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Processing and Characterization of SiC_p Reinforced Functionally Graded AA 6061 Aluminium Metal Matrix Composites

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Abstract* — Functionally graded materials (FGM) are advanced class of engineering materials in which location specific properties are made use in components of specific applications in a more economical and performance efficient ways. Functionally graded metal matrix composites (FGMMC) have graded distribution of reinforcements; whose volume fraction varies continuously in a component leading to a tailored microstructure with continuously changing properties. AA 6061 FGMMC with 10 wt% silicon carbide particles (SiC_p), of 23 µm sizes, reinforced composite is processed by liquid metal stir casting method followed by vertical centrifugal casting to obtain the FGM ring. The SiC_p due to their higher density than the matrix diffuse towards the outer periphery giving a graded structure. While the porosities, impurities and agglomerates with lower densities accumulate towards the inner periphery and can be removed by machining. Microscopic image analysis shows higher volume percentage of SiC near the outer periphery of 45 % volume. The various mechanical characterizations confirm the presence of three different graded regions, namely particle rich, transition and particle depleted/ matrix rich regions. It is also found that the outer regions have better hardness, wear resistance and tensile properties compared to the inner region due to superficial reinforcement concentrations.

Keywords— Functionally graded materials, Metal matrix composites, Stir casting, Silicon carbide

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I. Introduction

Metal matrix composites (MMCs) reinforced with ceramic or metallic particles are widely used in transportation sector, recreational and infrastructure industries due to their better high specific modulus, strength and wear resistances properties over the conventional materials. Aluminium matrix composites (AMCs) possess higher wear resistance and lower friction coefficient with increasing volume fraction of reinforcement particles, compared to aluminium alloys and are preferred over monolithic metals or alloys in a number of specialized applications [1] [2] [3]. MMCs can be tailored through appropriate selection of constituents to meet specific requirements and for specific application. Since properties of matrix and reinforcements vastly differ from each other, the properties of MMCs can be varied over a very broad range that spans from those characteristic of metals to those of the ceramics by appropriate adjustment of reinforcement volume fraction, morphology and distribution [4]. FGMs are new class of advanced two component composite characterized by a compositional gradient of one component to another along a certain direction. FGM's ability to obtain two conflicting properties in a single component enables its functionally specific applications economically [5] [6]. Centrifugal casting route is easy and the best economical technique utilized successfully among the numerous available FGMs processing techniques [7] [8] [9] [10]. Two steps FGM processing includes the synthesis of MMC by liquid stir casting followed by pouring melt into the rotating moulds fitted in a vertical centrifugal casting machine. Depending on the density of reinforcement particles and matrix phase, subjected to centrifugal force and particle diffusion, different regions are formed during the solidification namely; outer surface chilled zone, particle rich, transition and particle depleted/matrix rich zones. The centrifugal force causes the lighter particles segregate towards the axis of rotation and the denser ones move away from axis of rotation the positions and size of different zones and its gradation inside the component depends on parameters like the densities of the particle and matrix, melt temperature, centrifugal pressure, metal viscosity, particle size, cooling rate and magnitude of centrifugal acceleration [11] [12].

II. Materials and Methods

The wrought aluminium alloy, AA 6061, used for synthesizing FGMMC and its composition is given in the Table 1. Green SiC particles of average size 23µm are used as reinforcements and their properties along with the major properties of alloy are listed in Table 2. The MMC melt is synthesized by liquid metal stir casting method and later poured into rotating mould of vertical centrifugal casting machine to obtain the FGMMC component.

The SiC particles were preheated to 600 °C and 1% Mg was added to the melt while stir casting before the SiC addition to improve the wettability. Steady liquid vortex and uniform addition of particles is used to ensure proper mixing and consistency of MMC melt. Sufficient mechanical and hand stirring are also done before pouring. The melt at 780 °C is poured into metal mould, coated and preheated to 300 °C, which is rotating, at 1300 rpm, in vertical centrifugal casting machine.

