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Erosive wear response of SiC_p reinforced aluminium based metal matrix composite: Effects of test environments

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ABSTRACT

In the present investigation, the erosive wear behaviour of a 10 wt.% SiC particles reinforced aluminium based metal matrix composite has been studied. The composite was fabricated by dispersing SiC particles of size 50-100 µm into the matrix alloy. The resulting material cast was characterised in terms of microstructure, hardness and erosive wear behaviour. The wear response was examined by the sample rotation technique using the slurry pot erosion tester. The effects of speed, sand content and slurry environment on the slurry wear behaviour have been studied. It was observed from the microstructural studies that the interfacial bonding strength between the aluminium matrix and the SiC particles was good and the particles were distributed uniformly. Moreover, in basic medium matrix alloy exhibited a minimum wear rate compared to the composite whereas in the case of an acidic and saline medium, an improved wear resistance was obtained in the case of the composite. The rate of material loss is found to be higher with the increased sand concentration due to the increased impinging action of the sand particles. Also, the rotational speed has a mixed effect on the wear rate. It can be concluded that the material loss was caused by the synergistic effect of corrosive, erosive and abrasive actions of the slurry medium although in the acidic medium, erosion was the dominant mode of material removal whereas corrosion was dominant in the case of a basic medium.

Keywords: Slurry erosion tester (TR-40); SEM; AMCs; Aluminium-Silicon Alloy; SiC particulate.

INTRODUCTION

Aluminium is potentially an important class of material for a variety of engineering applications due to its unique properties such as light weight, low density, good thermal and electrical conductivity, good fabricability and excellent corrosion resistance. Because of having such characteristics, it has found applications in various sectors such as transportation, packaging, electrical industries, chemical and food industries, architecture etc. But conventional aluminium alloys do not always impart the required properties under all the service conditions owing to its poor room temperature and elevated temperature strength and stiffness, low wear and seizure resistance. To overcome these limitations, another class of material came into existence, which is universally known as aluminium matrix composites (AMCs) [1]. The composites are fabricated by encompassing two or more materials having mutually different properties and the newly

formed compound gives an entirely new set of properties [2]. The advantage of the composites with respect to their substrates reflects in the improvement of the mechanical properties primarily in the increase of the specific elastic modulus, increased hardness, improved wear properties, as well as the resistance to corrosion [3]. Various processing methods have emerged for the synthesis of AMCs, which include stir casting [4], squeeze casting [5], Rheo-casting (compo-casting) [6], spray deposition [7], powder metallurgy (P/M) [8], mechanical alloying [9] etc. Each of these methods has its own advantages and limitations. In fact, the suitability of a method primarily depends on the reinforcement shape, size, and volume fraction as well as on the type of application. However, among the different processing methods available for the synthesis of composites, Stir-Casting is found to be the most commercially viable method, especially for the synthesis of particle reinforced composites where the aluminium matrix is completely melted and ceramic particles are added into the molten metal in a vortex created using a mechanical stirrer [10]. Over the past few decades, the wear behaviour of AMCs was extensively studied and impressive attention has been paid by the researchers to expand the utilisation of aluminium matrix composites in the marine environment [11]. The potential application for these composites incorporates a mixed bag of marine structures, for example impellers and agitators, which are subjected to slurry erosion in a marine environment. In this manner, a comprehension of the slurry erosion-corrosion attributes of the material is required before MMCs can be connected to create the wear-safe auxiliary parts [12]. Erosion-corrosion concerns the removal of surface material by the impingement of solid erodent particles suspended in a corrosive carrier fluid. Practical examples on this context include the hydraulic transport of slurries in dredging and drilling operations, fire-fighting and cooling systems not only in naval vessels but also within oil and gas production, power generating industries and commercial shipping, such as pumps, impellers, propellers, valves, heat exchanger tubes and other fluid handling equipment [13].

Erosive wear is a complex phenomenon due to the presence of too many variables hence it is important to develop a systematic understanding of the influence of various parameters on the wear behaviour of materials in order to effectively exploit its application potential. In this context, it has been observed that target parameters (composition, microstructure, mechanical properties), process parameters (particle size, shape, velocity & particle concentration), and environmental parameters (temperature, humidity, etc.) are important sets of variables that basically control the overall wear response [14]. Accordingly, a more realistic assessment of the parameters becomes imperative in order to arrive at a meaningful assessment of material performance in a given set of conditions. In recent years, several attempts have been made to understand the erosion-corrosion response of aluminium based alloys and their composites. In this context, Das et al. [11] reported that the interface of the matrix/dispersoid plays a significant role in controlling the overall performance of the composites under a corrosion medium. In another study, Yu et al. [15] delineate that the interfacial attack as well as corrosion is minimised due to the formation of a nobble intermetallic layer in the interface. Saraswathi et al. [16] investigated the combined influence of material related parameters such as the matrix microstructure, reinforcement volume fraction as well as experimental parameters such as sand content and speed on the erosion/corrosion behaviour of AMCs in three different environment types, namely marine, synthetic mine water and basic media. Their study concluded that AMCs exhibited better wear resistance than the base alloy in NaCl and acidic media irrespective of the sand content and speed. Moreover, the wear resistance increased with the SiC content irrespective of the matrix

