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# The influence of interfacial characteristics between $SiC_p$ and Mg/Al metal matrix on wear, coefficient of friction and microhardness

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**Abstract**

The aim of the present investigation is to characterize the interface between the $SiC_p$ as the reinforcement and Al and Mg metals of the metal matrix composites (MMCs) prepared through vacuum infiltration technique. The weight loss as an index of abrasive wear using pin-on-disc apparatus, the coefficient of friction, the microhardness value and the interparticle distance were determined under dry conditions and these results were correlated to characterize the interface as a function of properties of metal and the reinforcement. The results of the investigation indicate that interparticle distance in cast infiltrated composites strongly influences the tribological properties of these composites. Microhardness on the reinforcement particles and interparticle distance are good indicators of the strength of the interface between particle and the matrix. Magnesium base composites in general show better wettability as compared to the aluminium base composites. Coating of $SiC_p$ reinforcements with Ni and Cu generally leads to good quality interface characteristics in Al matrix composite as both microhardness and wear properties are improved. Oxidized $SiC_p$ reinforcements behave in complex manner in influencing the interfacial characteristics in aluminium/magnesium matrix composites possibly due to the formation of reaction product at the interface.


*Keywords:* Metal matrix; Coefficient of friction; Microhardness

## 1. Introduction

Largely the structures and the properties of the reinforcement/metal interface control the mechanical properties of metal matrix composites (MMCs). It is believed that a strong interface permits transfer and distribution of the load from the matrix to the reinforcement, resulting in an increased elastic modulus and strength [1,2]. The nature of the interface depends on the matrix composition, the nature of the surface of the reinforcement and the fabrication method of the composite [2].

Two major types of interaction occur at the interface between a liquid and a solid phase: (a) physical and (b) chemical. Physical interactions determine the wettability by non-reactive liquids such as water and organic which have tens of $J/m^2$ as surface energies. However, chemical interactions are dominant in reactive systems where liquid phases have several $J/m^2$ as surface energies, and provide most of the bonding energy [3]. An intimate contact between the reinforcement and the matrix needs to be established through satisfactory wetting [4–6] of the reinforcement by the matrix to ensure adequate adhesion and the rate of chemical reaction at the interface should be very low and extensive interdiffusion between the component phases should be avoided so that the reinforcement will not be degraded. The choice of the reinforcing and matrix materials for a composite system often cannot satisfy these requirements at the same time [1]. One of the ways of achieving such a desired interface while not having to sacrifice the performance of the composite is to apply a thin coating or coatings on the reinforcement [7,8], which is chemically compatible with both the reinforcement and the matrix. Oxidized SiC particles have been found to retard interfacial reaction and provide superior bonding in the case of aluminium base alloys [2,9,10]. The silica layer grown naturally or artificially on the surface of SiC fibres or particles used in aluminium-based matrix composites is supposed to have two functions: protection of the SiC from aluminium attack and improvement of the wettability of SiC by aluminium which would result from the reaction between aluminium and $SiO_2$ [11]. Selective addition of alloying elements has also proved to be effective in improving wettability and reducing interdiffusion [1,12–14]. From a mechanical point of view, the behaviour of interface plays a significant role in controlling the strength of com-

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posites. The normal component of interfacial stresses would tend to cause interface debonding, while the shear component could be the cause of splitting of phase boundaries [1].

The micro-indentation test has been developed over a number of years as a mean of extracting and quantifying the characteristic parameters of the interface between the matrix and the reinforcing fibre [15]. In the present investigation, this technique has been extended to characterize the interface between the matrix and the reinforcing particles. The microhardness on the SiC particles have been shown to be a simple and easy way of measuring the strength of the interface between the matrix and reinforcement indirectly [16].

Many of the applications for which discontinuously reinforced aluminium matrix composites are desirable also require enhanced tribological performance. There exists a large body of literature concerning the wear performance of such materials, much of it showing the composites in a good light compared to the alloys in the unreinforced state [17,18]. The introduction of reinforcing particles in an aluminium matrix reduces the wear rate [19–22] and the coefficient of friction. The particle size, volume fraction, or compositions do not significantly affect the coefficient of friction of the Al composites [22]. Hence, in the present investigation emphasis has been led on the variation of the interface through coating of the reinforcement and also through change of the matrix. Strong bonding between particle and matrix is desirable for wear resistance as well as other mechanical properties [23,24]. The kinetics of wear can be determined in terms of vertical displacement or material loss as a function of load and time [25].

Improvement in dispersiancy characterized in terms of interparticle distance is used as a parameter. Surface characteristics of reinforcement as their effect on dispersion has been related to wear property. Researchers [26] have shown that the dispersion parameters such as percent of particles touching, and the average interparticle distance sufficiently describe the agglomeration and dispersion of SiC particles in the matrix. They have also shown an improvement in the wear resistance of Al–1.5% Mg/$SiC_p$ MMC having good dispersion of particles in the matrix. Recent studies revealed that in addition to the spatial distribution of second-phase particles, wear resistance is largely affected by the strength of particle–matrix interfaces as well as the mechanical properties of matrix materials [24].

The bulk of the data on the interfacial characterization pertains to either SiC or alumina particles reinforced aluminium matrix composites. Moreover, most of the studies have been conducted on composites made by the casting route (excluding vacuum infiltration technique, which has its own advantages [13,16,27] over other casting techniques) or powder metallurgy route. In this study, in contrast, the Al and Mg composites have been made using vacuum infiltration technique and were used to characterize the interface between the reinforcement and matrix, correlating data on the average interparticle distance, microhardness on $SiC_p$, coefficient of friction and wear of the composite.

## 2. Experimental

The samples of $SiC_p$ reinforced Al and Mg metal matrix composites were prepared through vacuum infiltration setup described elsewhere [16]. The Al and Mg used for the present study are of commercial purity (99.5%). The reinforcement is black α-SiC particulate of 100 μm average diameter.

The composites prepared were of 15 mm diameter and contain about 0.5 volume fraction of $SiC_p$. A number of infiltration experiments with varied preheat temperature of SiC bed (500, 550, 600 and 650°C) have been carried out to investigate its influence on the microhardness on $SiC_p$ reinforced into the matrices of Al and Mg, average interparticle distance, coefficient of friction and wear of the composites. In the case of Al, the melt temperature has been varied (720, 800 and 850°C) to study its influence on the interparticle distance, coefficient of friction, wear and microhardness on $SiC_p$ reinforced in the Al matrix. In the case of Mg, study has been conducted only to observe the effect of variation of preheat temperature of the $SiC_p$ preform on interparticle distance, coefficient of friction, wear and microhardness on $SiC_p$ reinforced in the Mg matrix. The effect of dynamic oxidation of SiC particles has been compared with that of untreated SiC particles reinforced in the matrices of Al and Mg. The dynamic oxidation of the $SiC_p$ has been carried out in a fluidized bed furnace at 900°C for 4 h. The Cu and Ni coatings have been obtained on $SiC_p$ by electroless coating.

