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SYNTHESIS OF FUNCTIONALLY GRADED ALUMINIUM COMPOSITE AND INVESTIGATION ON ITS ABRASION WEAR BEHAVIOUR

N. RADHIKA[1,*], R. RAGHU[2]

[1]Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore,
Amrita Vishwa Vidyapeetham, Amrita University, India
[2]Department of Metallurgical Engineering, PSG College of Technology Coimbatore, India
*Corresponding Author: n_radhika1@cb.amrita.edu

Abstract

Functionally graded aluminium (Al-Si5Cu3) metal matrix composite reinforced with 10 wt-percent of boron carbide particles having average size of 33 µm was synthesized through horizontal centrifugal casting method. The specimen of length 150 mm and outer diameter of 154 mm with the thickness of 20 mm was produced under the centrifuging speed of 1000 rpm. Composite specimens were prepared as per ASTM standards from the casting and subjected to microstructural evaluation, hardness testing and three body abrasion wear test. The microstructural observation was done on the surfaces at the distance of 1, 2.5, 10 and 15 mm from the outer periphery of the casting and the result shows that larger amount of particles observed at distance of 2.5 mm and very less particles observed at the distance of 15 mm. The hardness test was conducted on the different surfaces in the radial direction from the outer periphery and found decrease in hardness from 2.5 to 15 mm. The abrasion wear test was conducted using dry abrasion tester for various loads of 28, 40 and 52 N at different distances from the outer periphery of the casting and the results revealed that wear rate gradually increases when moving towards the inner periphery and also with the increasing load. Therefore higher wear resistance was observed at the outer periphery and the lower wear resistance was obtained at the inner periphery. This property makes them suitable for using in wear applications such as in cylinder liners.

Keywords: Functionally graded materials, Aluminium, Boron carbide, Metal matrix composite, Stir casting, Horizontal centrifugal casting, Three body abrasion wear.

Nomenclatures

d	Density, g cm^{-3}
F_c	Centrifugal force
G	Gravitational coefficient
M	Applied load, N
R	Radius of cast cylinder, mm
S	Sliding distance, m
W_a	Abrasion wear rate, mm^3 N^{-1} m^{-1}

Greek Symbols

ΔG	Mass loss, g
ω	Mold rotation rate, rad s^{-1}

Abbreviations

FGM	Functionally Graded Material

1. Introduction

Functionally Graded Materials (FGMs) are the new class of advanced composite materials that are developing in the recent years, in which microstructure and the composition gradually varies in a specific direction. FGMs are mainly used in automobile applications, where high wear resistance and high bulk toughness are needed within a part. It also has application in aerospace, biomedical, electronic, defence and power engineering. These properties can also be achieved using the surface modification and the coating process, but such kinds of treatments are costly [1]. Numerous methods are available for the fabrication of FGMs, but those methods are also cost effective [2].

Centrifugal casting method is the most economical way for producing FGMs reinforced with particles. The advantage of the centrifugal casting lies in good mold filling characteristics and controlled gradient in composition of the fabricated FGMs [3]. In this method, centrifugal force acts on the composite, produced by the rotating die. Depending upon the speed of the die, the amount of acting centrifugal force varies. Low speed produces less centrifugal force results in smooth compositional gradient of the particles and the high rotational speed produces sharp compositional gradient [4].Thus, the centrifugal force makes the particles to attain gradient in composition from the inner to outer surface of the part, due to the density difference between the reinforcement and the molten metal [5]. The denser particles will move towards the outer periphery and lighter particles will move towards the inner periphery. In case of centrifugally produced silicon carbide (SiC) reinforced FGM, more volume fraction of SiC particles obtained at the outer periphery due to its high density than the molten alloy and this surface tends to serve high wear resistance [6]. Thus, these particulate reinforced materials are developed for the production of highly wear resistant components.