alloy, sand content and speed in acidic and NaCl media. Ramachandra and Radhakrishna [17] investigated the erosive wear of AMCs containing 15 wt.% of fly ash particulates and observed that wear resistance increased with the increase in the fly ash content. Ramesh et al. [14] studied the effect of experimental parameters, such as the slurry concentration, impinging particle size, velocity time duration and quenching media and aging duration on the slurry erosive resistance of Al6061 alloy and concluded that the slurry erosive wear increased with an increase in the sand concentration, slurry rotation speed and impinging particle size. Desale et al. [18] investigated the effect of particle size on the erosion wear of AA6063 and reported that there is a minimum kinetic energy of the particles, which changes the mechanism of material removal from erosion to three body abrasion. Jha et al. [13] studied the effects of the parameters on the erosive wear behaviour of commercial aluminium and observed that erosive wear increased with the increasing impingement angle and the rotational speed of the specimen. Gupta et al. [19] studied the effect of the T6 heat treatment on the erosive-corrosive wear properties of the eutectic Al-Si alloy and concluded that the erosion-corrosion resistance of the as-cast Al-Si alloy was superior to that of the conventional Al samples and that the heat treatment deteriorated the erosion resistance of the Al-Si alloy. Karabay [20] studied the effect of heat treatment on the solid-particle erosion behaviour of the AA2014 and summarised that the erosive wear of the AA2014 increased with the increasing hardness of the material.

There are a number of methods available to predict the erosive wear of materials using equipment, such as the small feed erosion test rig, particle jet erosion test rig, coriolis erosion tester and slinger erosion test rig. None of the methods is universal; however, such tests give a comparative rating of a simulated material test which is identical to the real situations [13]. From the literature survey, it is reported that the erosive rate of aluminium metal matrix composites has been reduced where the matrix alloy contained hard particles such as SiC, Al_2O_3, SiO_2, Si_3N_4, glass etc. and most of the researchers have focused their attention on the wear response of the aluminium based alloys in liquid environments with/without suspending solid mass [21-26]. However, there is a paucity of information pertaining to the erosive wear response of the aluminium based alloys and the review left the scope for the researcher to study in this area. In view of the above, the present work has been carried out to investigate the erosion wear behaviour of the aluminium alloy (ADC-12) and its composite reinforced with 10 wt.% of SiC particles. The influence of sand concentration, the rotational speed of samples and slurry environments on the wear response of the samples was also investigated. Narrow-sized particulate slurry of an Indian standard sand mixture (silica-quartz) with a mean size varying in the range of 37.5–655 μm is used as an erodent to evaluate the wear response of the aluminium based alloy and its composites at a rotational speed of 600, 900, 1200 and 1500 rpm in three different environment types, namely marine, synthetic mine and basic media. The primary objective of this investigation is to propose a potential material with improved quality and performance over the conventional aluminium that could be effective in a marine environment.

MATERIALS AND METHODS

Material Preparation

The matrix material used in the experimental investigation was an Al-Si alloy (ADC12 alloy), whereas the silicon carbide particles were chosen as reinforcing material. It has been reported by several researchers [27-31] that silicon carbide (SiC) is an ideal

reinforcement for several matrix materials, including aluminium because of its significant ability to enhance the strength, modulus, thermal stability, and wear resistance of the matrix materials. The Al-Si based matrix alloy and composite were prepared by the liquid metallurgy route using graphite crucibles for melting. The composites were fabricated by incorporating 10 wt.% of 50-100 µm Silicon Carbide particles in the vortex of the melt of the matrix alloy. It was reported earlier that 10% SiC is the most feasible content of reinforcement for AMCs [32]. The particles were preheated in air at 600 ^{o}C for 2 hours prior to being incorporated in the alloy melt. The vortex was created with the help of a mechanical stirrer rotating at a speed of 600 rpm. The dispersion of the SiC particles in the melt was carried at 800 ^{o}C while the pouring temperature was 850 ^{o}C. Cast iron moulds were used for the solidification of the alloy and its composites. The moulds were also preheated to around 200 ^{o}C before pouring the melts. All the castings were made in the form of plates (thickness: 12 mm, length x width: 120 × 120 mm). Table 1 shows the chemical compositions of the sample materials.

Table 1. Chemical composition of the test materials.

Elements	Elements, wt.%							
	Si	Mn	Mg	Cu	Fe	Ni	Al	SiC
ADC-12	10.29	0.12	0.47	1.98	0.75	0.80	Balance	-
ADC-12 + SiC Composite	10.29	0.12	0.47	1.98	0.75	0.80	Balance	10

Microstructural Examination

Microstructural studies were carried out on 10 mm diameter, 10 mm thick samples. The samples were polished metallographically and etched suitably. Keller's reagent was used for etching the samples of the aluminium (matrix) alloy and composite. The microstructural characterisation of the samples was carried out using scanning electron microscopy.

