 – 490

Jordan Journal of Mechanical and Industrial Engineering

Characterization of Al-SiCP Functionally Graded Metal Matrix Composites Developed through Centrifuge Casting Technique

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Received August 31 2020 *Accepted October 29 2021*

Abstract

Centrifuge casting is a new technique wherein a mold assembly is made to rotate at a certain speed that will induce higher 'G' force to the molten metal.The existing higher rotational force creates a compositional gradient that segregate phases with different densities. In this work, an attempt has been made to develop Al alloy/ SiCP FGMs. It has been observed that due to the higher density of SiC compared to Aluminum, the bottom part of the casting is rich in SiC particles with good resistance to wear, and the top of the casting results in high toughness as it is more of Al alloy. In the present work FG Composites are produced using hypereutectic (17%Si) Al-Si alloy using centrifuge casting technique with SiC particulate(SiCP) as reinforcement using stir casting followed by centrifuge casting. The samples were characterized for microstructure, hardness, and wear. It was found that there is a gradation in the sample for all the above said properties from top to bottom of the sample. It was found that Al-17wt% Si matrix alloy reinforced with 2% SiCP yielded a maximum hardness of about 66BHN at 400rpm while for 4% and 6% the hardness was found to be 82 and 94BHN.The results revealed that the wear resistance was high at both the ends of the specimen due to segregation of Si at one end and SiCp at the other end.

Keywords: FG composite, Centrifuge casting, Microstructure, Hardness, Wear;

1. Introduction

High strength, thermal stability, and wear resistance of Aluminum based Metal Matrix Composites (MMCs) in general and particle-reinforced composites are used extensively in the automotive industry. It is well known that increasing the percentage of the SiC_Preinforcement in Metal Matrix Composites (MMCs) increases the overall performance [1-3]. These MMCs, however, do not show improved performance for load bearing applications. Functionally Graded MMCs (FGMMCs) are new class materials intended to eliminate the drawback of the MMCs in which the surface of one side provides higher hardness, but the interior region will have higher resistance towards the crack growth [4]. Because of low dissipation of energy due to the high segregation of reinforced particles at the boundary, the fracture toughness is low for small crack lengths in case of composite system [5-6].

In this study, SiC particle-reinforced Al-Si alloy based FGMMCs have been produced by centrifuge casting process. The developed in-house centrifuge-casting machine operates on vertical axis and pouring of the molten metal is carried while the mold is stationary. The centrifuge casting machine used in the current research work has an arm with metal mold attached at one end which can swing, and counterweight is placed at the other end. The arm is mounted centrally on the output vertical shaft of a0.5HP motor.

The castings were produced at 200, 300 and 400rpm of the mold. The alloy Al-17wt%Si has been used as matrix material with 2, 4 and 6 weight % of SiC_P added as reinforcement to the matrix. The samples were cast at 900°C teeming temperature and mold temperature of 180°C. The graded composites sample were tested for volume fraction and hardness along the length. The wear tests were conducted on the both end surfaces of the casting, which reveals the gradation in the properties [7-9].

2. Methodology

In Aluminum alloys, Silicon is the most common and least expensive alloying element used. Silicon plays an important role in making the alloy suitable for the aerospace and automotive industry. It mainly increases cast ability and fluidity. In addition to lowering of aluminum alloy density to 2.34 g/cm^3 silicon increases strength to weight ratio and wear resistance of aluminum alloy [10-11].

Fenfe Metallurgical, Bangalore, India supplied the commercially available Al alloy. Table 1 represents the composition of the Al alloy used.

Table 1. Composition of Al-Si alloy

Alloy	Composition (wt.%)					
	Si	Fe	Sr	Ti	B	Al
Al-17Si	17	0.1	-	-	-	Balance

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Table 2. Characteristics of Silicon Carbide

Mechanical characteristics	Units	Values
Density	gm/cc	3.18
Poisson's Ratio	—	0.13
Hardness	Kg/mm^2	2700
Purity	%	99
Thermal Conductivity	W/m•°K	120
Coefficient of Thermal Expansion	10^{-6}/°C	4.0

Several researchers have worked on the SiC_P reinforcement in different Aluminum alloys. In this study we have considered SiC_P supplied by M/s Fenfe Metallurgical, Bangalore and we have used volume fractions of 2%, 4%, and 6%. The average size of the SiC_P is 60 microns.