Most commonly, these components suffers from two types of wear, namely adhesive and abrasive. Large numbers of studies are already carried out on adhesive wear behaviour of composite materials [7, 8, 9], whereas in abrasive wear behaviour of the composites, only fewer amounts of researches are found

[10, 11]. Studies on the three body abrasive wear characteristics of Al/Frit composite shows that, the increasing volume fraction of the reinforcement reduces the abrasive wear loss of the composite due to the good interfacial bonding between the matrix and the reinforcement [12]. Investigation on the effect of different abrasive medium on the wear rate of the aluminium composite indicates that harder abrasive medium produces more mass loss on the composite specimens than the less hard one and also for the increasing load; more material removal is observed [13]. More material removal is also observed at high speed due to utilization of more total energy on producing abrasion action on the specimen rather than dissipation of the energy to the adjoining area, but the composite has shown better wear resistance than the alloy in all test conditions [14]. In contradiction to that, less wear rate is also recorded at high speed for the composites tested at different speed conditions and the decreasing trend of wear rate is observed for increasing the speed of the wheel due to the less time of contact with the specimen [15].

From the view of above literature review, this study is aimed to investigate the three body abrasion performance of Functionally Graded Aluminium Metal Matrix Composite (FGAMMC) fabricated using horizontal centrifugal casting method.

2. Synthesis of Composite

In this study, Aluminium (Al-Si5Cu3) is chosen as the base alloy due to its wide application range in the automotive field. The composition of Al-Si5Cu3 alloy is shown in Table 1. Boron Carbide (B_4C- 33 µm) of 10 wt-percent is taken as reinforcement due to its good wettability with the aluminium alloy, wear resisting performance and higher hardness comparable to other reinforcements. The density of alloy and the reinforcement are 2.75 gcm^{-3} and 2.52 gcm^{-3} respectively. Thus, Aluminium (Al-Si5Cu3) and B_4C are chosen for the fabrication of FGAMMC.

Table 1.Chemical composition of aluminium Al-Si5Cu3 alloy.

Chemical composition	(%)
Si	4.3
Fe	0.5
Cu	2.2
Mn	0.20
Mg	0.16
Cr	0.01
Ni	0.039
Zn	0.30
Ti	0.028
Pb	0.02
Ca	0.007
Al	92

2.1. Preparation of homogeneous composite

Stir casting process is employed to form the homogeneous composite of the $AlSi_5Cu_3$ alloy with incorporation of B_4C particles. Initially, aluminium is loaded in graphite crucible and kept inside the electrical resistance furnace for the melting purpose, which is integrated with the mechanical stirrer for the mixing process. The illustration of the electric resistance furnace is shown in Fig. 1. The melting of the alloy takes place in an argon gas atmosphere, which produces defect free casting. A provision is provided in the furnace for the supply of argon gas into the heating chamber. After attaining melting condition, the preheated particles (400 °C) are added gradually to the molten metal through the hopper provided at the top of the furnace. Simultaneously, the mixing is done for 5 minutes using the mechanical stirrer which is made of stainless steel. The stirrer is made to rotate at 250 rpm, which runs through the motor on bevel gear transmission. This mechanical means of stirring ensures the uniform dispersion of the reinforcement particles in the molten metal to form the homogeneous composite. Then this molten metal is poured at the temperature of 750ºC into the preheated metallic die.

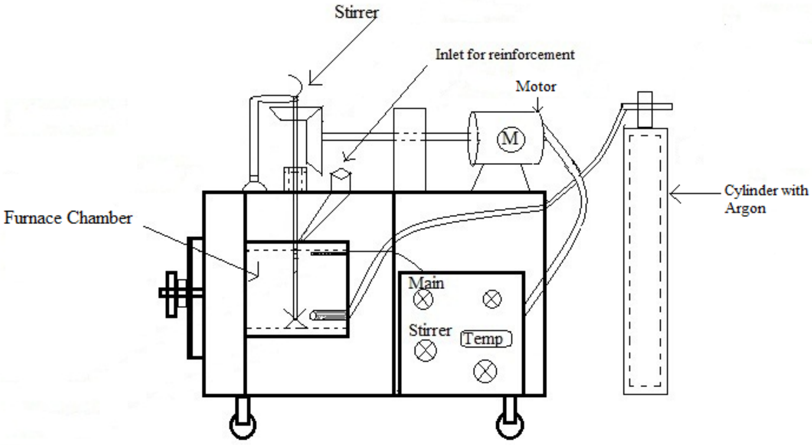

Fig.1. Electric resistance furnace with mechanical stirrer.