Morphological Analysis of Particles

The particles were dipped in alcohol and stirred for some time, and then with the help of a pipette, a drop of alcohol plus particle slurry was placed on the double sided tape fixed on a copper stud. After drying, the SiC particles on the copper stud were platinum coated and then observed in the SEM in order to examine their morphology.

Measurement of Hardness and Density

The hardness measurements of the test materials were carried out on metallographically polished samples by utilising a Vickers hardness tester. The measurements were done at an indentation load of 30 kg. The methodology for density measurement was adopted from the reference [33]. The density measurement of the materials was done by using the Archimedean method at room temperature. The initial weight of samples, which are freely suspended in air, was initially noted by the Mettler microbalance. Then the specimens were immersed in water filled in a beaker and the corresponding volume rise of water indicated the volume of the specimen. As the specific gravity of water is 1, it can be used as the weight of the specimen in water. The ratio of the initial weight to the final weight gives the density of the specimen.

Slurry Wear Test

The tests conducted on metallographically polished specimens of 76 × 25.4 × 6.35 mm in size along with a central hole of 8 mm using the sample rotation method on Ducom Bangalore make the Slurry Erosion Test Rig (TR-40). The model of the test apparatus is shown in Figure 1. The test rig consists of a frame, 6 station slurry vessel with a drive and control system. A hollow rectangular shape cooling tank is installed in the frame which is filled with cooling water to carry away the heat generated during the erosion test with inlet & outlet ports for water and 6 holes on the top face to seat the slurry vessel. 6 no's of stainless steel slurry vessels having the outer diameter 120 mm & height 120 mm are placed inside the holes of the tank & locked by screwing. The drive system drives 6 no's of independent spindles fitted with the specimen through a common belt. On the inner diameter of the vessels, 3 fins are fixed vertically to prevent the rotation of the slurry during specimen rotation; the bottom portion of the vessel is submerged inside the water tank to carry away the heat generated during the test. The tank is raised and lowered by a mechanical jack fitted at the bottom and guided by two vertical pillars for aligning the slurry vessel below each specimen. By raising the water tank, the specimen gets submerged in the slurry. The spindles on each station are clamped to the top plate of the frame, on each spindle top a crowned flat belt pulley is mounted to accept the drive to rotate the spindle. A rubber sheet is pasted on the bottom surface of the top plate to seal the slurry vessel to prevent spillage during rotation.

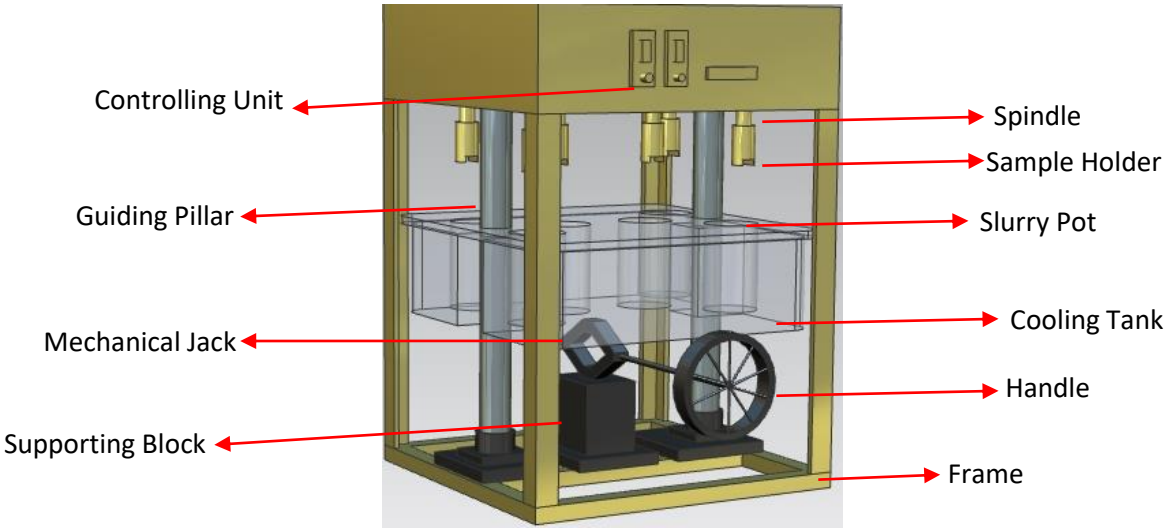


Figure1. Model of the wear test apparatus.

