Fabrication and dry sliding wear analysis of centrifugally casted A 356- 10% SiC\textsubscript{p} functionally graded metal matrix composites at different rotational speeds

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Abstract. Functionally graded materials (FGMs) are advanced composite materials characterized by their variation in the composition or microstructure in a specific direction. The composition of FGMs is continuously varying. The desired properties can be achieved in a single bulk material of FGM which makes them especially applicable for mechanical and tribological applications. Using a vertical centrifugal casting machine fabrication of aluminium A 356- SiC\textsubscript{p} functionally graded metal matrix composites (FGMMC) were done. 10% by volume of SiC\textsubscript{p} particle were taken. An average size of 34 μm is chosen for additive SiC\textsubscript{p}, so that dispersed particulate matter in matrix of A-356 will enhance mechanical and tribological properties such as wear resistance, ultimate strength and hardness. The castings were carried out at 1100 rpm, 1200 rpm, 1400 rpm, 1550 rpm, 1700 rpm and 1950 rpm of the machine. The microstructural analysis projects a good gradation at 1700 rpm. The observations are validated using hardness analysis. Dry sliding wear behaviour of FGMMCs fabricated at rotor speeds of 1550 rpm, 1700 rpm and 1950 rpm were done. Hardness improvement at outer radial position than that of inner radial position of FGMMCs are 1.19, 1.29, 1.35 and 1.54 times at speeds 1400, 1550, 1700 and 1950 rpm of the machine respectively. The casting at 1700 rpm showed a good gradation at transition region compared to others. Wear resistance at outer surfaces of FGMMCs are improved with the presence of SiC\textsubscript{p} at the expense of COF.

1. Introduction

300 series aluminium alloys have good corrosion resistance, good formability with moderate strength due to the presence of manganese (0.005-1.8%). Functionally graded aluminium composites are potential material due to excellent physical, mechanical and tribological properties [1]. S Singh et al. fabricate functionally graded Al/Al\textsubscript{2}O\textsubscript{3} with the help of investment casting. The microstructure studies show the most of the particle found at bottom of the mould [2]. This is because of during autoclaving reinforcement particles are falling down to bottom-most surfaces, as a result of gravitational pull [3].

Functionally graded Ti6AlV/TiC composite developed using laser metal deposition process. Chumanov I.V et al., successfully developed Al-Si alloy reinforced by CNTs which fulfil the requirements of the piston ring [4]. Marwan a. Madhloom et al. developed a vertical centrifugal casting machine for preparing FGM of Al/TiO\textsubscript{2} [5]. It is found that clustering of (TiO\textsubscript{2}) will weaken
the tensile strength of prepared materials but increase the wear resistance. E. Jayakumar et al. using liquid stir casting technique and vertical centrifugal casting aluminium functionally graded metal matrix composite reinforced with SiCp of average size 23 µm were processed successfully [6]. The study reveals the microstructure of produced functionally graded aluminium metal matrix composite has been affected by the centrifugal force. The spatial distribution curves of SiCp reinforcements about radial direction showed that final position and magnitude of SiCp depends on the percentage of initial SiCp addition. There is a shift in the position of the maximum concentration outward for additives with a higher percentage. Ramakrishna Vikas S et al. studied how the gradient composition and varies properties of the FGM rings [7]. The reinforcement provided using SiCp increases the wear resistance. Ali H. Ataiwa, Alaa et al. analysed effect of centrifugal forces on structures [8].

Investigation shows considerable change in the tensile and yield strength as the centrifugal force increases. N Radhika et al. investigated functionally graded Al/B₄C, Al/Al₂O₃, Al/TiB₂ which are successfully carried out through centrifugal casting and base alloy selected as Al-12Si-Cu [9]. A. Mohan et al. casted aluminium A 356 T6 alloy with 5% and 10% SiCp using centrifugal casting and studied property variation such as hardness, wear resistance, ultimate strength and compressive strength at different radial positions [10]. The study revealed that the centrifuging effect causes improvement in properties at the expense of friction. The size of SiCp is also having much effect on the hardening mechanism. The centrifuging action had great influence on the microstructure of the component casted, outer region has more reinforcement. There are many advantages for FGMs, like wear resistance, less weight, corrosion resistance, damping properties etc. [11-15]. There are variety of methods mentioned in many researchers like hot pressing, laser metal deposition, CO2 forming, powder metallurgy, fused deposition and centrifugal casting. Among the above-mentioned techniques, the centrifugal casting is optimum in all aspects that is easy to operate, less expensive, maintenance etc. The rotocasting (centrifugal casting) machine is using the centrifuging action to solidify the molten metal. Mould is rotated via a belt or direct supply from the motor with suitable couplings. Proper rotation of the mould ensures the required centrifugal force to solidify the molten melt. Continuous gradient FGMs are prepared economically using centrifugal casting machine [16-17].