2.2. Fabrication of functionally graded composite

A horizontal centrifugal machine (Fig. 2(a)) is used for the fabrication of FGAMMC. The molten metal is poured into the preheated die of 154 mm inner diameter and the length of 150 mm. The die is preheated to the temperature of 350 ºC and is made to rotate at 1000 rpm. The die is rotated with the help of the 1.49 kW motor through the belt and pulley transmission. A coolant tank is provided in the machine that supplies coolant around the shaft that connects the die and the pulley. This avoids the heat transfer from the die to the transmission belts and prevents the damaging of the belts. The molten metal enters the exact center of the preheated die and due to the rotation of the die, centrifugal force and gravitational force acts on the particles in the molten metal. The centrifugal force pushes the particles in the molten metal towards the wall and is given by $F_c=m\omega^2 r$. The gravitational force is given by mg. The ratio of the centrifugal force to the gravitational force gives the gravitational co-efficient or G number and is given by the Eq. (1)

$$G = \frac{\omega^2 r}{g} \tag{1}$$

where ‘ω’ is the mold rotation rate (rad/s), ‘r’ is the radius of the cast cylinder taken (m) and ‘g’ is the acceleration due to gravity (m s^{-2}). From the Eq. (1), it is known that centrifugal force is G times higher than the gravitational force and thus gravitational force is negligible. This clearly denotes that the G value increases as the centrifugal force increases. Thus for the rotated rpm of 1000, the applied G number is 86. The die is allowed to rotate till the completion of solidification. After solidification, the cast part (Fig. 2(b)) is ejected from the die.

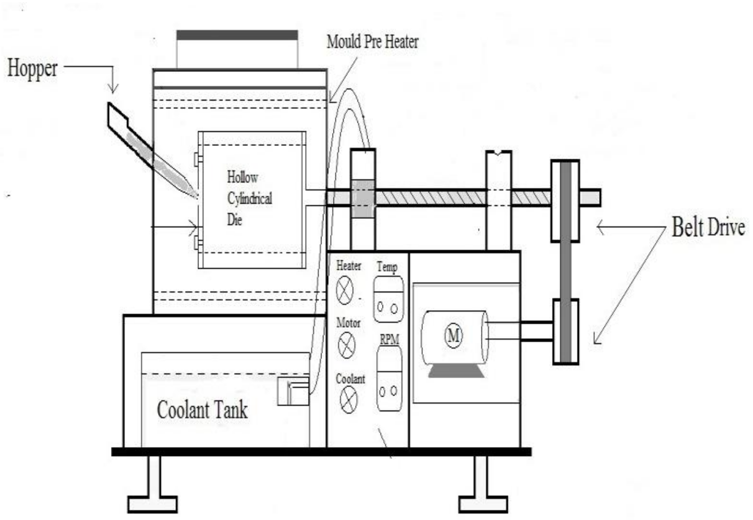

Fig. 2(a). Schematic illustration of the horizontal centrifugal casting machine.

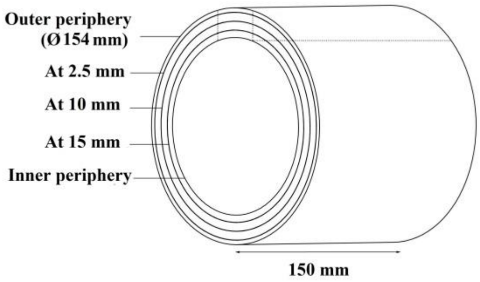

Fig. 2(b). Hollow cylindrical cast component.

3. Microstructural Examination

The specimens for the microstructural evaluation have taken from the cast part and are metallo-graphically polished and etched with Keller’s reagent. Microstructure of composite samples are observed using Zeiss Axiovert 25 CA Inverted Metallurgical Microscope. The specimens of length 15 mm and diameter 10 mm are cut from the samples to examine the microstructure. The microstructure is taken at the distances of 1, 2.5, 10 and 15 mm from the outer periphery towards the inner periphery of the FGAMMC reinforced with B_4C particles (Fig. 3).

