SiCp/Al2O3 Ceramic Matrix Composites Prepared by Directed Oxidation of an Aluminium Alloy for Wear Resistance Applications

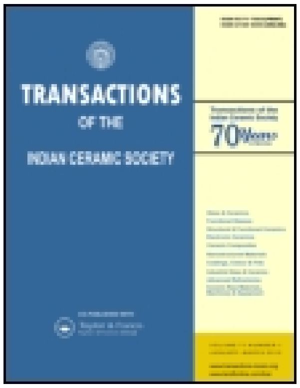
Article *in* Transactions - Indian Ceramic Society · November 2012

DOI: 10.1080/0371750X.2012.738485

4 authors, including:

Santhosh Kumar
Central Water and Power Research Station

Thank Rajasekharan
DMRL, Hyderabad, India



Transactions of the Indian Ceramic Society
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tcer20

SiC_p/Al_2O_3 Ceramic Matrix Composites Prepared by Directed Oxidation of an Aluminium Alloy for Wear Resistance Applications

M. Devaiah [a], S. Santhosh Kumar [a], T. Srihari [b] & T. Rajasekharan [a]

[a] Ceramics and Composites Group Defence Metallurgical Research Laboratory, Kanchanbagh P.O., Hyderabad, 500 058, AP, India

[b] Department of Mechanical Engineering, Shadan College of Engineering and Technology, Peerancharu, Hyderabd, 500 008, AP, India

Published online: 19 Nov 2012.

To cite this article: M. Devaiah, S. Santhosh Kumar, T. Srihari & T. Rajasekharan (2012): SiC_p/Al_2O_3 Ceramic Matrix Composites Prepared by Directed Oxidation of an Aluminium Alloy for Wear Resistance Applications, Transactions of the Indian Ceramic Society, 71:3, 151-158

To link to this article: http://dx.doi.org/10.1080/0371750X.2012.738485

Trans. Ind. Ceram. Soc., vol. 71, no. 3, pp. 151-158 (2012).

ISSN 0371-750X (Print), ISSN 2165-5456 (Online)
http://dx.doi.org/10.1080/0371750X.2012.738485

SiC_p/Al_2O_3 Ceramic Matrix Composites Prepared by Directed Oxidation of an Aluminium Alloy for Wear Resistance Applications

M. Devaiah*, S. Santhosh Kumar, T. Srihari[1] and T. Rajasekharan

Ceramics and Composites Group
Defence Metallurgical Research Laboratory
Kanchanbagh P.O., Hyderabad – 500 058 (AP), India

[MS received January 16, 2012; revised copy received September 03, 2012]

SiC_p/Al_2O_3 ceramic matrix composites were fabricated using DIrected Metal OXidation (DIMOX) process. Continuous oxidation of an Al-Si-Mg-Zn alloy with appropriate dopants along with a preform of SiC particulate has led to the formation of alumina matrix surrounding silicon carbide particulates. The fabricated composites were investigated for wear resistance on a pin-on-disc tribometer against gray cast iron. Wear surfaces were examined under scanning electron microscope in order to identify the wear mechanisms involved. SiC_p/Al_2O_3 matrix composites were found to possess enhanced mechanical properties such as flexural strength, fracture toughness and wear resistance, all at an affordable cost of fabrication. The superior high temperature resistance of SiC_p/Al_2O_3 based ceramics makes them suitable for tribological applications above room temperature or in high speed non-lubricated sliding.

[Keywords : Wear resistance, Ceramic matrix composites, Metal infiltration, Silicon carbide, Alumina]

Introduction

Processing of advanced ceramic materials is an emerging technology with a very broad base of current and future potential applications, and adding to an ever growing list of material compositions. The promise of performance improvements is the main force driving the development of ceramic materials. The use of ceramics in various applications is due to a combination of excellent properties such as abrasion and wear resistance, chemical stability, high strength, high compression strength, high temperature capability, hardness, stiffness, corrosion resistance and relatively low density. A major attraction of ceramics is its relatively high mechanical strength at high temperatures.[1]

Ceramic matrix composite (CMC) is a material consisting of a structure combined with a ceramic (usually oxides, carbides) as dispersed phases. Ceramic matrix composites are used in various industries such as automobile, electronics, aviation, defence, etc. The most common ceramic matrix composites are SiC particulates reinforced Al_2O_3 composites. These composites have been of immense interest as valves, seals, armour, etc.[2–4] Ceramic matrix composites have properties that make them ideal for many elevated temperature applications such as heat exchangers and turbine engines. In an effort to enhance these properties one approach that has been adopted is the development of specialtycomposite materials. In a composite material two or more basically dissimilar materials with different mechanical and physical properties are combined to achieve a product whose final properties are superior to its individual constituents. Other than offering high melting temperatures, many ceramics possess other significant characteristics, like low density, high temperature strength as well as resistance to creep deformation, thermochemical stability (i.e. lack of reactivity in contact with other materials and various atmospheres) and high wear resistance.