Functionally Graded Metal Matrix Composites (FGMMCs) are produced using centrifuge technique. Due to the difference in density of the materials (ρ_{Al}=2700 kg/m^3, ρ_{Si}=2320 kg/m^3, ρ_{SiC}=3210 kg/m^3) and the rotating speed which implies high centrifugal force on the molten metal, within the liquid Al matrix, volume fraction of the Si and SiC_P reinforcement is gradually increased along the length of the casting. The centrifuge machine is shown in Fig. 3.2. This machine operates on vertical axis and pouring of the molten metal is carried while the mold is stationary. Thus, centrifugal forces are not applied immediately as in the traditional casting methods since the mold takes some time to reach its casting speed. The principal advantage of this is good mold filling combined with micro structural control, which usually results in improved mechanical properties. Author has successfully used this technique to produce Al-Si FGMs [12-13].

The experimental setup for processing of alloy/MMC FGM is fabricated in house. Fig. 1 shows the details of centrifuge casting machine and the solidified casting in the mold.

Optical microscope is used for microstructure characterization and an inverted microscope of Dewinter make interfaced with Metalife image analyzer software is used to capture and analyze the image. The image captured is analyzed for phase/volume fraction analysis (ASTM-E562 1995), (ASTM-E1245 1995), Si and SiCP distribution [14].

In the present work for Brinell Hardness testing the specimen is cleansed to remove dirt and oil on the surface prior to the testing. The tests are conducted as per ASTM E-10, the testing machine to IS-Specification 1754. As per ASTM standards, in this test a ball indenter of diameter 5mm and a load of 15.625 Kgs are selected.

In this study wear tests were conducted as per ASTM standards (ASTMG-99 1995) using Pin-on-Disc type wear testing machine (model TR-20LE, Ducom make). The maximum load capacity of the system is 200N. The rpm and the sliding speed of the disc were 0-2000rpm and 0-10m/s respectively. The disc is made of En-32 steel, having hardness value of HRC65 with dimensions of 160mm diameter and 8mm thickness is used [15].

3. Result and Discussion

3.1. Microstructure

The microstructure of the FGMMC with 2% SiC_P cast at 200, 300 and 400rpm is shown in Fig. 2.