TABLE I. CHEMICAL COMPOSITION OF AA 6061 ALLOY IN PERCENTAGE

Alloy	Si%	Mg%	Cr %	Cu %	Fe%	Ti %	Mn %	Zn%	Al%
AA 6061	0.82	0.65	0.15	0.26	0.15	0.02	0.1	0.04	97.81

TABLE II. STANDARD PROPERTIES OF AA 6061 ALLOY AND SiC_P PARTICLES

Property	AA 6061 alloy	SiC_P Particles
Density g/cm^3	2.7	3.2
Melting Point °C	580 (Approx.)	2300
Elastic Modulus GPa	69	410
Tensile Strength (T6 condition) MPa	276	250
Percent Elongation %	12	Less than 1
Hardness (T6 condition) BHN	95	120

Figure 1 shows the picture of the FGM casting with 25 mm thickness, fixed outer diameter of 230 mm, average inner diameter of 140 mm and weighs about 2.5 kg. Standard specimens are cut for mechanical characterization. The standard T6 heat treatment procedures, solution treatment at 535 °C for 4 h, quenching in warm water and artificially aging at 175 °C for 8 h, is used for AA 6061 FGMMC specimens. Optical Emission spectrometer, SPECTRO MAXX LMM05, is used for chemical composition analysis.

Microstructural characterization is carried out by using DMRX Leica optical microscope and Leica Qwin image analyser is used for the measurement of volume fraction of the silicon carbide particles in the matrix. INDENTEC hardness tester is used for Brinell hardness measurements from outer to the inner periphery in the as-cast and heat treated conditions. Dry linear wear analysis is carried out by using DUCOM pin-on-disc tribometer. Wear surface morphology is taken by Zeiss stereo microscope. Tensile test is carried out on INSTRON 1195 – 5500R series tensile and compression tester for specimens taken from both inner and outer zones of the cast.

Figure 1. FGMMC Cast Ring

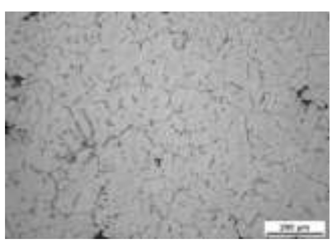
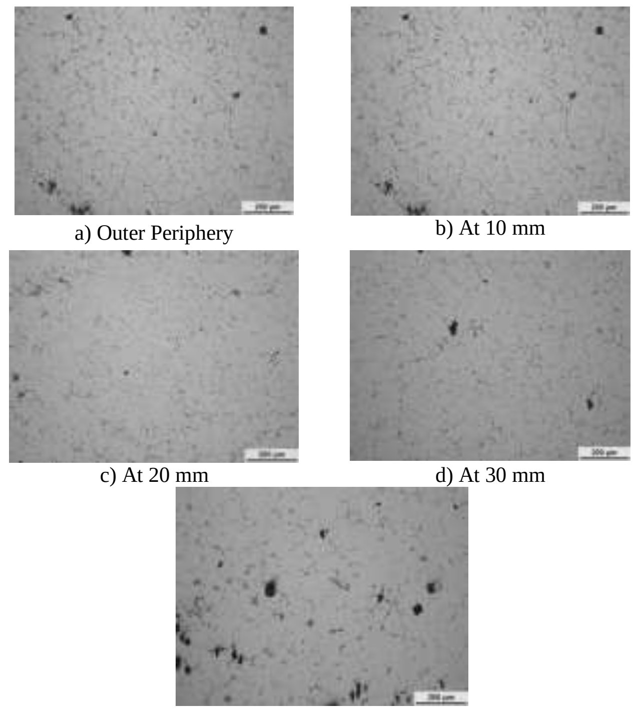