However, the relatively low fracture toughness is the most important disadvantage of the ceramic materials, which resists the propagation of fine crack.[5] The lack of toughness renders them sensitive to sudden catastrophic failure in response to accidental overloading, contact damage, or rapid temperature changes. Hence the processing methods of ceramic composite production were much emphasized to overcome the drawback of low fracture toughness. Several methods and their variants were proposed in order to increase the fracture toughness in the ceramic materials.[6, 7]

Among various processing techniques known for ceramic matrix composites fabrication, the directed metal oxidation process, developed by Lanxide Corporation, is the most interesting one. The process has the potential to form a three dimensional network of Al alloy which is the source for the formation of Al_2O_3 matrix and has been used for fabrication of Al_2O_3 composites reinforced with various ceramics such as SiC, Si_3N_4, AlN, titanium diboride, boron nitride and B_4C.[8] The desired rapid oxidation process requires minor amounts of other constituents or dopants.

*Corresponding author; additional affiliation: Department of Mechanical Engineering, Geethanjali College of Engineering and Technology, Keesara (M), Rangareddy Dist, AP, India; e-mail:devaiah.malkapuram@gmail.com

[1]Department of Mechanical Engineering, Shadan College of Engineering and Technology, Peerancharu, Hyderabd – 500 008 (AP), India

For example, a binary combination up to few wt% of Mg and elements of group 14 (Si, Ge, Sn, Zn or Pb) can be introduced as constituents of the parent aluminium alloy. Alternately, either or both doping elements could be introduced externally in the form of elemental or oxide powders that also promote rapid oxidation.[9] Temperatures within a limited process envelope, typically in the range of 900°-1350°C, depending on the dopant materials used, are also necessary for practical reaction kinetics.[10]

Constantine *et al.*[11] examined the sliding wear behaviour of aluminium composites, reinforced with different volume fractions of the particle, against stainless steel. They reported that the addition of reinforcement particles increased the resistance of the composite to sliding wear under dry conditions, even for small volume fractions of particles. They observed the presence of a surface layer on the both surfaces. Roy *et al.*[12] characterized the wear behaviour of aluminium matrix composites reinforced with particulates of SiC, TiC, TiB_2 and B_4C by sliding wear tests, which were conducted at 80 and 160 N loads using pin-on-disc apparatus. The results of the investigation indicated that the wear rate of the composites was lower than pure aluminium. Type and size of the reinforcement had a negligible influence on the wear rate of the composites, however, volume fraction of the reinforcement had a marginal influence on the wear rate.

This paper is an extended work of the present authors,[13] where Al_2O_3 matrix composites containing different volume fractions of SiC particulates (SiC_p/Al_2O_3) were prepared by directed metal oxidation (DIMOX) process and their different mechanical behaviour were studied.[13] In the present study the dry sliding wear characteristics of different SiC_p/Al_2O_3 ceramic matrix composite pins as well as gray cast iron as counter body have been studied.

Experimental Details

Fabrication of SiC_p/Al_2O_3 Composite

The fabrication process and mechanical properties of SiC_p/Al_2O_3 composites were discussed elsewhere.[13] Typical growth rates of the ceramic matrix composites were in the range of 0.1-0.3 $mm.h^{-1}$.[14] Silicon carbide particulate reinforced alumina matrix composites obtained were sectioned into requisite dimensions for sliding wear resistance measurement.

Characterization of SiC_p/Al_2O_3 Composites

When the interface between two bodies is in relative motion, progressive removal of material/s from the contact surface of one or both the bodies can take place. This phenomenon is called wear. During this relative motion of interfaces, forces are transmitted, energy is consumed, physical and chemical nature of the materials are changed, the surface topography is altered and loose wear particles are generated.

For tribological testing, the SiC_p/Al_2O_3 ceramic matrix composites, infiltrated under oxygen at 950°-980°C were selected. 0.35-0.43 vol% SiC reinforced alumina matrix composites were subjected to dry sliding wear tests in air at room temperature using a pin-on-disc machine (Monitor TR-20LE: Ducom, India) according to ASTM-G99 standards.[15] Cylindrical pin specimens of 6 mm diameter and 15 mm height were machined from the ceramic matrix composite block. The disc or counterface material was a gray cast iron disc with a diameter of 160 mm and thickness of 5 mm; 65 HRc. The wear tests were conducted at different applied loads in the range of 15-30 N in steps of 5 N. Such range of applied loads was chosen because no wear transition was observed at the lower loads (5 and 10 N) and wear transitions at 25 to 30 N loads resulted in an increase in wear rate of over an order of magnitude. The tests were carried out at a constant speed of 2.0 $m.s^{-1}$ with a sliding distance of 1000 m at time intervals of 500 s. A fresh disc was used each time and before each test. The discs were cleaned with acetone to remove any possible trace of oil, grease and other surface contaminants and were dried thoroughly. The specimens were cleaned with ethanol and were weighed before and after the tests using an electronic balance (accuracy 0. 1 mg).