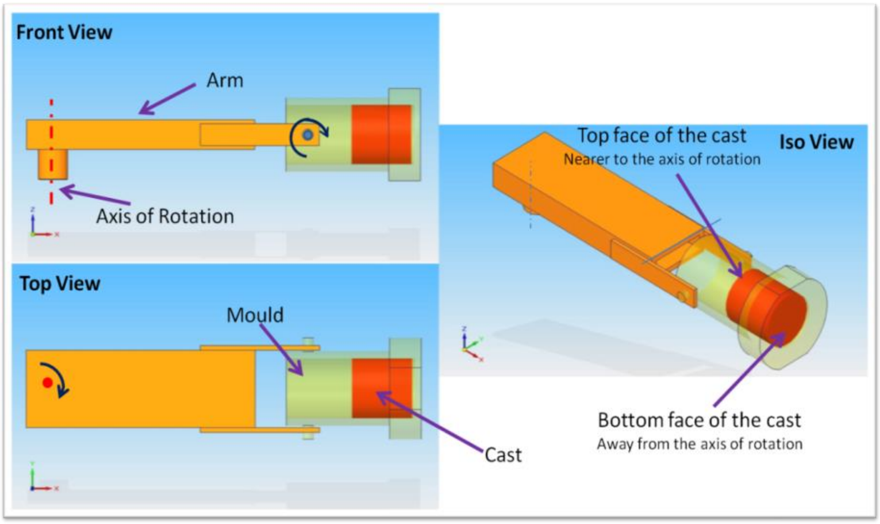


Figure 1. Centrifuge machine with its parts

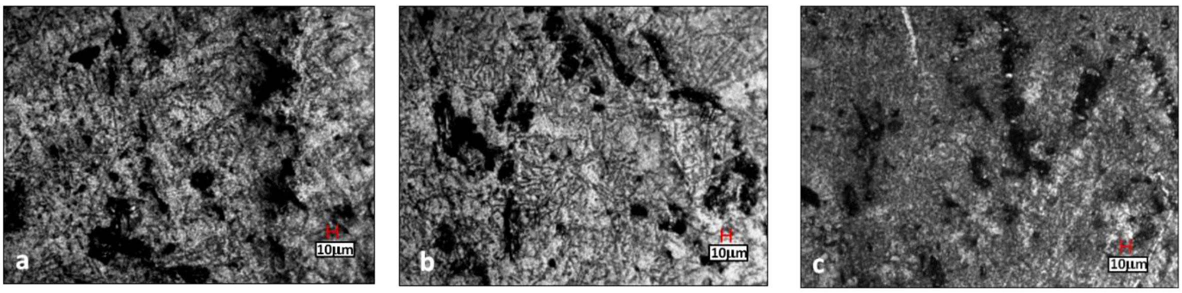


Figure 2. Microstructure of Al-17wt%Si-2% SiC_P system at 200, 300 and 400rpm

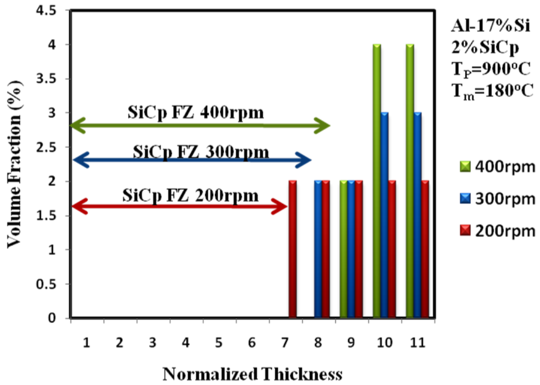


Figure 3. Distribution of SiCPalong the length of the sample for 2wt% reinforcement.

The segregation of SiC$_P$ is more at 400rpm when compared to the other two rpms. For 2% SiC$_P$reinforcement the amounts of enrichment at the lower surface of casting are 2%, 3% and 4% respectively at 200, 300 and 400rpm. The rim thicknesses of the SiC$_P$ rich zone from the bottom of the casting are 16mm, 12mm and 8mm respectively. The volume fraction of SiC$_P$ and SiC$_P$ free zone with respect to the bottom end are shown in Fig. 3.

With increase in volume fraction of SiC$_P$ from 2% to 4% the segregation of SiC$_P$ at the bottom end of the casting increased to 5, 7 and 8% at 200, 300 and 400rpm respectively, while the rim thickness remained same as in the case of 2% and further similar trend was observed at 6% SiC$_P$ with the amount of segregation increasing to 6%, 8% and 10% as shown in Fig. 4.

The distribution of SiC particles in the Al-17% Si castings is better when it is cast centrifugally casting method compared to other methods (Fig. 5). This is due to the fact that alloy solidification develops in a very constricted zone at the interfaces between particles; this helps in getting homogeneous nucleation of matrix because of rapid movement of particles in molten metal. During this time, the primary α-Al, which is developed in this zone, attracts SiC particles between thin primary α-Al phases. In the free particle zone, coarse primary α-Al are developed due to low under cooling. Therefore, coarse primary α-Al and thin granular eutectic Si phase are observed.

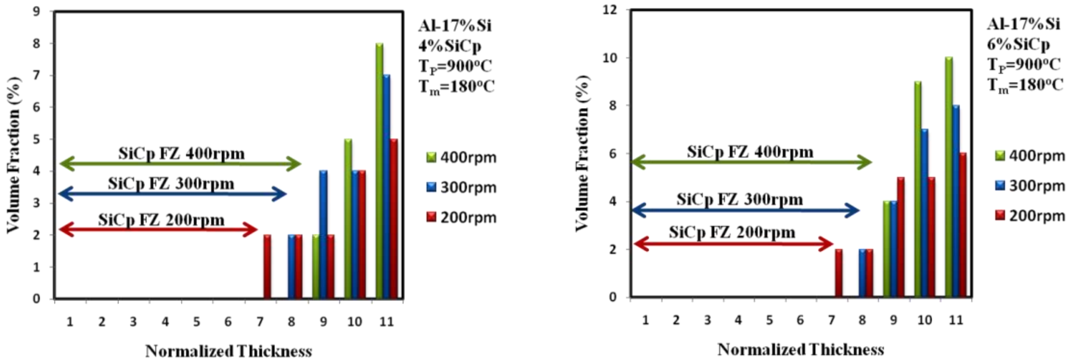


Figure 4. Distribution of SiC$_P$along the length of the sample for 4wt% and 6wt% reinforcement.