Four different speeds viz., 600, 900, 1200 and 1500 rpm were adopted for the slurry erosion tests in three different environments namely 3.5% NaCl, (4 gram NaCl + 5ml H_2SO4 + 10L H_2O) and 3.5% NaOH conforming to marine, mine water and basic media, respectively. Sand particles of (37-655 µm) in size were suspended in solutions and filled in the slurry tank. The slurry level is maintained at 15 mm above the specimen top or at 60 mm depth from the top face. The concentration of the sand in the slurry was varied as 0, 20, 40 and 60wt.%. The tests were conducted for the fixed test duration of 1 hour. The mass loss method was used to calculate the wear rate. A Mettler instrument make microbalance was used for this purpose. The samples were cleaned ultrasonically

prior to and after the wear test. An average of three observations was reported in this study.

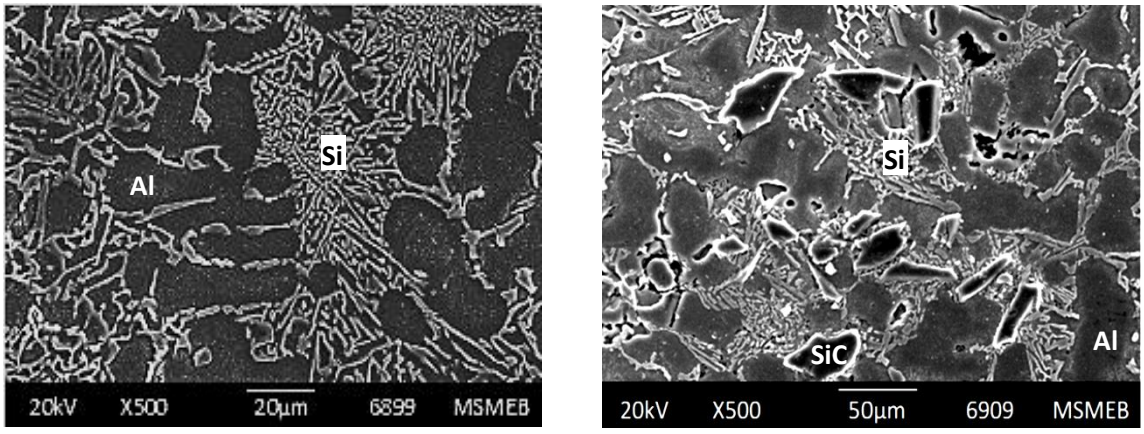
Eroded Surface

The eroded surface of the tested specimens at 1500 rpm for 0 wt. % sand concentrations in marine, mining and basic medium was studied using SEM. The eroded surface was cut and mounted on brass studs. The samples were cleaned with acetone in an ultrasonic cleaner prior to their SEM examination.

RESULTS AND DISCUSSION

Microstructure

The microstructure of the aluminium alloy (ADC12 alloy) solidified in a cast iron mould shows aluminium dendrites with a dendritic arm spacing in the range of 25 microns. The eutectic silicon solidifies in the inter-dendritic region and around the dendrites. The micrograph (Figure 2a) depicts plate shaped eutectic silicon and the other intermetallic phases. The plate shaped eutectic silicon is usually 20-30 micron in length and 2-5 micron in width. As the ambient temperature solid solubility of Silicon in aluminium is negligible, the eutectic structure contains aluminium and silicon. The composite showed features similar to the matrix alloy except the presence of the dispersoid SiC particles. Moreover, the SiC particles are homogeneously distributed in the matrix alloy and instead of the interdendritic region these particles are trapped within the primary aluminium dendrites (Figure 2b). Good interfacial bonding and a uniform distribution of the dispersoids help in retaining the particles in the matrix alloy during wear while on the other hand a poor dispersoid/matrix bonding and agglomeration of dispersoids leads to the easy removal of the dispersoids from the matrix, thus causing higher wear rates than the matrix alloy [34].



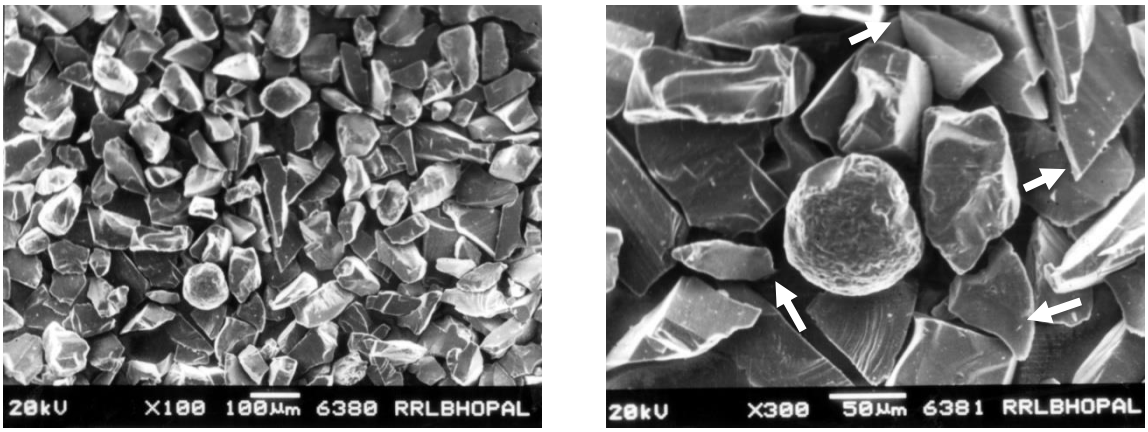
(a) (b)

Figure 2. (a) Microstructure of the matrix alloy depicting the dendrites of aluminium and eutectic silicon and (b) composite depicting the dispersed SiC particles along with the dendrites of aluminium and eutectic silicon.