Figure 2. AA 6061 Gravity Microstructure

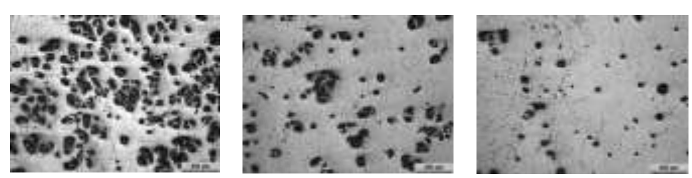
III. Result and Discussion

Figure 2 shows the microstructure of AA 6061 alloy on gravity casting. The microstructures of centrifugally cast ring of AA 6061 alloy without SiC addition are shown in Figure 3. The micrographs are taken from outer periphery to inner zones in a radial direction. Since, there is only very less volume percentage of Si, Cu or Mg in the alloy, the volume of different phases formed in the composition is less and hence there are less effective diffusions visible in the microstructures. It is observed that the grain size at the outer periphery is smaller in size than that of inner periphery and this is due to the pressure force generated during the centrifugal casting process by the molten melt which comes in contact with solidifying edge. The solidification edge moves from mould outer periphery towards inner regions while the pressure force acts from inner to outer in an opposing radial direction producing a squeeze effect. The less dense gas porosities, slag inclusions and agglomerates are observed at the inner periphery. These can be easily removed from components while machining.



a) Outer Periphery
b) At 10 mm
c) At 20 mm
d) At 30 mm
e) At 40 mm

Figure 3. Optical microstructures of AA 6061 centrifugal cast ring taken at different locations starting from outer periphery towards inner periphery



a) Outer powder rich zone
b) Transition zone
c) Matrix rich inner zone

Figure 4. Optical micrograph of AA 6061–10% SiC FGMMC ring taken at different regions starting from outer periphery towards inner periphery

Figure 4 shows the graded distribution of 10 wt % SiC particles in AA 6061 alloy FGMMC ring at three specified regions namely particle rich outer periphery, transition and matrix rich inner periphery respectively. The outer periphery of the casting shows a higher concentration of SiC particles than the inner and a clear transition region in between is also visible. The microstructural features of the matrix alloy also vary from outer to inner periphery. The grain size of the aluminium in particle enriched zone is very fine, which becomes coarser towards interior. The presence of high volume fraction of SiC particles inhibits growth of primary aluminium and also the shear caused by movement of ceramic particles during solidification can break the arms of dendrites to form fine structure [13]. The image analysis results depicted in Figure 5 shows that the outer periphery of 10% SiC FGMMC ring contains a maximum of 45 vol. % SiCp followed by a gradual reduction to lower levels. In the transition zone, between 20mm and 30 mm away from outer periphery, the reduction SiC volume percentage is steep and reaches value below 10 near the inner periphery. By subjecting a homogenous MMC melt of AA 6061 and10 wt.% SiC to centrifugal force, a maximum volume fraction of 45% is obtained at the outer periphery leading to selective improvement in specific properties such as hardness, wear resistance and tensile properties. The inner most periphery regions of the casting show the presence of gas porosity and few agglomerated particles. The agglomerates constituting partially wetted or non- wetted particles or both and gases having lower overall density are also pushed towards the inner periphery by the centrifugal force. Further, the movement of gas bubbles from the outer periphery towards the inner during the rotation can hinder the particle movement in the opposite direction and carry away few particles.

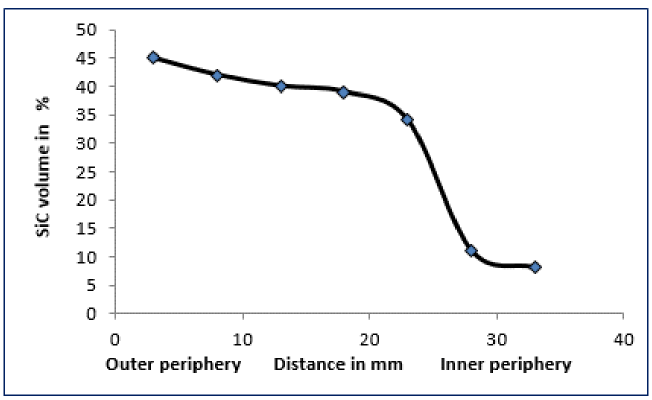


Figure 5. Volume percentage of silicon carbide in AA 6061 – 10% SiC FGMMC ring from outer periphery towards inner periphery of the casting.