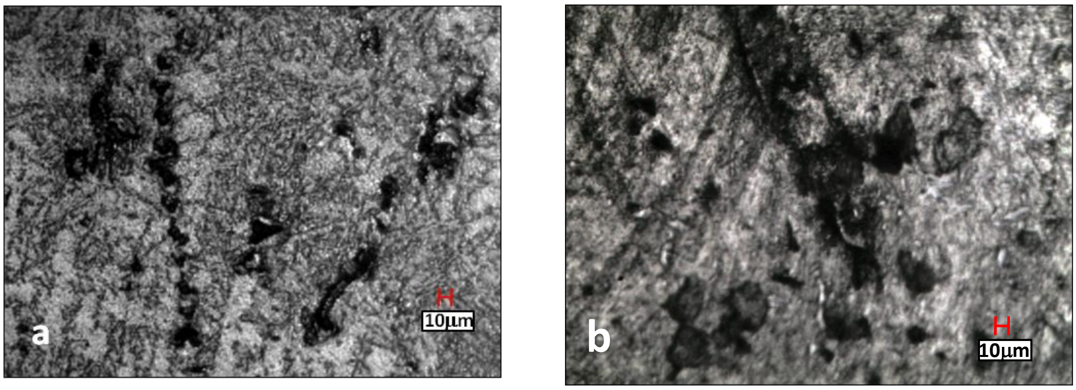


Figure 5. Microstructure of FGMMC by Centrifuge technique

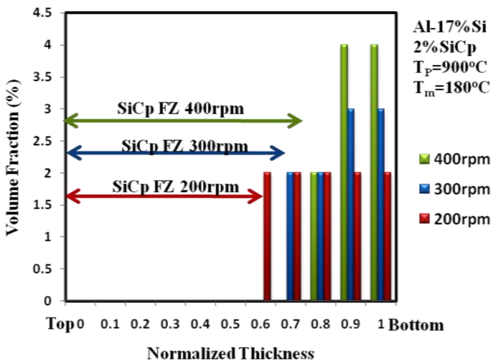


Figure 6. Distribution of SiC$_P$along the length of the sample for 2wt% reinforcement.

With increase in percentage (volume fraction) of SiCP to 4%, the segregation of SiCP at the bottom of the casting FGMMC measured was 7%, 7% and 5%, for 400, 300, 200rpm and the rim thickness changed to 8mm, 12mm and 16mm respectively. Similarly, at 6% SiCP the corresponding values were 8%, 7% and 6% and 8mm, 12mm and 20mm respectively as shown in Fig. 7.

3.1.1. Effect of rotational speed

During the centrifuge casting, segregation of particles takes place in the melt due to the 'G' force implied upon and the difference in densities between the particles and the melt, which in turn increase the movement of the particles. The solid particles are subjected to radial buoyancy (F_c) and radial moving velocity (V_c) as given by equations 4.1 and 4.2.

$$F_c = \frac{\pi d^3 (\rho_p - \rho_l)\omega^2 r}{6} \quad 4.1$$

$$V_c = \frac{d^2 (\rho_p - \rho_l)\omega^2 r}{18\eta_c} \quad 4.2$$

Where d is the diameter of the reinforced particle (m), $\rho_p$is the density of the particle and $\rho_l$is the density of the liquid (kg/m^3). The distance of the particles from the axis of rotation (m) is given by 'r', angular velocity of the mold ω in (rad/s).η_c is the viscosity of the liquid with solid particles (Pa.s). The particles move toward the top part of the casting, if $\rho_p<\rho_l$, then $V_c<0$.the particles move away from the axis of rotation (bottom of the casting), if $\rho_p>\rho_l$, then $V_c>0$. In this Al-Si- SiC_P system, as the SiC_P is denser than that of the liquid metal, the particles are forced tp move towards the bottom surface of the casting[16].

From the Figs. 6 and 7 it can be observed that the thickness SiC_P segregated zone decreases with the increase in centrifugal force of the rotating mold.

This can be further explained as the effect of chilling. At lower rotational speeds, the velocity of the solidification front is more than the particle velocity. This results in melt solidifying firstly and no new particles can reach this region. The time required to solidify increases as the solidification front moves to the core of the casting, which in turn gives the particles more time to settle in the casting, which induces a segregated zone. As the centrifugal force on the particles increases, the solidification front leads to a shortened section. It has been observed that the heat transfer coefficient for Al at the metal/mold interface increases with an increase in the centrifugal force and at a higher forces, a induced high pressures of liquid metal on the solidified layer, results better heat transfer coefficient between the mold wall and solidified layer interface [17].

3.1.2. Effect of Temperature

Increase teeming temperature, decreases thickness of the SIC_P rich zone. To start the solidification a large quantity of heat must be extracted from the melt of Al-Si-SiC_P when the temperature is increased. Hence, this extra time gives more time to solidify forFGMMCs, the reinforcement particles get more time to segregate, forming a rich segregation zone. In addition, at higher mold temperature, the rate of heat extraction from the melt to the mold is reduced due to negative thermal gradient. This increases the solidification time, giving more time for particulates to segregate and pack into rich thinner zones.