Morphological Analysis of the SiC particles

To study the morphology of the SiC particles, the SiC particles were fixed on a double sided tape coated with gold and observed in SEM. A typical scanning electron micrograph of the SiC particles shows the morphology of the particle (Figure 3a). It may be noted from the figure that the particles are equiaxed in nature, with sharp corners marked by

arrows. A higher magnification micrograph (Figure 3b) clearly depicts the sharp edges equiaxed morphology. As noted from the literature review [14] the type, shape and size of the reinforcements would directly affect the properties of the composite material. Hence, it was found necessary to understand the basic structure of the reinforcement.



(a) (b)

Figure 3. (a) SEM micrograph of the SiC particles showing morphology (b) A higher magnification micrograph of the SiC particles clearly depicting the equiaxed nature with sharp corners of the particles marked by arrows.

Hardness and Density

The density and hardness of the test material are presented in Table 2. The density of the matrix alloy increased after the incorporation of SiC particles due to a somewhat higher density value of the SiC particles than the base alloy. Moreover, the composite attained higher hardness than the corresponding matrix alloy. Hardness is a measurement of resistance of the material to indentation under standard conditions. The resistance of the material is actually a localised plastic deformation. The increase in hardness is quite obvious and expected since the SiC particles constitute a hard dispersoid and contribute positively to the hardness of the composites. An increase in the hardness of the metal matrix composite with SiC dispersoids has been reported by several researchers [35-37].

Table 2. Hardness and density of the specimen.

S No.	Type	Vickers Hardness (HV)	Density g/cm^3
1	Matrix Alloy	92.3	2.64
2	SiC Reinforced Composite	98.7	2.78

Erosive Wear Response

The erosive wear loss of the test materials plotted as a function of sand concentration in various environments is shown in Figure 4. Figure 4(a-b) represents the volume loss at a rotational speed of 600 rpm for the matrix alloy and composite respectively while the volume loss at a rotational speed of 1500 rpm is depicted in Figure 4(c) and d for the matrix alloy and composite, respectively. It is observed that the volume loss increased with the increasing sand concentration in the marine and mining environments, however in basic environments, a reverse behaviour trend is obtained. This is due to the fact that upon increasing the sand content, large numbers of particles are impinging on the surface and hence this increases the severity of the erosive/abrasive attack. Similar reports have

been made by Ramesh et al. [14], who have observed that the increase in sand concentration increases the slurry erosive wear. It is also observed that with the incorporation of sic particles into the matrix alloy, volume loss declines in the marine and mining environments but when the samples are tested in a basic environment, the volume loss increases in the case of the composite. The slurry erosion processes observed in the unreinforced matrix alloy were associated with its corresponding plastic deformation, which typically reveals pits, gouges and chips. The unit of the chips by ductile fracture appeared to form the basic mechanism of metal loss during the test. In the case of the composite, the operating erosion mechanism was broadly similar to the matrix alloy with additional protection of the matrix alloy. The addition of SiC particles to the matrix alloy considerably increases the hardness of the composite and results in a reduction in the extent of the plastic deformation of the base metal.