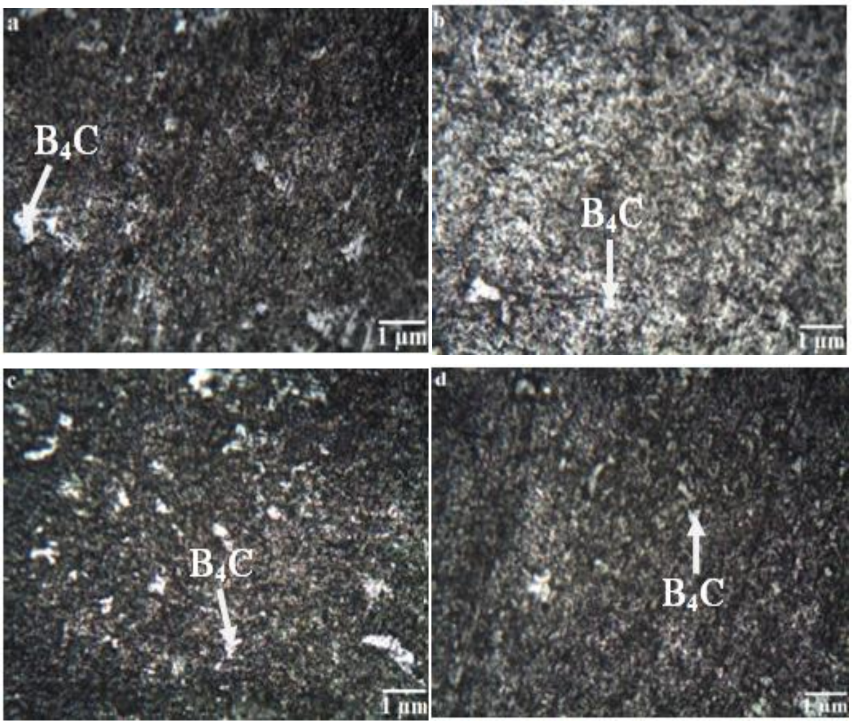

Fig. 3. Microstructure of the FGAMMC (Al-Si5Cu3/B4C$_p$) at the distance of a) 1 mm b) 2.5 mm c) 10 mm d) 15 mm from the outer periphery.

4. Hardness Testing

The surfaces at the distance of 1, 2.5, 5, 7.5, 10, 12.5 and 15 mm from the outer periphery of the FGM are taken for evaluation of hardness in Vicker's hardness tester (Fig. 4). The specimens are polished using the emery sheets of grades 1/0 and 2/0 to remove the presence of scratches from the specimen surface. The specimen is placed over the base plate of the tester by the aid of holding jaws and load of 0.98 N is applied on the surface of the specimen for the time of 15 seconds. After the indentation time, the indenter is automatically released from the specimen surface and the diagonal lengths of the indentation are measured in order to evaluate the hardness. The tests are repeated for five times to establish the accuracy in the hardness measurements. The obtained hardness for the different surfaces from the outer to inner periphery of the FGM is given in Fig. 5.

5. Three Body Abrasion Wear Test

The three body abrasive wear test is carried out using Dry abrasion tester-TR 50 (Fig. 6) at the room temperature condition. The specimens of size 76x25x12 mm are machined from the cast part and made to the surface roughness of 0.8 µm. Before test, each specimen is weighed in an electronic balance with an accuracy of 0.1 mg. Initially, the abrasive wheel is dressed before the test and the hopper is loaded with the required amount of abrasive medium to perform the test without interruption. Silica sand AFS 50/70 is the abrasive medium used for producing the abrasion at the specimen, which falls through the nozzle, exactly between the rubber wheel and the specimen. The abrasion test is conducted at the surfaces of 1, 2.5, 5, 7.5, 10, 12.5, and 15 mm from the outer periphery of the casting. The specimen is fixed at the specimen holder and the load is applied through the lever mechanism for the continuous contact with the chlorobutyl rubber wheel.

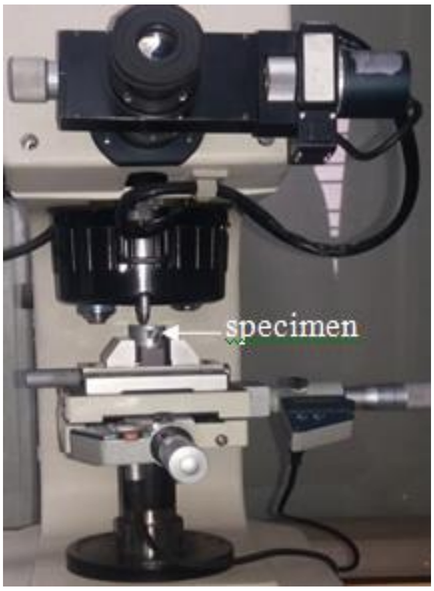

Fig.4. Vickers hardness tester.