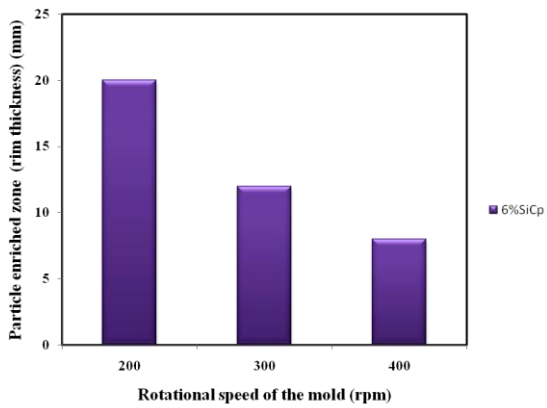
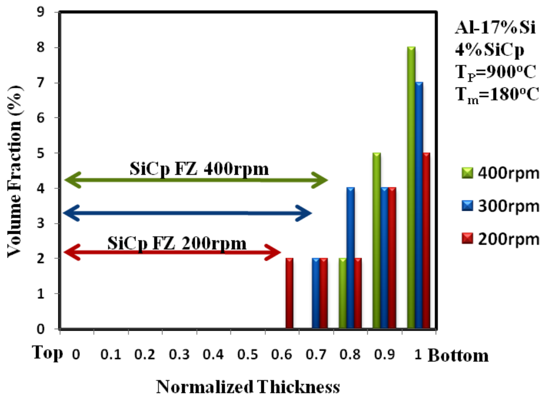


Figure 8. Effect of speed on rim thickness



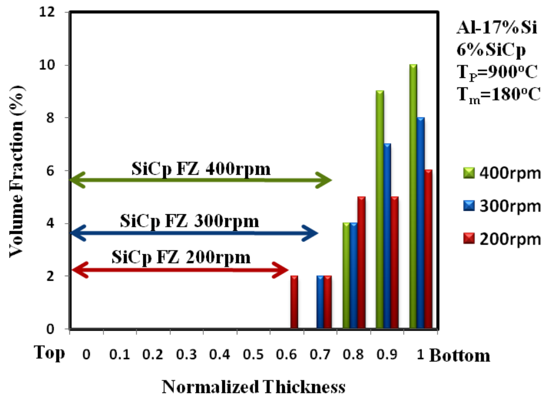


Figure 7. Distribution of SiC_Palong the length of the sample for 4wt% and 6wt% reinforcement.

3.1.3. Effect of Matrix and Reinforcement

At 2% and 4% reinforcement, the segregation of the SiC particles towards the bottom is almost increased by 100% whereas for 6% reinforcement it is 66% in Al-17wt%Si. This may be attributed to the fact that the increase in % of the SiC has decreased the fluidity of the system which in turn decreased segregation. Moreover, it has been observed that cooling rate is enhanced with increasing mold rotation speed because of better heat transfer; i.e high centrifugal forces produce a tight contact between the mold wall and the melt. Due to the presence of thermally insulating SiC particles, higher SiC particulate contents reduce the amount of heat to be removed and this initiates an increase in the solidification rate. High cooling rate gives rise to a much finer cast microstructure [18].

The distribution pattern of centrifuge cast silicon carbide particles reinforced Al-17wt%Si alloy show that there is a more SiC enriched zone. This is obviously due to solidification range being larger in 17% alloy i.ethe difference in freezing range and viscosity of the alloy. The SiC particle distribution graphs show that the gradient of SiC is more for Al-17wt%.At 200rpm the SiC particles are spread for 16mm from the bottom.

It has been noted that the segregation for SiC particles towards the bottom end of the casting depends not only on the speed of rotation of the mold but also on the matrix. The 'G' factor forces the SiC particle towards the bottom end along its direction due to the density difference it has got with melt. The content of the Si in the matrix affects the fluidity, which reduces the temperature range solidification which in turn increases the rate of phase transformation allowing very less time for particle movement.

3.2. Hardness

As evident from the Figures 9 to 4.80 in case of FGMMCs there is a substantial increase of hardness at the bottom portion of the specimen. Best results were obtained for 6% SiC_p reinforcement for both the matrix materials. At the top region, leading to segregation of Si, hardness. Thus, a middle region of comparatively lower hardness is sandwiched between harder top and bottom.

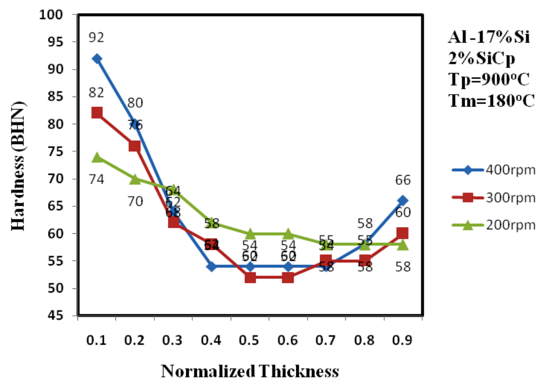


Figure 9. Hardness values along the length of the casting for Al-17wt%Si-2wt% SiC_P FGMMC.