Previous studies on the functionally graded metal matrix composites (FGMMCs) of hypoeutectic-aluminium and SiCp do not gone through the effects and comparison wear and hardness of composite at different rotational speeds of the machine. Here the analysis is done on aluminium A 356 T6 base matrix reinforced with particulate matter of SiC. Vertical centrifugal casting machine is used for preparation of FGMMC. The average size of reinforcement is 34 µm, so that SiCp is made to disperse in the matrix of A-356 T6 alloy. This will enhance the mechanical and tribological properties like wear resistance, strength and hardness through dispersion hardening [18]. Castings were carried out at 1100 rpm, 1200 rpm, 1400 rpm, 1550 rpm, 1700 rpm and 1950 rpm of the machine.

2. Experimental Details

2.1. Material
The base alloy selected is A356 T6 alloy. It has got applications in aircraft parts, pump housings, high velocity blowers, impellers, truck parts etc. The reinforcement chosen is silicon carbide particulate matter (SiCp) due to its high hardness and wear resistance. The Vickers hardness number for the A356 alloy is 99 VH. Reinforcement used is 10% by volume with an average particle size of 34 µm. The density of A356 alloy is 2.67g/cc and that of SiCp is 3.1g/cc. Chemical composition of A356 alloy is given in table 1.

2.2. Preparation of FGMM Composites
The ingot of A356 alloy is made into small pieces. It is rinsed well and dried. About 1330 g of A356 is placed in the 2 kg graphite crucible. The crucible is set inside an electric stir casting furnace. It is heated to 840 °C. Slag and impurities in the alloy were removed from the melt. 15 g (1% by volume) of Mg is added to the homogenous melt of A356. Aluminium foil is used to cover the Mg to avoid the
sudden burning of Magnesium. Processed SiCp of weight 150 g is taken and preheated to 350 °C. Using pin and gun the preheated SiCp is pumped to molten metal at 5g/s, while proper stirring with mechanical stir is given to the melt. When the mixing of SiCp finished, the melt is stirred thoroughly at 220 rev/min for 55 to 70 sec for obtaining homogeneous melt of A356- SiCp. Using a funnel the homogeneous mixture is then poured into the disc shaped die. The die and funnel are preheated to 400 °C. The die is mounted on vertical centrifugal casting machine just before pouring. The die is rotated at respective speed using belt connected to the motor. The die is rotated until solidification. The castings were carried out at 1100 rpm, 1200 rpm, 1400 rpm, 1550 rpm, 1700 rpm and 1950 rpm of the machine.

2.3. Testing
The cast is removed from the die after cooling and heat treated. The casting is cut using abrasive cutting machine and prepared for the microstructural analysis. Using emery papers of grades P120, P220, P320, P400, P600, P800, P1000, P1200 and P2000 the surface is polished well [19]. Using diamond pastes of particle sizes 3 µm and 0.5 µm in the buffing machine the surface of FGMMC is made mirror finished. After etching the surface is dried. Microstructural images were captured using Leica optical microscope. For analysis of volume percentage of SiCp Leica Qwin analyzer is used. Density was found with Archimedes principle experimental setup. Mitutoyo HM-200A Vickers Hardness Testing Machine is used for hardness evaluation. A load of 0.3 Kgf is applied with an indenter speed of 60 µm/s. The time for loading is 5 sec and that for unloading is 5 sec. ASTM E-92 procedure were followed. Measurements were taken 2 mm from the inner periphery up to 37 mm in radial direction towards the outer periphery with a step value of 5 mm. Ducom Pin on Disc Tribotester apparatus is used for sliding wear and coefficient of friction (COF) analysis. ASTM G99 codes of procedure were followed.