The microhardness measurements on $SiC_p$ have been measured using a Vickers microhardness tester with 100 g load. The indentation was taken on the particles of same average size. However, while taking the measurements, all the readings wherein particle cracking has been observed have been rejected in order to get the true hardness value of the particle. Each reading of microhardness in the graphs corresponds to that of the average of microhardness measurement on 30 SiC particles in the composites of Al and Mg matrices and the scatter in the hardness values in each case is quite small, i.e. of the order of 0.1% [16].

To understand the dispersion behaviour of the particles in the matrix, interparticle distance of the reinforced particles was measured using an NEOMET image analyzer. In order to have better understanding of the coefficient of friction behaviour of these materials, the same were measured using a pin-on-disc wear-testing machine against an alloy steel of specification EN-24 that had hardness of 57 Rc, using a load of 19.6 N at 230 rpm and disk track diameter of 120 mm at 31.9°C and RH 90%. In an endeavour towards better understanding of the mechanical wear of particulate reinforced composite materials as a function of interface property, wear tests were carried out on Al/$SiC_p$ and Mg/$SiC_p$ composites. The wear testing of MMCs were done using the pin-on-disc technique. The transverse section of each specimen of 15 mm diameter was polished on diamond cloth. The wear test was performed on a 220 grit emery paper for 2 min at a linear sliding speed of 1.67 m/s and at disk track diameter of 145 mm. The total rubbing distance covered was kept constant for all specimens. A load of 9.8 N was put on the pins. For every specimen, a fresh emery paper was used. The weight loss observed after the experiment is a measure of the wear property of the material. The values for wear reported are average of three experiments and the error was of the order of 0.01%.

Scanning electron microscopy (SEM) analysis on the infiltrated composite sample was done after wear test. The samples were sputter coated with gold and were characterized by SEM using JEOL SEM. The X-ray mapping and line scanning of the worn surfaces were also done on the same SEM.

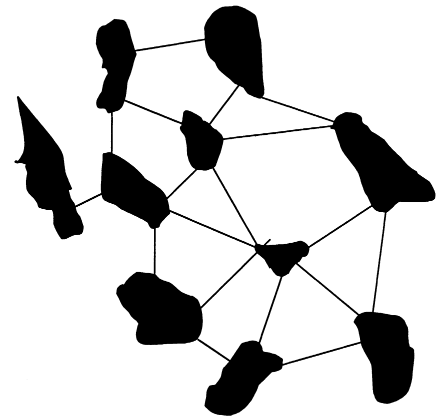


Fig. 1. Computer generated image analysis picture to measure the minimum interparticle distance of Al/SiC$_{p(Cu\text{-}coated)}$ composite prepared at a preheat temperature of 650°C and melt temperature of 720°C.

## 3. Results

The following sections present results of measurement of interparticle distance, microhardness measurement, coefficient of friction and wear done on composite samples produced with different surface treated SiC particles. The results are presented as graphs giving correlation of their properties with preheat temperature of reinforcement bed, and in combination of properties. Most of the results are presented as function of interparticle distance.

### *3.1. Interparticle distance and microhardness measurements against preheat temperature*

The dispersion of SiC particles in aluminium and magnesium metal matrix composites was measured to study the effect of matrix, preheat temperature of the SiC$_p$ preform, melt temperature, and coating on the SiC$_p$ on the variation in average interparticle distance of the reinforced particles. Fig. 1 shows a computer generated image analysis picture for measuring minimum interparticle distance of Al/SiC$_{p(Cu\text{-}coated)}$ composite.

If the average interparticle distance is high (i.e. the dispersion of the particles in the matrix is good), the microhardness, coefficient of friction and wear properties would be influenced. The poor dispersion of the particles is due to the agglomeration of the particles in the matrix and may lead to the weakening of the mechanical properties.

The microhardness measurements have been taken on a number of SiC particles of Al/SiC$_p$ composites prepared with uncoated, Ni-coated, Cu-coated and dynamically oxidized SiC$_p$ at preheat temperatures of 500, 550, 600 and 650°C at the melt temperatures of 720, 800 and 850°C. The same measurements have been taken on SiC particles of Mg/SiC$_p$ composites prepared with uncoated and dynamically oxidized SiC$_p$ at preheat temperatures of 500, 550 and 650°C at the melt temperature of 720°C. The effects of preheat temperature and the melt temperature on the microhardness value and their correlation with the average interparticle distance has been studied. The average microhardness values of Al/SiC$_p$ composites prepared at a preheat temperature of 650°C and melt temperature of 720°C described elsewhere [16] have been repeated for the purpose of comparison of results.

For all the preheat temperatures of the SiC$_p$ preform, the average of the microhardness measurement on 30 SiC

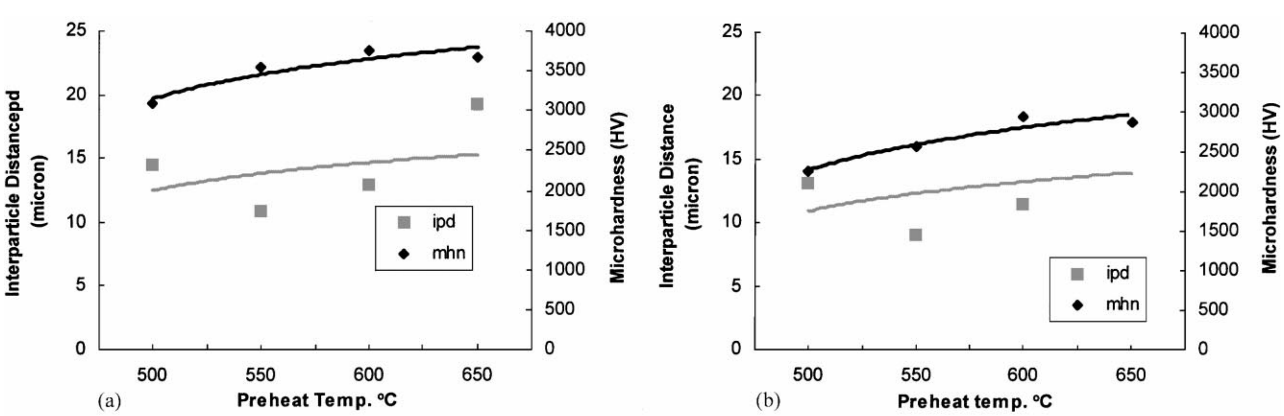



Fig. 2. Effect of preheat temperature on microhardness on SiC$_p$ reinforced in the (a) Mg/SiC$_{p(uncoated)}$ and (b) Mg/SiC$_{p(oxidized)}$ composite vis-à-vis interparticle distance.