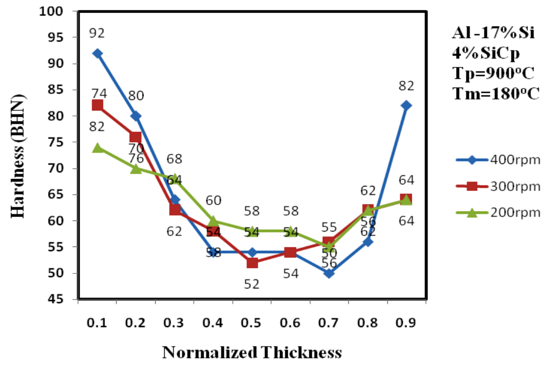


Figure 10. Hardness values along the length of the casting for Al-17wt%Si-4% SiC_P FGMMC.

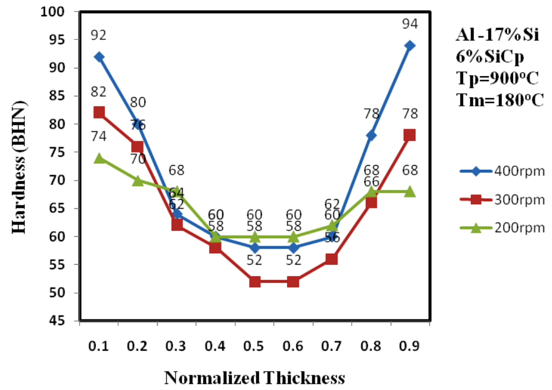


Figure 11. Hardness values along the length of the casting for Al-17wt%Si-6% SiC_P FGMMC.

For Al-17wt% Si matrix alloy a reinforcement of 2% SiC_P yielded a maximum hardness of about 66BHN at 400rpm while for 4% and 6% the hardness was found to be 82 and 94BHN.

In centrifugal castings solidification progresses radially inwards from the outside surface. This is because that the outside and bottom surfaces are in contact with the mold surface and the top surface is free. The liquid melt undergoes shear during solidification, and this prevents the formation of a crust on the top. High pressures developed due to the 'G' force, makes the air gap smaller and the formation of air gap is delayed. This in turn increases the heat transfer rate at the outer surface. High rates of heat transfer, and therefore solidification, leads to refined structure. We can see that by reducing the heat transfer rate, the rate of solidification can be reduced. This reduced solidification rate gives more time for the SiC_P to segregate towards the bottom. The segregation can be enhanced by increasing the pouring temperature and mold temperature.

When the mold temperature is low (room temperature) and the liquid melt temperature is high, a sharp gradient of the temperature is noted at the mold. This difference in temperature causes faster heat transfer resulting higher solidification rate at the mold-liquid interface. As the mold temperature is increased, the temperature gradient gets reduced resulting in lower solidification rate. More time is available for SiC particles to segregate better under G forces, and this results in higher hardness compared to molds which have not been subjected to higher mold temperatures at a slower solidification rate [19-21].

3.3. Wear

The top and bottom regions of the specimens were subjected to wear test at ambient temperature under dry sliding condition. The aim of this study is to find the volume loss, coefficient of friction variation under different loads.The loss of the material due to several wear regimes for the FGMMCs castings with 2, 4 and 6% SiC_P reinforcement in Al-17%Si are studied. The dry sliding nature of the Al-Si/ SiC_P FGM under different loads of 40, 60 and 80N at 1.446 m/s sliding speed is evaluated.

Volume loss of Al-17wt%Si-SiC_P FGM composite at both top end and bottom end of the casting is determined with respect to the applied load at a sliding speed of 1.466 m/s. The weight loss of both the ends having SiC_P and Si respectively increases with the addition of the load. The bottom end (having segregated SiC_P) showed lower volume loss. The top end of the casting has segregated Si and thus shows lower volume loss compared to the middle region which has neither the SiC_P nor the primary Si segregation [22-25].

From Figs. 12 to 14 at different test loads, for 2 volume percent of SiC_P reinforcement in Al-17%Si alloy/MMC, SWR decreased by about 11.3%, 8% and 10.34% at 40, 60 and 80N respectively at sliding speeds of 1.446m/s for castings produced at 400 rpm compared to 200rpm. For 4% of SiC_P reinforcement produced at 400rpm it has been noted that the SWR decreased by 15.8, 14.46 and 13.8% for 40, 60 and 80N test loads in comparison with 2% of SiC_P reinforcement FGMMC. But there is a significant improvement in case of 6% SiC_P reinforcement wherein the SWR decreased by 36.9%, 30.8% and 23.2% for 40, 60 and 80N test loads in comparison with 4% of SiC_P reinforcement FGMMC. This clearly shows that the additions of SiC_P to Al-Si alloys enhance the strength of matrix, reducing contact area at any given load leading to reduction in SWR. From these results, it is clear that the effect of increase of test load in improving the wear resistance is higher in MMCs with harder reinforcement particles embedded in softer matrix and vice versa [26-28]. The decrease of SWR with increase in test load can be attributed to higher strain hardening of matrix.