3. Results and Discussions
FGMMC obtained is in the form of a disc. The outer diameter of the disc is 150 mm with a thickness of 40 mm. It is obvious from the microstructural images shown in Figure 1. that SiCp particles are distributed with gradation in density, which is a function of speed of the machine. Figure 1. A represent the microstructural images of casting at 1100 rpm, B at 1200 rpm, C at 1400 rpm, D at 1550 rpm, E at 1700 rpm and F at 1950 rpm of centrifugal casting machine. At 1100 rpm and 1200 rpm speeds the SiCp particles are mainly concentrated near the inner region (8 mm from the inner surface) and this pointed out the failure of the casting. This may be because of the in time solidification of the cast. In the case of 1400 rpm and 1550 rpm of the machine distribution of SiCp particles at mid and outer regions (24 and 35 mm from the inner surface) are almost similar. So the centrifugal force requires to push the SiCp particles is not enough. So some amount of SiCp particles is sedimented at the inner part of inner zone. At 1700 rpm a good gradation is obtained. About 70% of the SiCp particles are concentrated at the outer region. The mid transition region shows an increase in density from inner to outer. Chilled zone thickness is 2 mm at the outer periphery. At 1950 rpm because of the high centrifugal force about 82% of the SiCp particles are located at the outer region. The density and volume fraction analysis shown in Figure 2 and 3 resembles the same result of microstructural analysis. The FGMMC's casted at 1550 rpm got 2.702g/cc, 2.825g/cc and 2.859g/cc at radial position inner, mid transition and outer respectively. The corresponding value for 1700 rpm are: 2.694g/cc, 2.773g/cc and 2.874g/cc and that of 1950 rpm are 2.672g/cc, 2.782g/cc and 2.897g/cc respectively.
Figure 1. Microstructural Images obtained at inner, mid and outer positions of the disc at (A) 1100 rpm, (B) 1200rpm, (C) 1400 rpm, (D) 1550 rpm, (E) 1700 rpm, (F) 1950 rpm of the machine.

Figure 2. Density Vs Radial position

Figure 3. Volume fraction of SiCp Vs Radial distance

A good gradation in density of SiCp is obtained at a speed of 1700 rpm of the machine. It is obvious from the microstructural analysis along with density and volume fraction analysis for casting FGMMC at lower fraction such as 7.5% of SiCp particle by volume, we can go for 1550 rpm.
rotational speed of the machine while 1950 rpm that for higher fraction such as 15% by volume of SiCp particle, even though a higher volume percentage addition become a tedious task in terms of mixing and pouring. The Vickers hardness Vs radial distance graphs of the FGMMCs were plotted at different rotor speeds of the machine are shown in Figure 4. From the graphs, moving from inner to outer region an increase in hardness is obtained for 1400, 1550, 1700 and 1950 rpm speeds of the machine. Good gradation hardness number is obtained for FGMMC casted at 1700 rpm speed of the machine. It is found that the hardness value increases with the density of SiCp particles. The main strengthening mechanisms responsible for high surface hardness are the increased thermally induced dislocation density around the particles and the matrix, constrained matrix plastic flow caused by the particles, deformation induced plastic strain gradients, Orowan particle strengthening effects, and the particle induced grain refinement [20].

![Figure 4. Vickers hardness Vs Radial distance](image)

The hardness value at the outer surface are; 1.19, 1.29, 1.35 and 1.54 times than that of the inner surface of FGMMCs at speeds 1400, 1550, 1700 and 1950 rpm of the machine respectively. Very high hardness at the outer periphery of the FGMMC at 1950 suggest that most of the SiCp particles are concentrated the outer periphery and very few at inner region. Even though good gradation in hardness is obtained for the castings at 1550 rpm speed of the machine, the thickness of outer region is high 15 mm for 1550 rpm which imply the shifting or narrowing of mid transition region. In the case of FGMMCs produced at 1100 and 1200 rpm speed of the machine, the hardness values are very high at the inner region. The hardness value decreases with radial position. This cannot be possible, because due to centrifugal action, the high density SiCp particles are required to be accumulated towards the outer region. Hence the castings can be considered as defected. The obtained hardness values are in accordance with the microstructure obtained.

![Figure 5. SWR Vs Radial position at 0.4m/s sliding velocity and a load of 45N](image)

![Figure 6. SWR rate at outer position Vs Load at 0.4m/s velocity of sliding](image)
Table 2. Process parameters of wear test

| Velocity (m/s) | Track diameter (cm) | Speed of disc (rpm) | Time (s) |
|---------------|---------------------|---------------------|----------|
| 0.40          | 6.0                 | 128                 | 1000.0   |
| 0.50          | 7.5                 | 127                 | 800.0    |
| 0.60          | 9.0                 | 128                 | 666.67   |