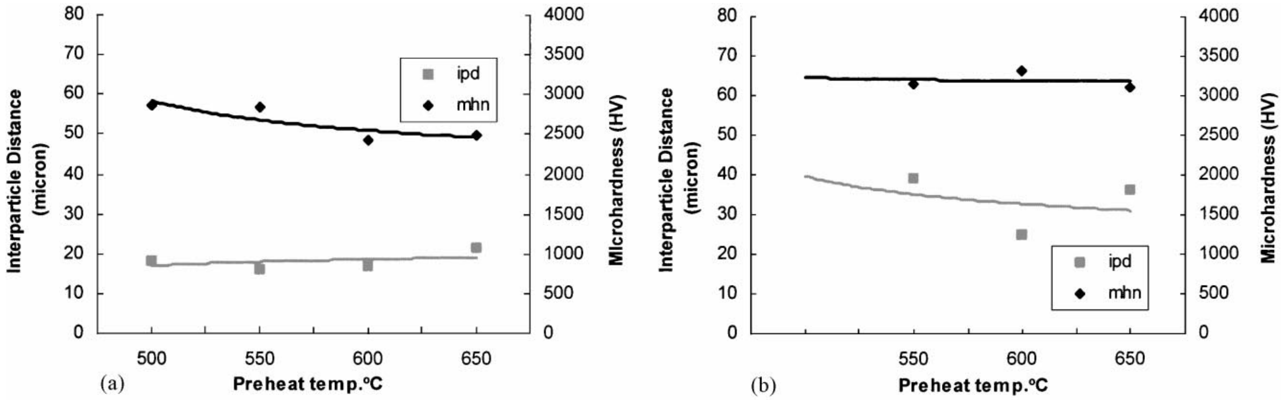



Fig. 3. Effect of preheat temperature on microhardness on $SiC_p$ reinforced in the (a) $Al/SiC_{p(uncoated)}$ and (b) $Al/SiC_{p(oxidized)}$ composite vis-à-vis interparticle distance.

particles in the Al and Mg matrices have been reported. These average values of the microhardness clearly show an increasing trend of hardness in the order of uncoated, Cu-coated, Ni-coated and dynamically oxidized $SiC_p$ reinforced Al matrix composite. It is interesting to note that for the $Mg/SiC_{p(uncoated)}$ composite, the average interparticle distance as well as the statistical average of microhardness increases with the increase in preheat temperature of the $SiC_p$ preform as shown in Fig. 2(a). The same is the case for the Mg composite reinforced with the dynamically oxidized SiC particulates as shown in Fig. 2(b). However, the microhardness measured on the oxidized SiC particle is less than that of on the untreated SiC particles reinforced in the matrix of Mg composites prepared at respective preheat temperatures. Thus, it can be concluded that increase in preheat temperature of the preform improves the interface strength and also leads to a better dispersion of the particles in the matrix.

In the case of $Al/SiC_p$ composite reinforced with dynamically oxidized $SiC_p$, the microhardness value as well as the average interparticle distance has a slight decreasing (because the slope of the curve is very small) trend with increase in the preheat temperature of the $SiC_p$ preform as shown in Fig. 3(b). However, for uncoated SiC particles reinforced Al matrix composite, the interparticle distance curve is shown to have slight increasing trend, whereas the microhardness curve has decreasing trend as shown in Fig. 3(a). That means there is hardly any effect of preheat temperature on the microhardness value or it can be said that the two effects, i.e. physical and chemical are perhaps nullifying each other in the process of improving wettability of the oxidized SiC particles reinforced in the aluminium metal. This is because the silica acts as an oxygen source that causes oxidation of liquid aluminium and is confirmed by SEM X-ray line scan in the present investigation [11].

The Ni-coated $SiC_p$ reinforced Al composites have shown an increasing trend for statistical average microhardness on the $SiC_p$ in the matrix vis-à-vis the average interparticle distance with increase in preheat temperature of the $SiC_p$ preform and also with increase in melt temperature as shown in Fig. 4(a) and (b), respectively. In the absence of possibility of interfacial reaction due to barrier of Cu and Ni, the increase of preheat temperature has a positive trend on interparticle distance and microhardness.

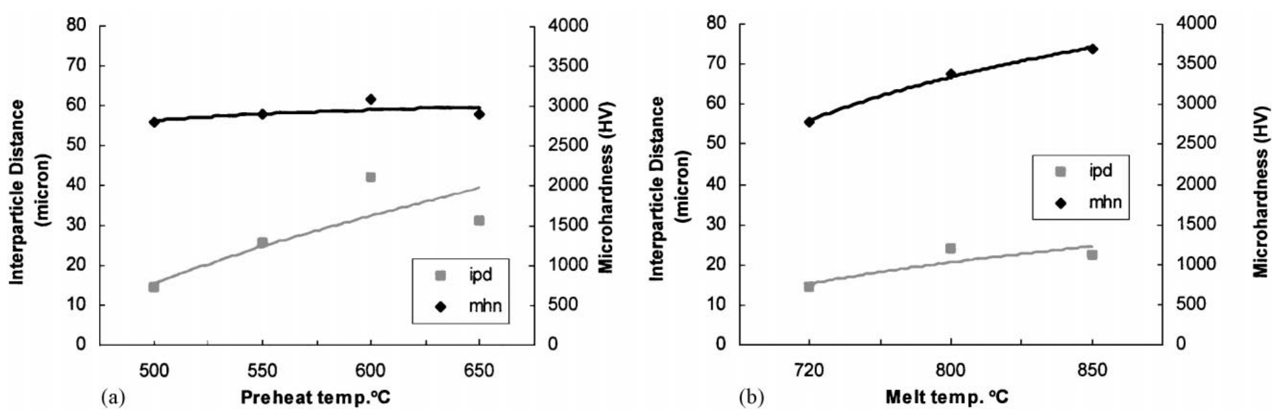



Fig. 4. Effect of (a) preheat temperature and (b) melt temperature on microhardness on $SiC_p$ vis-à-vis interparticle distance of $Al/SiC_{p(Ni-coated)}$ composite.