The variations of the Brinell hardness values for the as-cast and T6 heat treated samples from outer and inner zones of the FGMMC ring are shown in Figure 6. The curves clearly show that the hardness value varies in proportion to the volume fraction of SiC particles in both as cast and heat treated conditions for all compositions. It is also found that the heat treated ones have far better hardness than the as cast ones. The AA 6061 cast ring also shows similar trend because of grain refinement happened in outer zones compared with inner zones in addition to the densification caused by centrifugal pressure. The maximum hardness values in the particle rich zone is 80 BHN for 10% SiC FGMMC in as cast condition and is raised to 105 BHN in heat treated condition. In the transition region the hardness changes between 76-68 BHN in as-cast and 96-78 BHN in heat treated for 10% SiC FGMMC and the region of 15 to35 mm away from the outer periphery towards inner. The region near the inner periphery shows very low hardness of 50 BHN due to the presence of porosities and agglomerated particles.

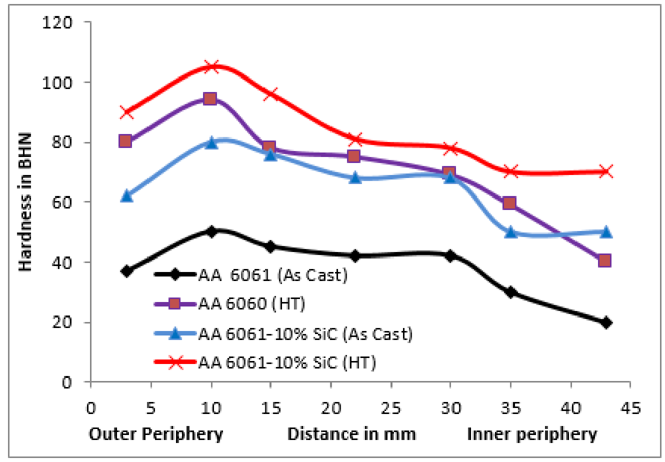


Figure 6. Brinell hardness of AA 6061 – 10% SiC FGMMC rings from outer to inner periphery, both in as cast and T6 heat treated condition

The ultimate tensile strength (UTS) value of 262 MPa and yield strength (yield) value of 165 MPa has been obtained for the AA 6061 base alloy at outer periphery and for inner the values are 236 MPa and 143 MPa respectively. The higher values at the outer periphery are due to finer grain size. The inner periphery specimens may also have porosities in them in addition to the coarser grain which lead to lesser tensile values. The UTS and yield strength values of 6061-10%SiC at outer and inner periphery. Both the values at inner and outer periphery are comparably lesser than that the values of base alloy. At the outer periphery the decrease is due to presence of high volume fraction of SiC particles which means there is less matrix material to yield leading to lower UTS and yield strength. In the case of inner specimens the presence of porosities and agglomerates contribute to the lower UTS and yield strength values.