The variation of Coefficient of Friction (COF) is shown in Figs. 15 to 17. The COF increased to a maximum as the rotating disc, reached its set speed on starting and then smoothly decreased to a constant value. At the start of the test, due to changes in pin and disc surfaces, the COF rises with time in the beginning and remains constant. The Al-Si eutectic with 23% free Si at the top end apparently shows lower COF. Whereas the lower end shows higher COF. The reinforcement of the 2% SiC_P led to no significant improvement in terms of wear and its properties. Comparison of COF at the bottom end of both FG alloy and SiC_P 2% reinforced FGMMC has shown a very little difference at all test loads.

With further increase in volume percent of SiC_P the coefficient of friction was found to decrease at the bottom end for different normal loads. On an average at different loads and at 1.446m/s, for an increment of 2 volume percent of SiC_P reinforcement, the coefficient of friction decreased by about 4% and COF decreased by 7% [29-32].

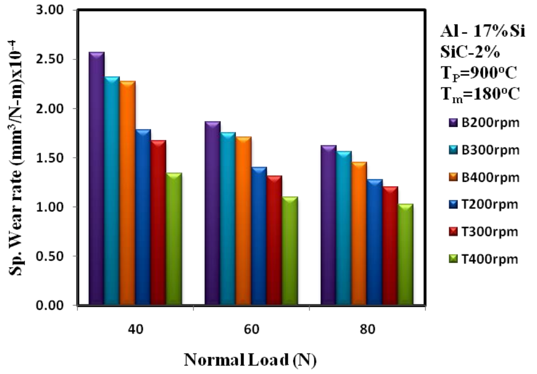


Figure 12. Specific Wear rate of Al-17wt%Si-2% SiC_P FGMMC.

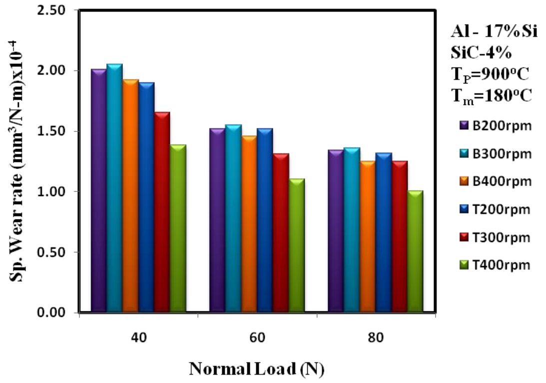


Figure 13. Specific Wear rate of Al-17wt%Si-4% SiC_P FGMMC.

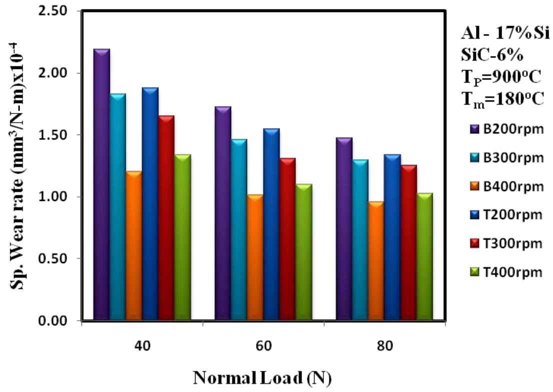


Figure 14. Specific Wear rate of Al-17wt%Si-6% SiC_P FGMMC.

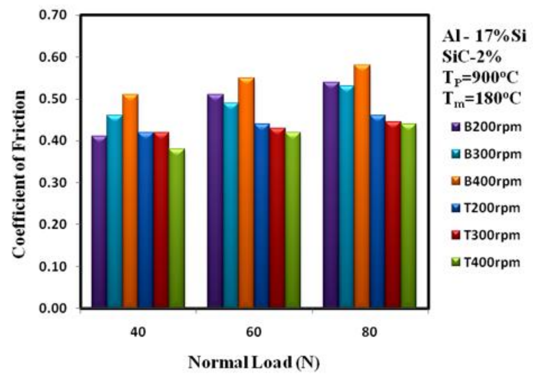


Figure 15. COF of Al-17wt%Si-2% SiC_P FGMMC.

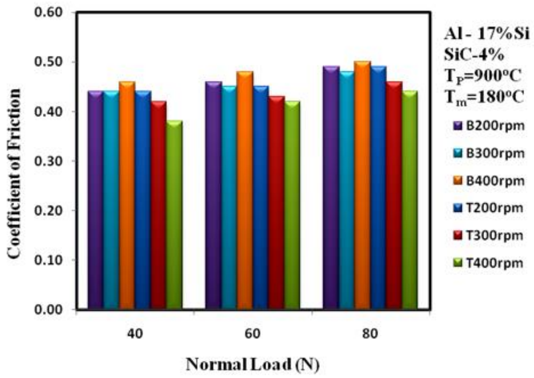


Figure 16. COF of Al-17wt%Si-4% SiC_P FGMMC.