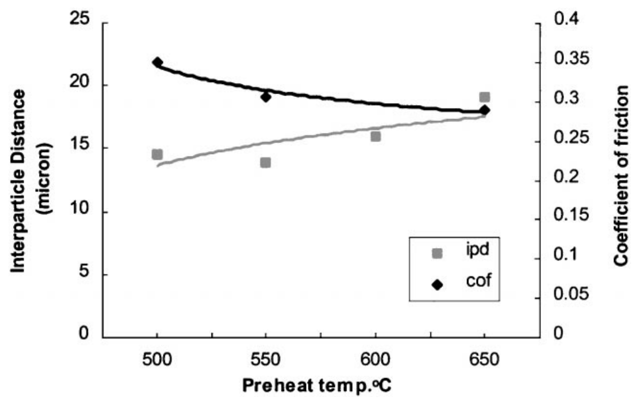



Fig. 5. Effect of preheat temperature on coefficient of friction vis-à-vis interparticle distance of $Mg/SiC_{p(uncoated)}$ composite.

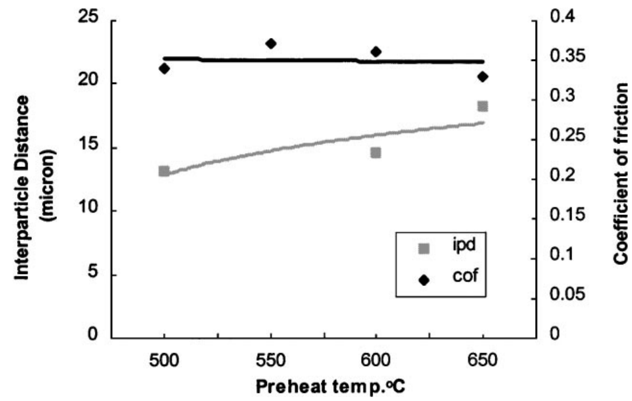



Fig. 6. Effect of preheat temperature on coefficient of friction vis-à-vis interparticle distance of $Mg/SiC_{p(oxidized)}$ composite.

### 3.2. Interparticle distance and coefficient of friction

In the present investigation, for $Mg/SiC_{p(uncoated)}$ MMC, the coefficient of friction decreases, whereas the interparticle distance increases with increase in preheat temperature of the $SiC_p$ as shown in Fig. 5. The same is true for the case of $Mg/SiC_{p(oxidized)}$ MMC as shown in Fig. 6. This clearly demonstrates that a good dispersion of the particle leads to a lower value of coefficient of friction of the composite.

For Ni-coated $SiC_p$ reinforced Al matrix composite, the coefficient of friction decreases, whereas the interparticle distance increases with increase in preheat temperature of the $SiC_p$ preform as shown in Fig. 7.

Thus, generally, improved dispersion characteristics of the composite lower the coefficient of friction values of the composites when the wettability of the reinforcement with the matrix metal is better as in the case of $SiC_p$ reinforced in Mg metal and also in the case of Ni-coated $SiC_p$ reinforced in Al metal.

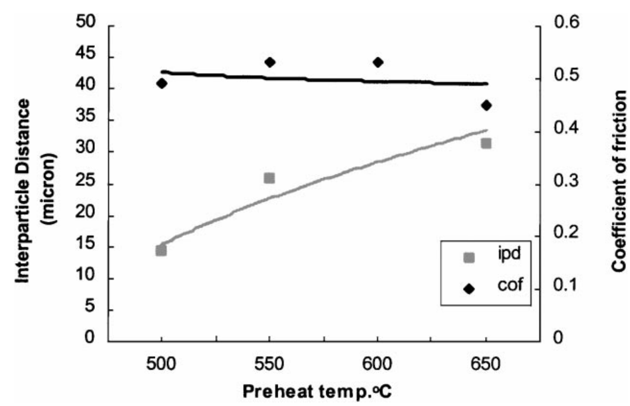



Fig. 7. Effect of preheat temperature on coefficient of friction vis-à-vis interparticle distance of $Al/SiC_{p(Ni\text{-}coated)}$ composite.

### 3.3. Interparticle distance and wear properties

In the wear test of the composite samples, it was found that $Mg/SiC_p$ composite has shown a decreasing trend for wear and increasing trend for the average interparticle distance with increase in preheat temperature of the $SiC_p$ as shown in Fig. 8(a). The same is true for the case of oxidized SiC particles reinforced Mg matrix composite as shown in Fig. 8(b). Thus, it can be concluded that the decrease in the agglomeration of the particle leads to a decreasing trend in the wear of the composite material with increase in preheat temperature of the $SiC_p$ preform. Also it is evident from the

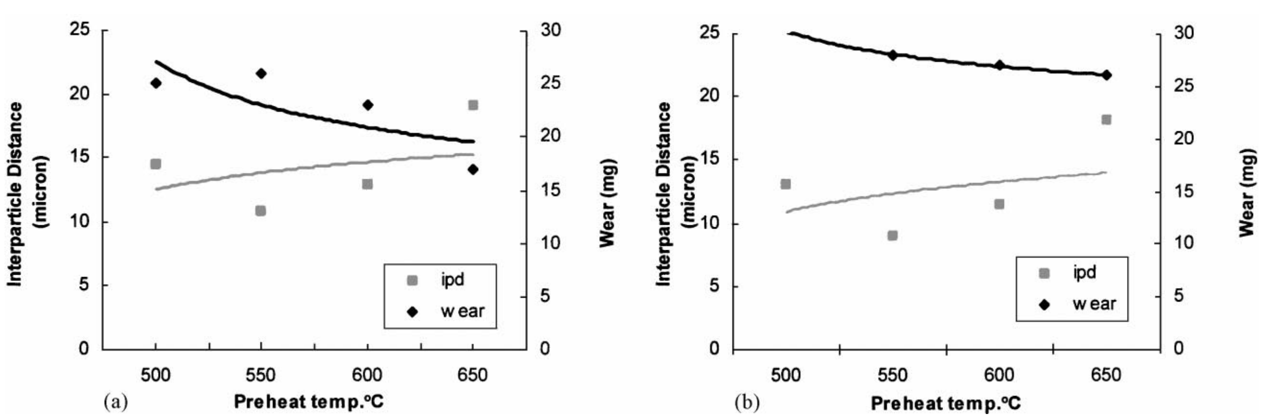



Fig. 8. Effects of preheat temperature on wear vis-à-vis interparticle distance of (a) $Mg/SiC_{p(uncoated)}$ and (b) $Mg/SiC_{p(oxidized)}$ composite.