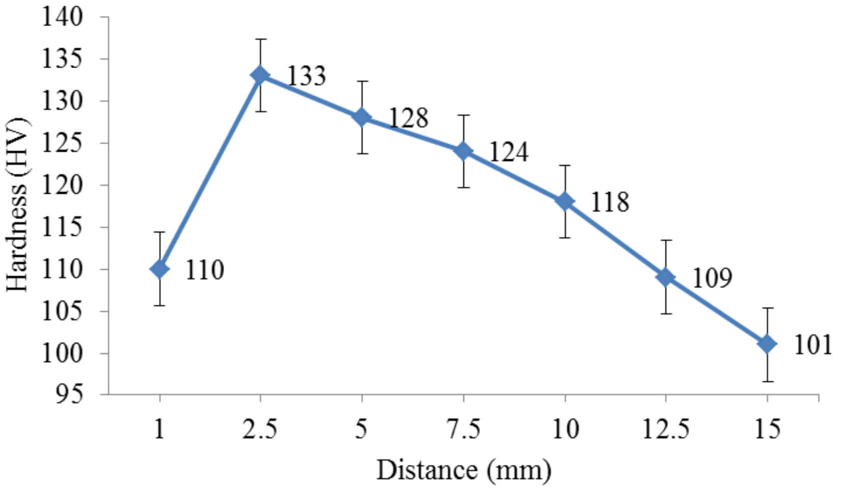

Fig. 5. Hardness of the different surfaces of the FGM in the radial direction.

For every 1 kg of load placed on the loading pan, the exerting load on the specimen is 2.4 kg. The hardness of the rubber wheel is durometer A-60 and with the diameter of 228 mm. The loads applied on the rubber wheel is 28, 40 and 52 N. Speed of the wheel is kept at 200 rpm and the time duration is kept constant as 5 minutes for performing the test. The flow of the sand is continuous and with the constant flow rate of 354 gmin^{-1}, till the completion of the test. After the test, the specimen is taken out and weighed again to determine the mass loss. From the mass loss, the abrasion wear rate is calculated using the formula (Eq. (2))

$$W_a = \frac{\Delta G}{dMS} \tag{2}$$

where W_a is the abrasion wear rate (mm^3 N^{-1} m^{-1}), ΔG is mass loss (g), d is density (g/cm), M is the applied load (N), S is the sliding distance (m).

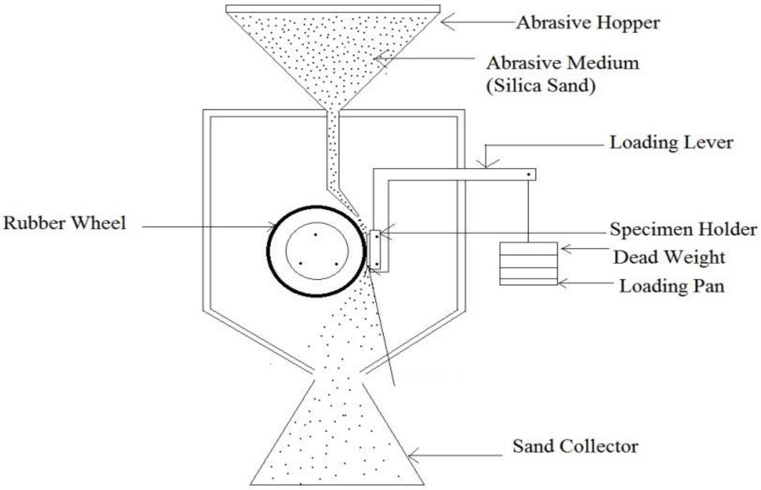

Fig. 6.Three body abrasion wear test apparatus.

6. Results and Discussion

The results of the microstructural observation, hardness evaluation and the three body abrasion wear test are discussed in detail in the following subheadings.