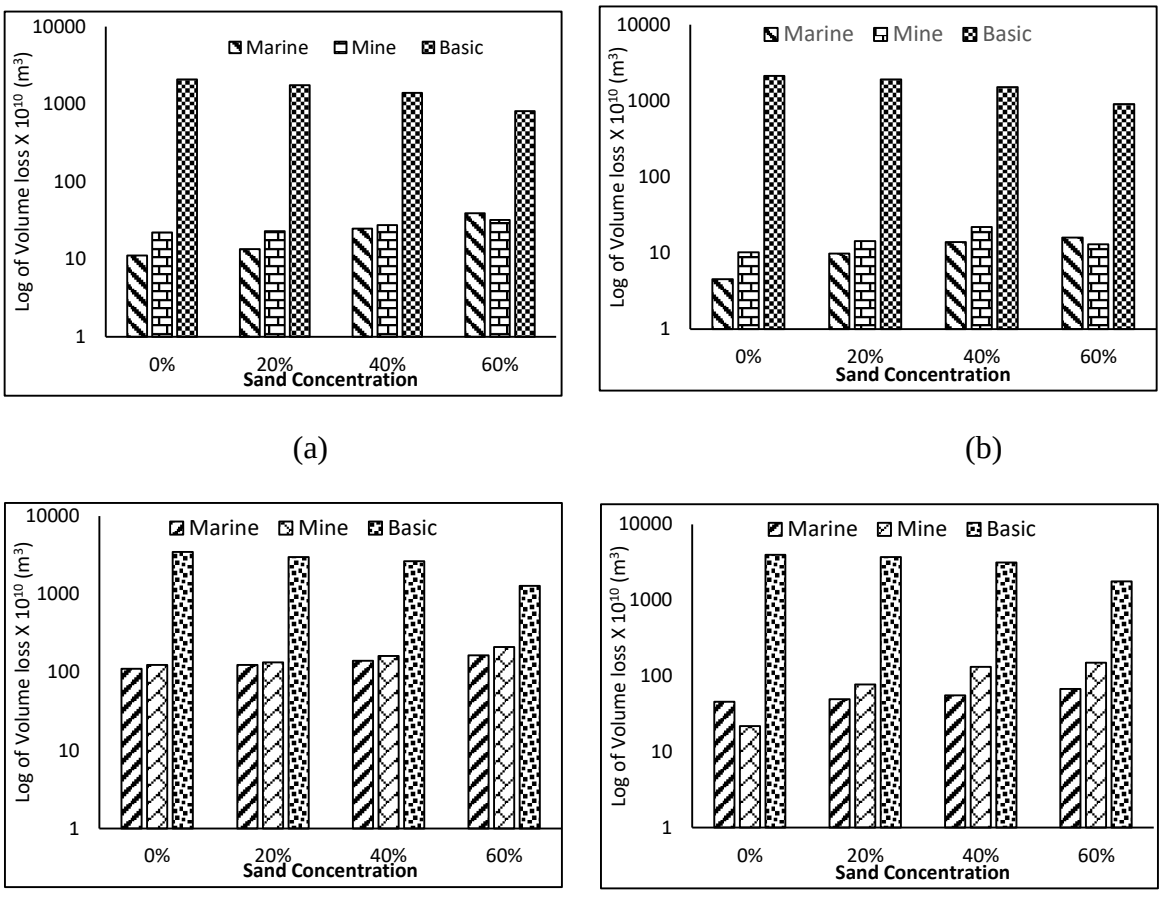


Figure 4. Erosive volume loss of the samples plotted as a function of sand concentration in various slurry environments at a rotational speed of 600 rpm and 1500 rpm for alloy (a) & (c) and composite (b) & (d), respectively

As far as the effect of the slurry medium on the volume loss is concerned, the matrix alloy as well as their composite revealed a higher volume loss in the basic medium than in the marine and mining medium. This is because of a severe corrosive attack in the basic environment that leads to the dissolution of aluminium leaving behind the silicon

network [16], which results in the formation of voids around the SiC particles of the composites. Thus, when the sand particles are abrading the composite, SiC particles are easily left out from the metallic matrix that leads to a higher wear rate in the case of the composites.