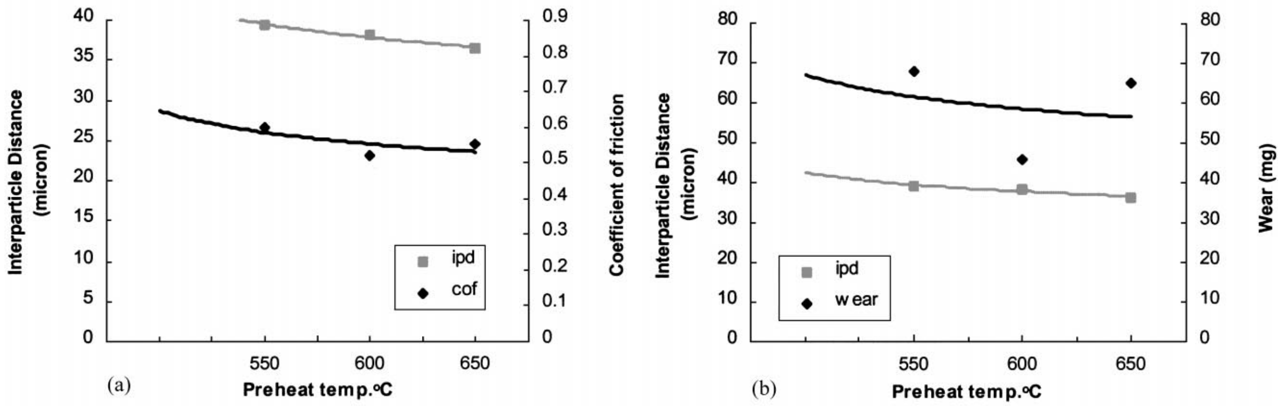



Fig. 9. Effect of preheat temperature on (a) coefficient of friction and (b) wear of Al/$SiC_{p(oxidized)}$ composite vis-à-vis interparticle distance.

Table 1
Chemical compositions of the compounds formed at the interface of Al/$SiC_{p(oxidized)}$ composite

| Element | % of element | Compound | % of compound |
|---|---|---|---|
| Al | 14.24 | $Al_2O_3$ | 26.91 |
| Si | 34.17 | $SiO_2$ | 73.09 |
| O | 51.59 | | |

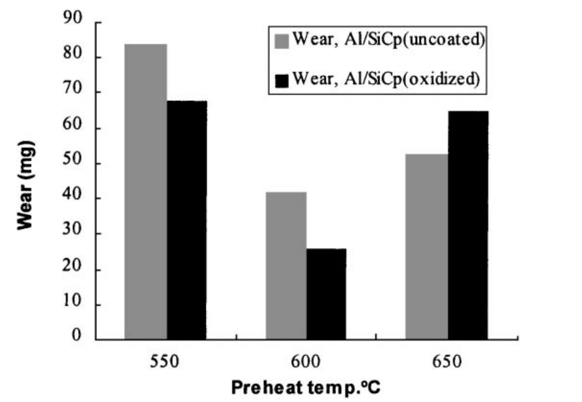



Fig. 10. Comparison of wear of Al/$SiC_p$ composite reinforced with uncoated and oxidized particles.

figures that the wear is more in the case of oxidized SiC particulate reinforced Mg composite as compared to that of untreated SiC particulate reinforced Mg composite.

The wear and the coefficient of friction of the dynamically oxidized $SiC_p$ reinforced Al matrix composite decrease with increase in preheat temperature of the $SiC_p$ preform. Also, the SiC particles tend to agglomerate with increase in preheat temperature of the $SiC_p$ preform in the matrix of the dynamically oxidized $SiC_p$ reinforced Al matrix. This is evident from Fig. 9(a) and (b) where the average interparticle distance decreases with increase in preheat temperature of the $SiC_p$ preform. It has been found after X-ray mapping of the surface of the cross-section examined and line scanning of the interface region of the composite material that 26.91% of $Al_2O_3$ and 73.09% of $SiO_2$ are present at the interface as shown in the Table 1. Perhaps, these compounds are responsible for improvement in the wear resistance and coefficient of friction of the composite material although the agglomeration has increased. X-ray mapping also showed slight smearing of Ni and Cu on the surface of the

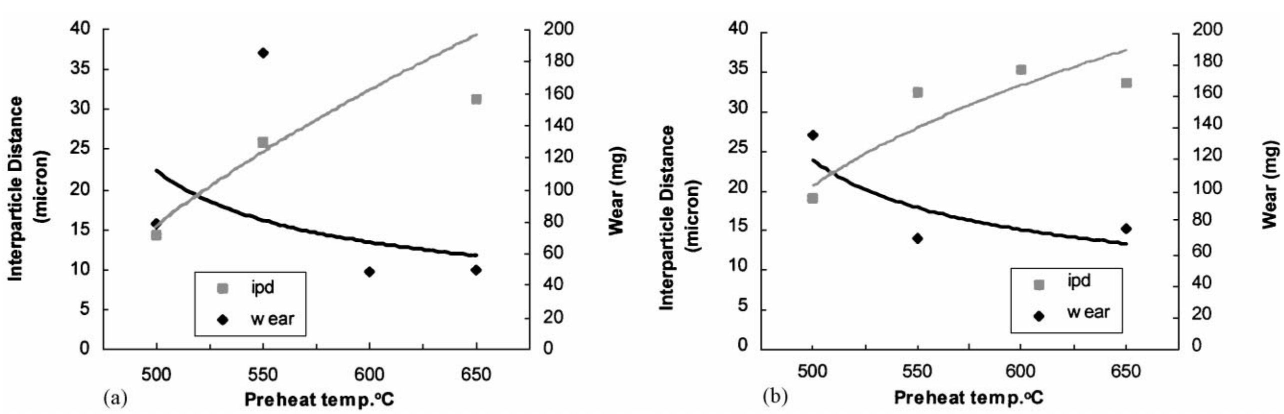



Fig. 11. Effect of preheat temperature on wear vis-à-vis interparticle distance of (a) Al/$SiC_{p(Ni\text{-}coated)}$ composite and (b) Al/$SiC_{p(Cu\text{-}coated)}$ composite.

composite material after wear test of the Al/$SiC_{p(Ni\text{-}coated)}$ and Al/$SiC_{p(Cu\text{-}coated)}$ composite materials, respectively.