Figure 5 depicts the variation in specific wear rate (SWR) with Radial position at 0.4 m/s sliding velocity and 45 N load of FGMMCs casted at 1550, 1700 and 1950 rpm speed of machine. The analysis is done for a sliding distance of 400 m. Table 2 shows the parameters of wear analysis. The specific wear at inner surface is $4.75 \times 10^{-2}$ μm$^2$/N, $5 \times 10^{-2}$ μm$^2$/N and $5.25 \times 10^{-3}$ μm$^2$/N for 1550, 1700 and 1950 rpm speed of the machine. The corresponding values at mid transition are respectively $3.75 \times 10^{-2}$ μm$^2$/N, $4.25 \times 10^{-2}$ μm$^2$/N and $4.75 \times 10^{-2}$ μm$^2$/N and that for the outer surface are $3.5 \times 10^{-2}$ μm$^2$/N, $3.25 \times 10^{-2}$ μm$^2$/N and $3 \times 10^{-2}$ μm$^2$/N respectively. The wear resistance increased at outer periphery compared to inner and mid transition regions. At inner and mid regions, the FGMMC casted at 1550 rpm speed of the machine showed good wear resistance compared to 1700 and 1950 rpm. But at the outer position, 1950 showed excellent wear resistance compared to the other two. FGMMC casted at 1700 rpm speed of the machine showed moderate wear in all positions. Figure 6 shown depicts the variation of SWR at outer position with thrust load applied on the pin at 0.4 m/s sliding velocity. The specific wear at 15N are $1.25 \times 10^{-2}$ μm$^2$/N, $1 \times 10^{-2}$ μm$^2$/N and $0.75 \times 10^{-2}$ μm$^2$/N respectively for 1550, 1700 and 1950 rpm speed of the machine, while that of 75 N are $6 \times 10^{-2}$ μm$^2$/N, $5.75 \times 10^{-2}$ μm$^2$/N and $5.25 \times 10^{-2}$ μm$^2$/N. By increasing the load the wear rate also gets increased and hence decreases the wear resistance.
Figure 7 shown depicts the variation of SWR at outer position with sliding velocity at a thrust load of 45N. Specific wear rate at sliding velocity 0.5 m/s are $4.5 \times 10^{-2} \text{ μm}^2/\text{N}$, $4.25 \times 10^{-2} \text{ μm}^2/\text{N}$ and $3.5 \times 10^{-2} \text{ μm}^2/\text{N}$ respectively for 1550, 1700 and 1950 rpm speed of the machine and that for 0.6 m/s are $6 \times 10^{-2} \text{ μm}^2/\text{N}$, $5.75 \times 10^{-2} \text{ μm}^2/\text{N}$ and $5.25 \times 10^{-2} \text{ μm}^2/\text{N}$ respectively. Wear rate increases with sliding velocity and hence decreases the wear resistance. On increasing the thrust load high wear is observed irrespective of rotational speed of machine. Presence of dispersed SiCp increases wear resistance of the FGMMCs through thermally induced dislocation density along with dispersion hardening mechanism. Centrifugal action on SiCp during casting results in reduced wear on outer peripheries. Hence the sliding wear analysis validates the microstructural results.

The variation of COF of FGMMCs casted at 1550, 1700 and 1950 rpm speeds of the machine with radial positions at a thrust load of 45N and 0.4m/s velocity of sliding are shown in Figure 8, the variation of COF with thrust load at outer position keeping sliding velocity at 0.4m/s are shown in Figure 9 and the COF variation at outer position at a thrust load of 45N are shown in Figure10. The trends are similar to wear loss except for varying sliding velocity. With variation in sliding velocity keeping the thrust load constant, no change is observed with COF value. This is because the friction is independent of velocity of sliding. The presence of SiCp in the matrix of the FGMMC increases the COF value. Wear affected surface are analyzed with optical microscope are shown in Figure 11. 10× magnification is used.

**4. Conclusions**
A 356- 10% SiCp aluminium alloy FGMMC are fabricated at 1100 rpm, 1200 rpm, 1400 rpm, 1550 rpm, 1700 rpm and 1950 rpm of the machine. The reinforcing particle size is 34 μm. Mirostructural analysis are validated using density, volume fraction and hardness analysis. The microstructural analysis showed a good gradation of SiCp at a speed of 1700 rpm of the machine. The dispersed SiCp
particles in the matrix of A 356 alloy enhanced hardness and wear resistance. At 1700 rpm of the machine, a good gradation at mid transition region is obtained. Hardness number at the outer surface are 1.19, 1.29, 1.35 and 1.54 times than that of the inner surface of FGMMCs at speeds 1400, 1550, 1700 and 1950 rpm of the machine respectively. The wear resistance of the FGMMCs fabricated increases with the density of SiCp particles. Outer region showed excellent wear resistance compared to the other parts. COF is increase with SiCp density.

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