6.1. Evaluation of microstructure

The microstructure observation on the Al-Si5Cu3/B_4C_p composite at different distances (1, 2.5, 10 and 15 mm) from the outer periphery of the casting clearly denotes that B_4C particles are found less initially at the distance of 1 mm and very high at the surface of 2.5 mm and gradually decreased towards the inner periphery forming very less reinforcement particles at the surface of 15 mm. This is attributed to the centrifugal force involved in the fabrication process which pushes the reinforcement particles contained in the molten metal towards the outer periphery with graded distribution along the radial direction towards the inner periphery. The surface at the distance of 1 mm displays non-linear behaviour of less reinforcement particles as this is due to the quicker solidification of the melt which hinders the movement of the reinforcement particles to the exact outer periphery. Hence the concentration of reinforcement particles is found high at the distance of 2.5 mm and fewer amounts of particles are observed when moving to the inner periphery which may be due to less centrifugal rotational speed of 1000 rpm. If rotational speed of the die increased further, there might be chance for all the particles to move to the outer periphery and very less or absence of particles will be occurring at the inner periphery. There is also gas porosities observed at the inner periphery of the casting and this might be due to lesser density of the gas bubbles that are thrown to the inner periphery when the centrifugal force acts on it. This action of the gas bubbles carries some particles with it towards the inner periphery which is also a reason for observing fewer particles in the inner periphery [16].

The microstructures (Figs. 3(a-d)) obtained from the different surfaces of the FGM are examined using image analyzer to predict the reinforcement concentration. This examination assures the compositional gradient produced across the thickness of the casting. The surfaces of 1, 2.5, 10 and 15 mm display the reinforcement concentration of 11 %, 31 %, 14 % and 4 % respectively. Thus, it is ensured that particle concentration is high at the distance of 2.5 mm and decreased when moving towards the inner periphery.

6.2. Evaluation of hardness

The surface at the distance of 1 mm (110 HV) displays less hardness than the surface of 2.5 mm (133 HV) which is due to less segregation of the reinforcement particles owing to the solidification front. Then the hardness is observed decreasing from the surface at the distance of 2.5 to 15 mm. The surface at the distance of 2.5 mm displays higher hardness due to large segregation of the reinforcement particles that offers resistance to the deformation caused by the indenter. The decrease in hardness towards the inner periphery is attributed to the decrease in the presence of reinforcement particles when moving towards the inner periphery as this is confirmed through the microstructural observation at 10 and 15 mm (Figs. 3(c) and 3(d)). The inner periphery of 15 mm displays the least hardness (101 HV) as this surface is largely composed of aluminium alloy which is unable to resist the deformation of the indenter. Thus, it is clearly understood that the presence of reinforcement particles on the different surfaces of the FGM decides its hardness and changes the graded properties along the radial direction of the casting.

6.3. Abrasion wear behaviour

The dry abrasion test is conducted on the composite specimens (Al-Si5Cu3/B_4C_p) and the experimental values are tabulated in Table 2. The abrasion is caused on the specimen by the silica sand abrasive medium that falls under gravity between the specimen and the rubber wheel. The plot for the observed wear rate is shown in Fig. 7. This figure gives the details of the abrasion wear rates of the specimens graphically.

Table 2.Abrasion wear rate for the loads of 28, 40, 52 N at various distances from the outer periphery.

Distance /mm	Abrasion wear rate /mm^3 N^{-1}m^{-1} Load /N 28	40	52
1	0.00614	0.00642	0.00737
2.5	0.00343	0.00486	0.00727
5	0.00344	0.00516	0.00729
7.5	0.00357	0.00541	0.0077
10	0.00363	0.0058	0.0087
12.5	0.00388	0.00587	0.00923
15	0.00517	0.00722	0.00967

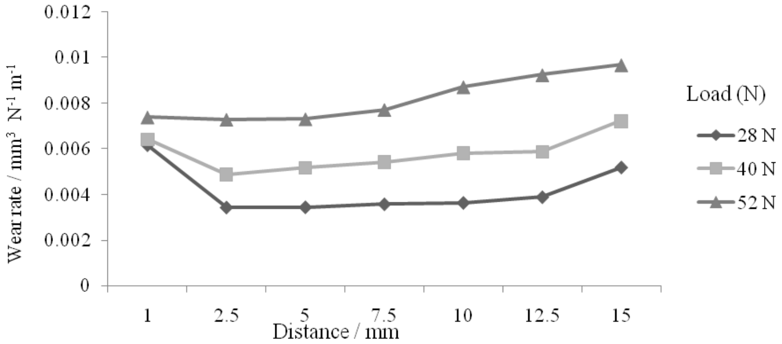

Fig. 7.Abrasion wear rate of the composite (Al-Si5Cu3/B4C$_p$) at the loads of 28, 40, 52 N at the constant speed of 200 rpm.