However, the comparison of the absolute values of the wear data clearly shows that the wear is more in the case of uncoated SiC particulate reinforced Al matrix composite than that of oxidized one as shown in Fig. 10, i.e. wear resistance is more for oxidized $SiC_p$ reinforced Al matrix composite as compared to uncoated one except at preheat temperature of 650°C.

In the case of Ni- and Cu-coated $SiC_p$ reinforced Al composite, the wear of the composite decreases, whereas interparticle distance increases with increase in preheat temperature of the $SiC_p$ preform as shown in Fig. 11(a) and (b).

## 4. Discussion

Let us examine the dispersion process and its relation with wettability, microhardness, coefficient of friction and wear and their correlation with the interfacial strength. In the early stages of the dispersion process [28], the solid–air interface is replaced by one between solid and liquid (wetting). The interparticle forces that must be overcome in dispersion may be surface tension forces, solid bridge forces, electrostatic van der Waals forces, forces arising from plastic welding or mechanical forces. Different methods of particle production give particles of different roughness, leading to changes in the interlock or friction forces between particles.

When appreciable quantities of liquid are adsorbed, the surface film covers the asperities and forms liquid bridges between particles in contact. The curvature of the meniscus determines the vapour pressure above the liquid bridge and the magnitude of the adhesive force owing to surface tension. For two smooth spheres, the total force $F_{tot}$ is

$$F_{tot} = \frac{2\pi r\gamma}{1 + (\tan\phi/2)}$$

where $\phi$ is the central angle (see Fig. 12), $r$ the particle radius, and $\gamma$ is the surface tension.

The four primary processes involved in stable dispersion are: (1) displacement of adsorbed gas on the solid phase by the liquid phase; (2) formation on the solid surface of a protective boundary to prevent particle–particle adhesion; (3) mechanical separation of these particles to allow the liquid phase complete encapsulation of them; (4) complete and homogeneous redistribution of the particles throughout the liquid volume [29].

If energy of wetting (enthalpy of wetting) by the liquid exceeds that of the adsorbed gas, the liquid in the drop will move outward until the internal force holding the liquid molecules together (essentially the latent heat of vaporization) balances the energy of wetting provided by the surface, i.e. the free surface energy.

The surface wetting by the droplet is the result of excess surface free energy. Surface molecules are thus being pulled in normally, toward the solid surface, a situation equivalent to a surface tension. The surface energy expended is not truly the total surface energy but that "left over" as a consequence of surface atoms or molecules being at the surface.

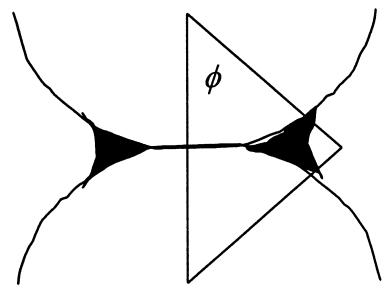



Fig. 12. Condensed liquid at the point of contact between two smooth solid spheres, assuming zero contact angle.

Well-dispersed solids as a powder have contact angles approaching zero and poorly wet surfaces angles approaching 90° or more (sessile conformation) [29]. This has been corroborated by the well-known Young equation:

$$\cos\theta = \frac{\gamma_{gs} - \gamma_{ls}}{\gamma_{gl}}$$

The force created by wetting energy is $\gamma_{ls}$, that for gas–solid by $\gamma_{gs}$, and the third force component, adsorption of the gas on the liquid drop, by $\gamma_{gl}$. In this equation the contact angle of the liquid on the solid, $\theta$, becomes a direct measure of the ability of the liquid to wet out the solid surface, or for the solid as a powder to disperse in the liquid as the bulk phase. This means that lower contact angle and hence better wettability leads to better dispersion of the reinforcement in the molten metal matrix. This should manifest as greater interparticle distance at same volume fraction of SiC particles. Also, it has been observed in the present investigation that well-dispersed particles in Al and Mg composites have shown improved microhardness, coefficient of friction and wear resistance. Previously [16] it has been shown that improved microhardness on the SiC particles is an indirect revelation of the interfacial strength. Researchers [18] have shown that the degree of clustering is expected to influence the wear performance by providing preferential sites for crack nucleation. Also the wear resistance is largely affected by the strength of the particle–matrix interface in addition to the spatial distribution of the particles [24]. Further, better dispersion of the particles within the composites enhances the friction coefficient [30]. Thus, it can be concluded that wettability, dispersion of the reinforcement in the matrix and interfacial strength are related to one another vis-à-vis microhardness value on the SiC particles, coefficient of friction and wear property of the Al and Mg metal matrix composite material.

Al would strongly wet Ni- and Cu-coated SiC particle. Also higher temperature always lead to lower contact angle $\theta$, thus, showing improvement in wettability. Thus, Ni as well as Cu coating and higher preheat temperature possibly improve the wettability of the ceramic/metal reinforcement and hence as discussed above are responsible for a better dispersion of the particles in the Al matrix. The Ni and Cu coating on $SiC_p$ wet the SiC and hence no reinforcement degradation is observed in Al matrix composite. Also the $SiC_p$ are well dispersed in the Ni- and Cu-coated $SiC_p$ reinforced Al and uncoated SiCp reinforced Mg composites. Contrary to $Al/SiC_{p(Ni\text{-}coated)}$, $Al/SiC_{p(Cu\text{-}coated)}$ and $Mg/SiC_p$ system, agglomeration of the $SiC_p$ are observed in the case of $Al/SiC_{p(oxidized)}$ composite. This might be due to the formation of $Al_2O_3$ at the interface as evident from the X-ray line scan where the compounds formed and their compositions at the interface are shown in Table 1.