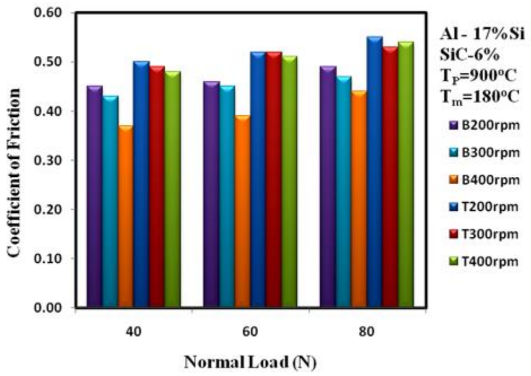


Figure 17. COF of Al-17wt%Si-6% SiC_P FGMMC.

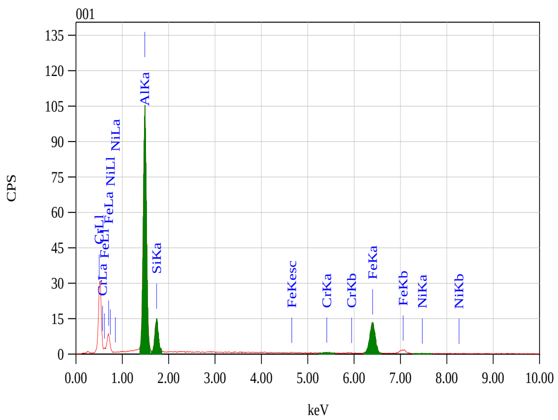


Figure 18. EDS spectrum showing material transfer of Fe on to Pin surface

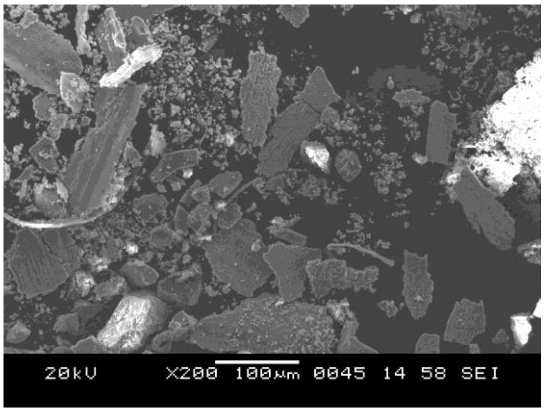


Figure 19. Flake or sheet like wear debris of delamination

It is seen that FGMMCs possess very good wear resistance. In this FGMMCs, the load is supported by SiC particles, which decrease the friction coefficient because of the lesser contact area between specimen and disc surface. This also prevents the surface from getting wear out from the hard little asperities, which intends to scratch and cut the surface. However, under high load, the reinforcing particles can longer protect the surface and does not remain stable. The abrasion grooves formed are very distinct in worn surfaces due to the ploughing and micro-cut action. During the wear test, it has been observed that flake type and stringer type debris are formed (material loss). The delamination occurs due to the removal of surfaces because of increase in shear strain near the cracks. It clearly shows that the main cause of wear is delamination, which causes cracking or breaking of the reinforcement and the matrix, results in weakening the wear resistance.

4. Conclusion

1. The segregation of SiC_P is more at 400rpm when compared to the other two rpms. For 2%SiC_P the rim thicknesses of the SiC_P rich zone from the bottom of the casting are 16mm, 12mm and 8mm respectively. Similarly, for 4% the rim thickness changed to 8mm, 12mm and 16mm and 8mm, 12mm and 20mm for 6%.
2. The segregation for SiC_P towards the bottom end of the casting depends not only on the speed of rotation of the mold but also on the matrix. The 'G' factor forces the SiC_P towards the bottom end along its direction due to the density difference between the melt and the SiC_P.
3. For Al-17wt% Si matrix alloy a reinforcement of 2% SiC_P yielded a hardness of about 66BHN at 400rpm while for 4% and 6% the hardness was found to be 82 and 94BHN.
4. The additions of SiC_P to Al-Si alloys enhanced the strength of matrix, reducing contact area at any given load leading to reduction in SWR. The effect of increase of test load in improving the wear resistance is higher in MMCs with harder reinforcement particles embedded in softer matrix and vice versa. The decrease of SWR with increase in test load is attributed to higher strain hardening of matrix.

Declaration:

Compliance with ethical standards: The authors declare that they have no conflict of interest.

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