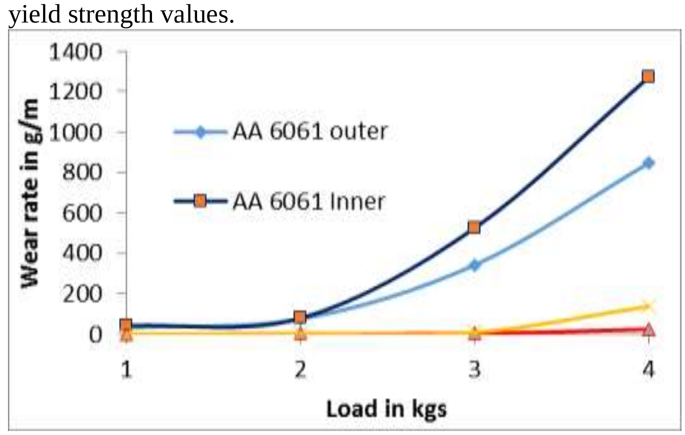


Figure 7. Pin on disc wear rate of AA 6061 and AA 6061-10% SiC FGMMC pins of inner and outer zones.

The dry pin on disc wear tests are conducted with pins, of diameter 6mm and 30mm long, from inner and outer regions. Figure 7 shows the wear rate versus load as a function of weight loss per meter. For AA 6061 alloy, from the graph, it is seen that the wear rate at outer periphery is lower when compared to the inner periphery which is due to the finer grain size of aluminium at the outer periphery when compared to coarser grain size at the inner periphery leading to lower wear resistance at the inner periphery. The wear rate increases by a large amount at increased loads. AA 6061-10% SiC FGMMC the wear rate at the outer periphery is much lesser than both the wear rate at inner periphery of the same ring as well as AA 6061 ring. This is due to the presence of high volume fraction of SiC particles at the outer periphery leading to higher wear resistance and the SiC particle concentration gradually decreases towards the inner periphery which leads to lower wear resistance at the inner periphery.

Figure 8 shows the coefficient of friction (μ) values as a function of loading. The μ value increases as the load increases showing that the wear resistance at higher loads is less. For AA6061 rings μ value ranges from 0.09 to 0.451 at outer periphery and 0.08 to 0.488 at inner periphery for loads 1 to 4kg. The μ values for AA 6061-10% SiC FGMMC at outer and inner periphery varies from 0.03 to 0.049 at outer and 0.117 to 0.105 at inner. The μ value fluctuates over the time period for the load applied due to heterogeneous nature of the FGM. While the test is being carried out if more SiC particles are exposed to the disc then both the wear and coefficient of friction will be less and when more of the matrix materials are in contact with the disc both will be high. General trend is as the load applied increases the μ value will also increase due to the increase in resistance to the relative motion. The μ value dependent on the frictional force, which varies with the operating temperature, in the dry sliding test, as the temperature of the pin and disc increase substantially which in turn decreases the wear resistance of the pin and thus changing the value of the coefficient of friction.

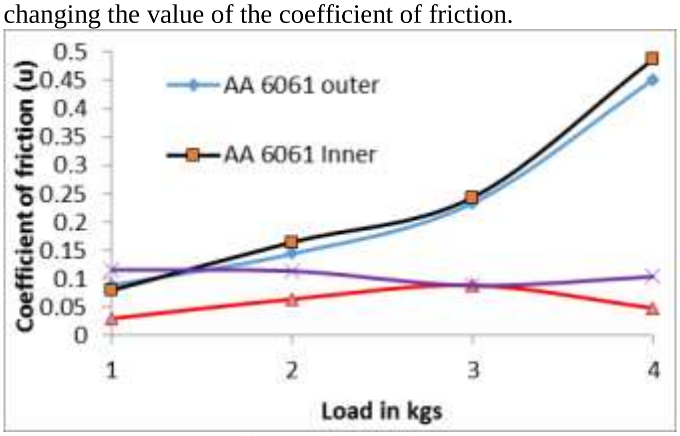
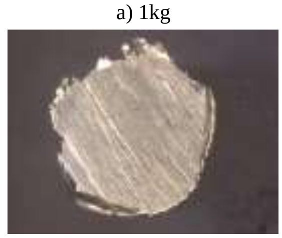


Figure 8. Pin on disc coefficient of friction of AA 6061 and AA 6061-10% SiC FGMMC inner and outer pins.