It has been reported that coating is dissolved during the fabrication of the composite leading to $NiAl_3$ phase formation and also that the formation of $NiAl_3$ phase at the interface has a weak influence on the degradation of the $SiC_{p(Ni)}/Al$ interface [31]. The Ni- and Cu-coated $SiC_p$ reinforced Al matrix composite have shown improvement in the microhardness value on the $SiC_p$ as compared to the uncoated $SiC_p$ reinforced Al composite with increase in the preheat temperature of the preform, although the difference in the statistical average of microhardness value on the SiC particle is nominal for Ni- and Cu-coated SiC particle reinforced Al composite. The Ni- and Cu-coated $SiC_p$ reinforced Al composite have also shown an improvement in the wear and coefficient of friction properties of the composite with increase in the preheat temperature of the preform. Nevertheless, the oxidized SiC particle reinforced Al composite has shown a remarkable improvement in the microhardness value on SiC particle. Although, the dispersion of the oxidized SiC particles in Al matrix is poor at higher temperature, the oxidized $SiC_p$ reinforced Al composite has also shown better wear and coefficient of friction properties as compared to that of untreated $SiC_p$ one. This is likely due to the formation of $Al_2O_3$ at the interface and hence improved wear and coefficient of friction properties. The improvement of coefficient of friction and wear resistance with decrease in interparticle distance as shown in Fig. 9(a) and (b) can be explained [32] as the difficulty in impinging the matrix directly by the erodant particles of the emery paper due to short interparticle distance between the $SiC_p$ reinforced in the metal matrix of the composite material as is revealed in Fig. 13. This model in Fig. 13 clearly shows

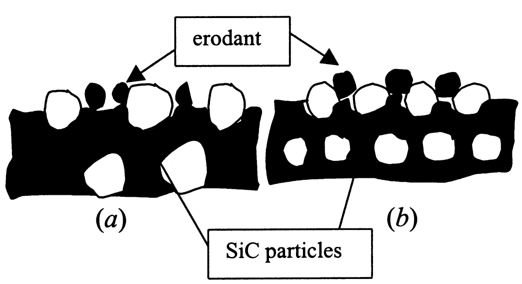


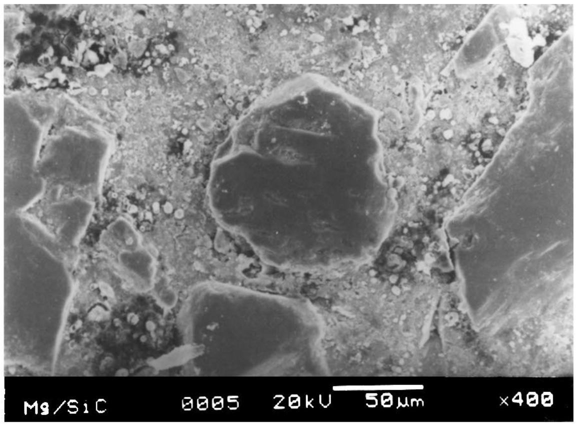

Fig. 13. (a) Erodant impinge effectively; (b) erodant prevented due to "short space" [32].

that if the interparticle distance of the reinforced particles in the composite material is short, then the erodant particles of the emery paper are, perhaps, prevented to erode the $SiC_p$ of the composite material, whereas the erodant particles of the emery paper can erode the $SiC_p$ of the composite material when the reinforced $SiC_p$ are dispersed at higher distances.

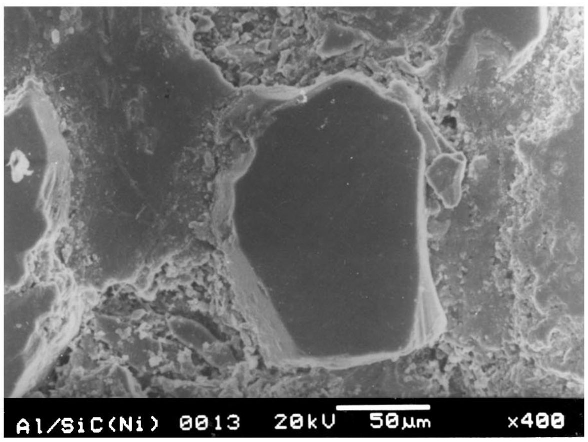
Indeed SEM studies done on worn surfaces, confirmed the above model. The SEM micrographs of worn samples shown in Fig. 14(a)–(c) for $Mg/SiC_p$, $Al/SiC_{p(Ni\text{-}coated)}$ and $Al/SiC_{p(Cu\text{-}coated)}$, respectively, clearly show the absence of grooves. This reflects the strength of bonding between the $SiC_p$ reinforcement and the Al and Mg matrices of the composite materials prepared through vacuum infiltration technique. Earlier Taha et al. [33] have shown in general a rough granular surface with a lot of debris on the surface in the observation of the worn surfaces using SEM. Pramila Bai et al. [34] have shown that none of the SiC particles at the surface seem to have undergone any fragmentation, nor is there any decohesion at the particle–matrix interface. Contrary to this, Manish Roy et al. [22] have noted the presence of distinct grooves in the investigation of worn out surfaces of $Al/SiC_p$ composites. Although this comparison is not rational because the wear tests in the preceding case were done on steel disc at a higher load of 80 N, whereas in the present investigation it is done on emery paper of 220 grit size comparably at a lower load of 9.8 N. (Also, the load is applied on a higher area in the present case.)

The interface region in $Mg/SiC_p$ composite clearly demonstrates no reinforcement degradation as shown in Fig. 14(a). To do the microanalysis of the $Mg/SiC_p$ sample, X-ray scanning of the transverse section of the composite was done which is shown in Fig. 15.

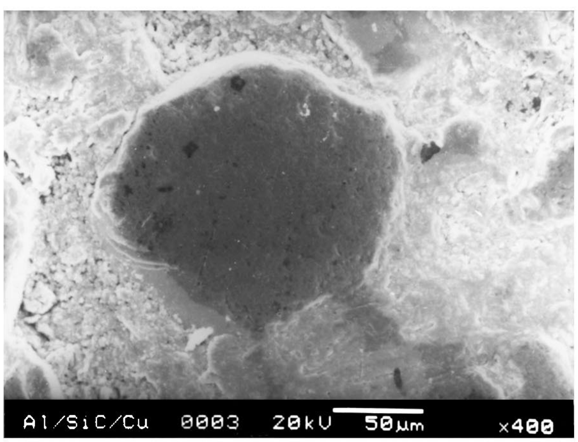
It is interesting to note that for Mg matrix composite, when the interparticle distance increases, both the coefficient of friction and wear decreases, and the microhardness on the $SiC_p$ increases, with the increase in preheat temperature of the reinforcement. This clearly demonstrates that the preheat temperature of the preform has a definite impact on the particle distribution in the matrix which is due to improvement in wettability. This also reflects that the improvement in the wettability causes the improvement in the microhardness on the $SiC_p$ reinforced in the Mg matrix and this improvement is in complete agreement with the improvement in wear resistance and coefficient of friction of the composite material. Thus, the microhardness value, wear and coefficient of friction value, and the interparticle distance are correlated among one another with the wettability and interfacial strength as discussed later. The microhardness increase represents better interface strength which is due to the increase in the wettability of the $SiC_p$ with Mg metal as indicated by decrease in the capillary pressure drop given by $\Delta P_\gamma = -\sigma S \cos\theta$ [35] as reported in the earlier work [16], where $\sigma$ is the surface tension of the melt, $\theta$ the contact angle, and $S$ is the specific surface area of the reinforcing phase.