From the plots, it is clearly observed that the wear rate gets gradually increased from the distance of 2.5 mm from the outer periphery towards the inner periphery of 15 mm irrespective of the load conditions. This clearly denotes that there is presence of more reinforcement particles at the surface of 2.5 mm, than the surface of 15 mm from the outer periphery. This movement of more reinforcement particles towards the outer periphery is mainly due to the centrifugal force acting on the particles during the rotation of the die. The centrifugal force produces the gradual distribution of the reinforcement particles across the thickness of the functionally graded materials. But in the surface of 1 mm from the outer periphery shows high wear rate than the surface of 2.5 mm. The reason for the high wear rate at the distance of 1 mm from the outer periphery might be due to the quick solidification of the melt at the inner surface of the die. The molten metal that enters to the die will start adhering to the walls due to the centrifugal force acting and this molten metal gets solidify within the fraction of time due to the large temperature difference between the die preheating temperature and the pouring temperature of the molten metal. Thereby, there is very less chance for the particles to move to the outermost periphery of the cast. There might be chance for the particles to move to this area when the rotation of the die is further increased or else raising the preheating temperature of the die will keep the molten metal to be in liquid condition for some time that keeps the chance for the particles to move to the outermost periphery at this condition. Thus from the surface of 2.5 mm from the outer periphery, the particles are distributed gradually towards the inner periphery which is evident from the wear rate values.

The very less wear rate of the composite for all the load is observed at the distance of 2.5 mm. This show that large amount of particles are presented at this surface, which has higher hardness than the matrix alloy, protects the matrix alloy from the penetration of the abrasive medium into the composite surface which results in less wear rate. The more reinforcement region shows less wear rate which ensures there is good bonding between the B_4C particles and the matrix alloy and there is no removal of the reinforcement particles at the surface when abrading. Therefore the surface at the distance of 2.5 mm from the outer periphery tends to serve high wear resistance. There is reasonable difference of wear rate between the distance of 2.5 mm and 15 mm. The wear rate (W_a= 0.00517, 0.00722, 0.00967 $mm^3 N^{-1}m^{-1}$) at 15 mm is higher than wear rate (W_a= 0.00343, 0.00486, 0.00727 $mm^3 N^{-1}m^{-1}$) at 2.5 mm for respective loads of 28, 40 and 52 N. This shows there is not much amount of particles observed in the inner periphery as like observed at the outer periphery. Thus the outer periphery serves the wear resistance and the inner periphery serves the better toughness with lesser wear resistance.

Large numbers of researches reported on studying the effect of different loads on the abrasion wear rate of the composites with keeping other parameters constant [17, 18]. Thus load is preferred to be as the varying parameter in this study and keeping other factors at constant. Considering the effect of load on the abrasion wear rate, for the increasing applied load the wear rate is more as it is due to the increased physical contact of the specimen with the rubber wheel and the abrasive particles. This allows more abrasive particles to penetrate on the surface of the specimen resulting in more material loss and the similar case is observed [19]. The wear rate increases for all the load conditions when moving from the outer to the inner periphery. The higher load (52 N) shows more amount of wear rate than the loads of 28 and 40 N at all distances from the outer periphery. This clearly shows that applied load plays a role in abrasion rate of the functionally graded composite.

7. Conclusion

Functionally graded aluminium metal matrix composite ($Al\text{-}Si5Cu3/B4C_p$) is successfully fabricated by horizontal centrifugal casting method. The microstructural observation has showed large amount of reinforcement particles at the surface of 2.5 mm and decrease in particle segregation along the thickness towards the inner periphery. The hardness evaluation result shows that hardness gets decreased linearly towards the inner periphery from the surface of 2.5 mm. The surface of 2.5 mm from the outer periphery tends to serve high abrasion wear resistance (0.00727 $mm^3 N^{-1}m^{-1}$) and the surface of 15 mm from the outer periphery serves the less abrasion wear resistance (0.00967 $mm^3 N^{-1}m^{-1}$). An increase of wear resistance of around 25 to 34 % is obtained at 2.5 mm compared to 15 mm. The abrasion wear rate of the composite increases with increasing the applied load at all distances from the outer periphery of the casting and also wear rate increases when moving from the outer periphery towards inner periphery at all load conditions. The developed functionally graded composite can be used for the tribological application in cylinder liner.

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