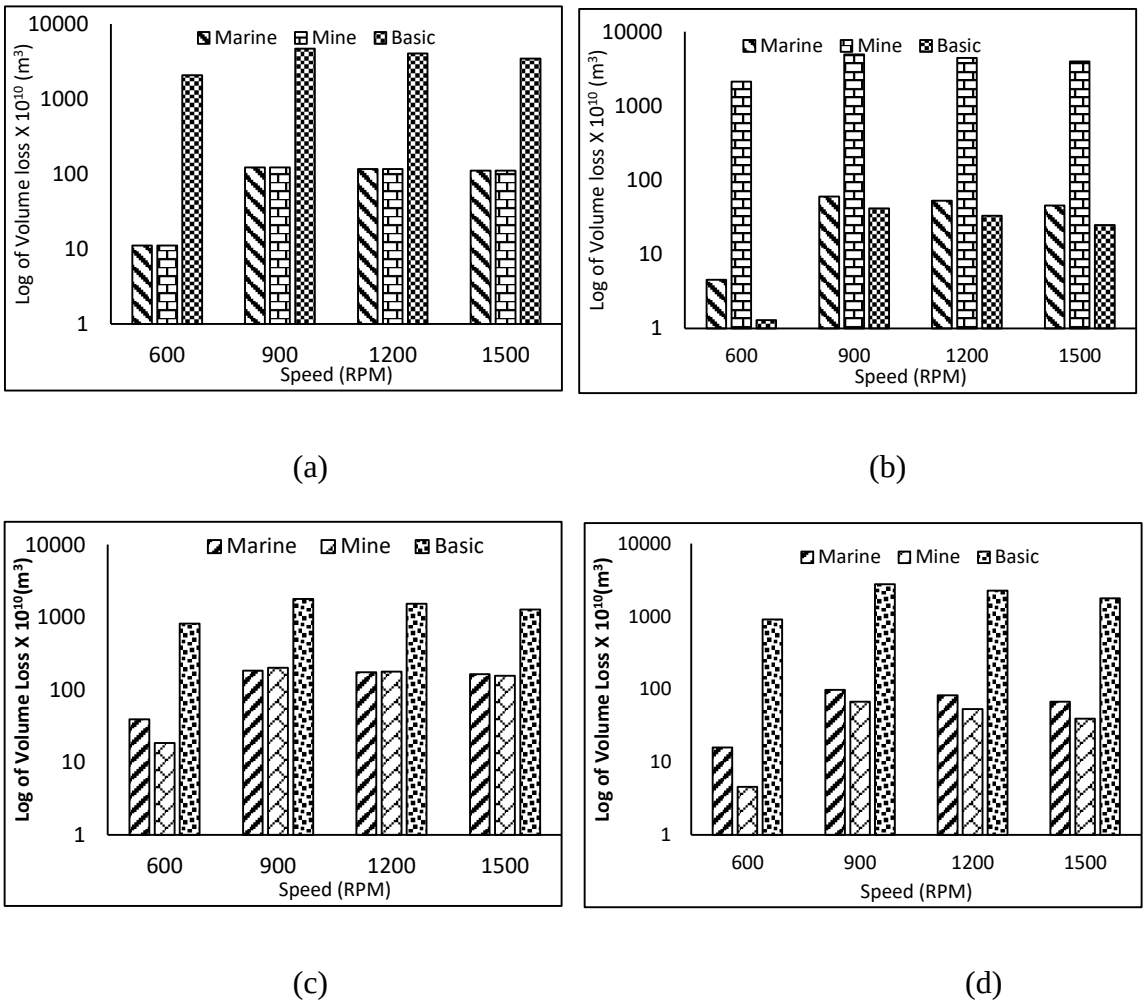
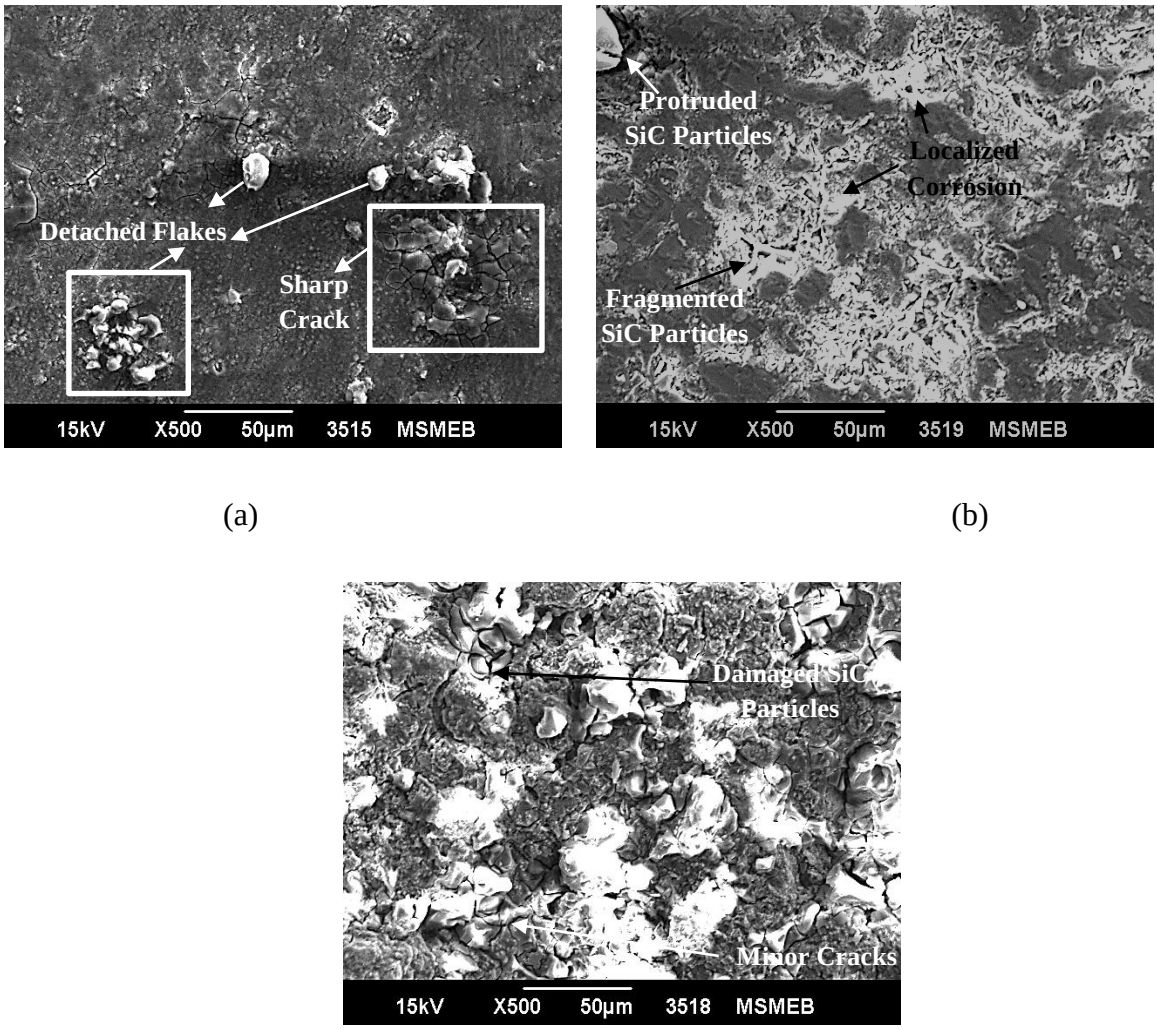