(*a*)




(*b*)




(*c*)

Fig. 14. SEM micrograph of (a) Mg/SiC$_{p(uncoated)}$, (b) Al/SiC$_{p(Ni\text{-}coated)}$ and (c) Al/SiC$_{p(Cu\text{-}coated)}$ showing worn surfaces of the composite samples tested for wear.

It is assumed that a strong interface between the matrix and the particle would resist indentation on SiC particles better than a weak interface. A weak interface is expected to allow pushing of the particle during the indentation and hence lead to a lower hardness value of the particle when compared to a strong interface and hence the microhardness on SiC$_p$ changes due to change in interface condition obtained through varying the surface condition (by coating of SiC by Ni and Cu and oxidizing SiC) and preheat temperature of the SiC$_p$ reinforced in the metal matrix and also through changing the metal matrix and its melt temperature (as in the case of Al). Thus, a statistical averaging of the hardness of SiC over a number of particles can be a simple and indirect measure of the interface strength in a composite [16].

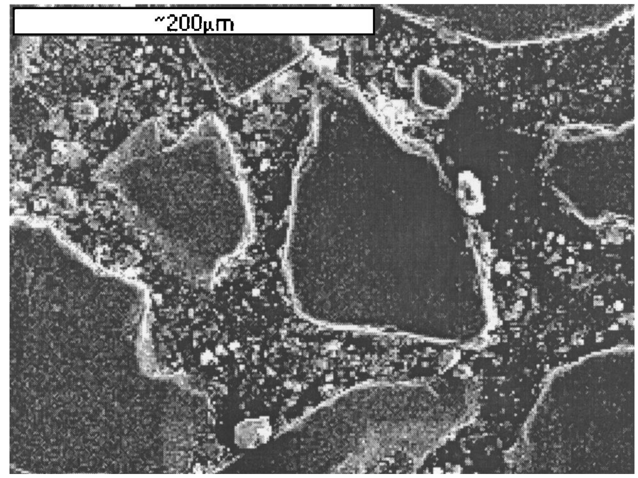



Fig. 15. SEM photograph of Mg/SiC$_{p(uncoated)}$ composite showing absence of interface degradation and uniform distribution of reinforcement in the matrix.

Similar results have been found for the coefficient of friction and wear test done for the Mg composite. The decrease in the coefficient of friction value and increase in the wear resistance are due to better distribution of the particle in the matrix which is due to the improvement in the wettability of the reinforcing phase with the matrix metal. This is in agreement with the works done by Rana et al. [26,30] where it has been shown that a better particle distribution in the matrix is responsible for low wear and coefficient of friction of the composite.

The same is true for oxidized SiC$_p$ reinforced Mg matrix composite where it has been found that microhardness increases with increase in interparticle distance, and the coefficient of friction and wear decrease with increase in preheat temperature of the preform as is the case for untreated SiC$_p$ reinforced Mg composite. This is attributed to the formation of $MgOSiO_2$ spinel at the interface. The matrix metals Al and Mg have responded differently to the reinforcement by the oxidized SiC$_p$. In case of Al reinforced with oxidized SiC$_p$, the microhardness on the SiC$_p$ has increased, whereas in the case of Mg reinforced with the oxidized SiC$_p$, the microhardness on the SiC$_p$ has decreased as compared to the Al and Mg reinforced with the untreated SiC$_p$, respectively. The same is true for the coefficient of friction and the wear tests. This clearly shows that the wettability improves in both the materials, i.e. Al and Mg reinforced with oxidized

$SiC_p$, but it has to be further investigated that to what extent these reaction products at the interface are responsible for physico-chemical effect on the improvement of wettability. Thus, the wear of the composite is related to interface property, due to compound formation at the interface that may cause easy void or crack nucleation. However, coefficient of friction of the composite material is related to the bonding of the reinforcement with the matrix metal, irrespective of nature.

Thus, perhaps two types of interface regions are identified. One, where better wetting is observed with no significant interface reactions. This is the case where Ni- and Cu-coated SiC particles are used for reinforcement. The second type is, where wettability is improved and some reaction products are formed. This is the case when oxidized SiC particles are used for reinforcing. Here, as stated, spinel type of compound formation, $MgOSiO_2$, in the case of $Mg/SiC_{p(oxidized)}$, and $Al_2O_3$, in the case of $Al/SiC_{p(oxidized)}$, takes place. This has been confirmed by X-ray scanning of the interface region. The higher wear loss in the case of untreated $SiC_p$ reinforced Al metal matrix composite takes place and that has been attributed to easy nucleation and growth of voids and consequently pull out of the particles [24,36].

The coefficient of friction is also the function of wt.% of SiC and particle size. If particle size is more, the coefficient of friction is more. Also, if wt.% of SiC is more, the coefficient of friction is less. Mathematically [30], coefficient of friction $f = 1.225 - 7.8 \times 10^{-2} M_1 + 1 \times 10^{-3} M_2 + 1.5 \times 10^{-4} P_2 - 1.67 \times 10^{-5} P_3$, where $M_1$ and $M_2$ are wt.% of SiC and particle size (materials variables), respectively, and $P_2$ and $P_3$ are temperature and speed (processing variables), respectively.

## 5. Conclusions

1. Interparticle distance in cast infiltrated composites strongly influences the tribological properties of theses composites.
2. Microhardness on the reinforcement particles and interparticle distance are good indicators of the strength of the interface between particles and the matrix.
3. Magnesium base composites in general show better wettability as compared to the Aluminium base composites.
4. Coating of $SiC_p$ reinforcements with Ni and Cu generally leads to good quality interface characteristics in Al matrix composite as both microhardness and wear properties are improved.
5. Oxidized $SiC_p$ reinforcements behave in complex manner in influencing the interfacial characteristics in aluminium/magnesium matrix composites possibly due to the formation of reaction product at the interface.
6. Interfacial characteristics in particulate reinforced metal matrix composites can reasonably be evaluated by correlating interparticle distance with microhardness on particles, wear and coefficient of friction.

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