Figure 9 shows the stereo micrographs of the surface morphology of the wear specimens at different loads. From Figure 9 for AA 6061 both inner and outer specimens the wear scars, at 1kg load, are fine. As the load increases the heat in between the pin and the steel disc increases resulting the softening of aluminium matrix which will sticks to the disc and this material will be thrown out leading to more adhesive wear and thus the smudging phenomenon takes place. The less fine wear scars at higher loads shows larger wear. It is seen that in AA 6061- 10 % SiC FGMMC inner and outer pins the wear scars at all the load are fine indicating less wear due to the presence of SiC particles. These SiC particles are very hard and do not wear off easily and quickly, thus imparting higher wear resistance to the component. Few SiC particles are only present in the inner pins causing higher wear rate with that of particle rich outer zone pins.

a) 1kg

b) 2**kg**



c) 3kg

d) 4kg

A) AA 6061 outer pin: wear surfaces at different loads

a) 1kg

b) 2**kg**

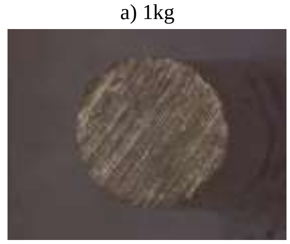
c) 3kg

d) 4kg

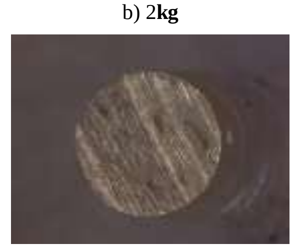
B) AA 6061 inner pin: wear surfaces at different loads

a) 1kg

b) 2**kg**

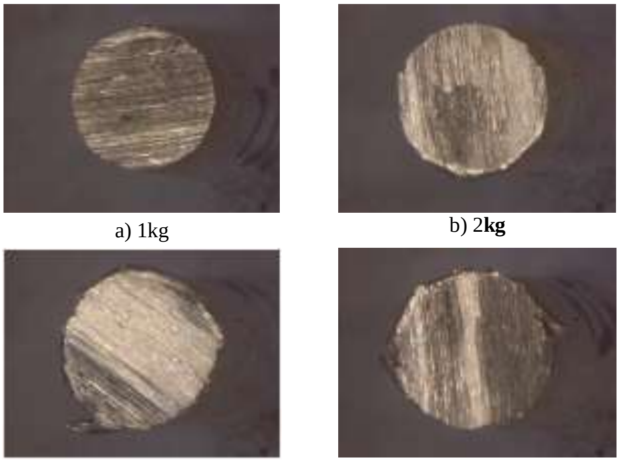


c) 3kg



d) 4kg

C) AA 6061-10% SiC FGMMC outer pin: wear surfaces at different loads



a) 1kg   b) 2**kg**   c) 3kg   d) 4kg

D) AA 6061-10% SiC FGMMC inner pin: wear surfaces at different loads

Figure 9. Stereo micrographs of wear surfaces AA 6061 and AA 6061-10% SiC FGMMC ring outer and inner pins under different loads (1kg to 4kg).

IV. Conclusion

Wrought aluminium AA 6061 FGMMC with SiC_p reinforcements have been fabricated successfully by the centrifugal casting process. The microstructure evaluation and image analysis reveals the functional gradation of SiC_p particles distribution from outer to inner as the particles are of high density material compared with aluminium matrix. The hardness of three regions of particle rich, transition and matrix rich regions are largely depends upon the concentration of SiC particles. SiC rich outer zones show lesser wear rate in comparison with other regions. The variation of wear rate with respect to applied load is linear. The weak interface bond between silicon particle and aluminium matrix at higher load and enhanced interface temperature is the main reason for the change in composite wear property under varying applied loads. Addition of SiC particle and heat treatment provide comparable improvements in the wear resistance. The study clearly depicts the gradient nature in the structure and properties of the FGM rings.

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