Figure 5. Erosive volume loss of the samples plotted as a function of rotational speed in various slurry environments for 0% and 60% sand concentration for alloy (a) & (c) and composite (b) & (d), respectively

The erosive volume loss of the samples plotted as a function of rotational speed in various slurry environments for 0% and 60% sand concentration is shown in Figure 5. The volume loss of the matrix alloy for 0% and 60% sand concentration is shown in Figure 5(a-b), respectively while Figure 5(c-d) represents the volume loss for the composite at 0% and 60% sand concentration, respectively. It is observed that the volume loss initially increased with the increase in rotational speed; however, a further increase in the rotational speed reduced the volume loss. Ramesh et al. [14], who obtained similar results in the case of the Al6061 alloy reported that the slurry erosive wear increases with an increase in speed. The pattern of increment/decrement of volume loss is almost similar for both the alloy and the composite, but as mentioned earlier, the incorporation of the SiC particles in the matrix alloy reduces the severity of volume loss in marine and mining environments, whereas in the basic environment, the composite exhibits a higher volume

loss than the matrix alloy. This is due to the fact that with the increase in rotational speed, the kinetic energy of the impinging particle increases and hence this increases the wear rate with the rotational speed. At a higher speed, the sand particles simply slide off instead of making any sensible impact as they do not have enough time to make an effective impact due to the decrement in mobility of the sand particles [16]. This led to the reduction in volume loss at a higher speed. The slurry erosive wear of a material in a sand and electrolyte involved material loss due to (i) corrosive attack by the electrolyte, (ii) erosion by the erodent in the slurry, and (iii) abrasion caused by the abrasive action of the suspended sand particles. The severity of the erosive/abrasive attack depends on the energy of the erodent, number of impacts made, number of impingement particles in the given volume of the slurry, angle of impact, shape and size of the erodent, speed of the impingement particles etc. [16] and the corrosivity of any medium as a function of its pH and anodic ion concentration [38].



(a) (b)

(c)

Figure 6. Eroded surfaces of the composite tested at a rotational speed of 1500 rpm in (a) marine, (b) mine and (c) basic media, respectively for 60 wt. % sand concentrations.

Affected Surfaces

The eroded surfaces of the composite tested at a rotational speed of 1500 rpm for 60 wt. % sand concentrations in various environments are shown in Figure 6. In marine environments, sharp cracks and deformed flakes were observed, which were caused by the abrading action of the erodent, whereas in the case of the mining environment, protruded/fragmented SiC particles along with localised corrosion were noticed. Similar results have been reported by Saraswathi et al. [16]. Moreover in the case of a basic environment, corrosion was the uppermost mechanism of wear although damaged SiC particles and minor cracks were also detected on the surface. This is because of the severe corrosive attack due to the formation of AlO_2^- ions in the basic solution that led to the dissolution of the primary dendrites of Al leaving behind the Si/precipitate network [39].

CONCLUSIONS

In the present investigation, the silicon carbide reinforced aluminium metal matrix composite was synthesised successfully by liquid metallurgy route. The resulting was characterised in terms of microstructure, hardness, density and pot erosion wear test in order to find its potential to expand its utilisation in the marine environment. The study reveals that the slurry erosive wear resistance of the matrix alloy increased with the dispersion of the SiC particles irrespective of the speed and sand concentration in the marine and mining environment although in the basic environment a reverse trend of behaviour is obtained. Furthermore for all the materials tested, the volume loss increases with the increase in speed from 600 to 900 rpm, but a further increase in speed reduces the severity of volume loss due to the decrease in the mobility of sand particles in the slurry and hence they do not exert a potential impact as the erodent and the wear loss at higher speed is mainly due to the corrosive action of the electrolyte. Also in marine and mining environments, the volume loss increases with the increase in the sand concentration regardless of the test materials although in a basic environment, the volume loss decreases with the increase in the sand content due to the fact that in a basic environment, corrosion is the dominant mode of material removal and upon increasing the sand content, the corrosivity of the electrolyte declines and hence results in a lower rate. It was also worth mentioning that in a basic environment, corrosive wear was the predominant mechanism of material removal and the erosion/abrasion modes of wear played a secondary role in general. However, in marine and mining environments, erosion was the dominant mode of material removal. This work can be further extended by studying the influence of the specimen material system, microstructure, composition and properties.

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