The dry sliding wear loss was computed using the weight loss of the pin and disc during the experiment. The wear rates were based on the wear volume (V in m^3), normal load (F in N) and sliding distance (s in m) and were calculated using the following equation (according to Archard, 1953):

$$V_i = k_i F s 	\quad ..(1)$$

where k is the specific wear rate coefficient given in $m^3.N^{-1}.m^{-1}$ or $m^2.N^{-1}$; the index i identifies the surface considered.

After ultrasonic cleaning, the wear surfaces of the pins were examined under scanning electron microscope (SEM, Thermo-electron Corporation, Hitachi; S-3400, Germany) to determine the nature of the wear processes. The fracture toughness of the composites (with dimensions $50 \times 8 \times 8$ mm^3) were measured by single edge notch beam technique according to ASTM E 399-90.[16] For Vickers hardness test, a diamond indenter, in the form of a square based pyramid with an angle of 136° between the opposite faces at the vertex, was pressed into the polished surface according to ASTM E92[17] using a Vickers hardness macro indenter (model: 270 VRSD, system AFFRI, Italy). Tests were conducted at an applied load of 30 kg for a dwell time of 10 s. Young's modulus was measured by sound wave velocity using ultrasonic pulse-echo technique. The data for the wear tests were taken from the average of three measurements. The observed variation in the wear rate was further compared with the experimental results available in the literature.

Results and Discussion

Fabrication of SiC_p/Al_2O_3 Composites

The fabricated sample of SiC_p/Al_2O_3 composite had grown almost to the dimensions of the refractory container (crucible) used[13] and the dimensions of the fabricated composite material were large enough for detailed characterization of wear resistance.

Pin-on-Disc Wear Resistance of SiC_p/Al_2O_3 Composites

The effects of reinforcement of volume fraction and applied load on wear behaviour of SiC_p/Al_2O_3 ceramic matrix composites (pin) are shown in Table I. The data for the wear tests have been taken from the average of three measurements. The wear volume is normalized with respect to load and sliding distance in order to obtain wear rates for pin and disc[18] as shown in Tables I and II respectively. The influence of varying loads (15, 20, 25 and 30 N) and wear loss of gray cast iron (disc) counterbody against SiC_p/Al_2O_3 composite (pin) under dry sliding conditions is illustrated in Table II. A rapid increase of wear loss of disc can be observed at the higher SiC volume fractions 0.40 and 0.43 for 25 and 30 N loads. The wear rate of disc increases with increasing SiC volume fraction at different loads.

The variation of wear rate of SiC_p/Al_2O_3 composite pins with applied loads and SiC volume fractions can be observed from Figs. 1 and 2 respectively. From both the figures it is observed that under non lubricating condition the wear rate remains almost constant for the samples with SiC volume fractions 0.40 and 0.43 for all loads. However, for the sample with SiC volume fraction 0.35, the wear rate decreases initially with increasing load from 15 to 20 N and then remains almost constant for further increasing the load.

The variation of wear rate of disc (gray cast iron) as a function of load for different SiC volume fractions is plotted in Fig. 3 and the wear rate variation as a function of SiC volume fractions for different loads is plotted in Fig. 4. It can be observed from the figures that under 15 and 20 N

Table I : Details of wear rate of SiC_p/Al_2O_3 ceramic matrix composite pins

Sl. no.	SiC volume fraction	Density ($kg.m^{-3}$)	Porosity	Load (N)	Wearloss (g)	Wear volume (m^3) $\times 10^{-10}$	Wear rate ($m^3.N^{-1}.m^{-1}$) $\times 10^{-14}$
1	0.35	3250	0.1043	15	0.00199	6.12	4.08
2				20	0.00036	1.11	0.55
3				25	0.00053	1.63	0.65
4				30	0.00065	2.00	0.67
1	0.40	3280	0.0874	15	0.00079	2.41	1.60
2				20	0.00156	4.76	2.38
3				25	0.00267	8.14	3.26
4				30	0.00316	9.63	3.21
1	0.43	3310	0.0947	15	0.00244	7.37	4.91
2				20	0.00373	11.26	5.63
3				25	0.00491	14.83	5.93
4				30	0.00673	20.36	6.79

Table II : Details of wear rate of gray cast iron disc

Sl. no.	SiC volume fraction	Density of disc ($kg.m^{-3}$)	Load (N)	Wear loss (g)	Wear volume (m^3) $\times 10^{-7}$	Wear rate ($m^3.N^{-1}.m^{-1}$) $\times 10^{-12}$
1	0.35	7300	15	0.7920	1.08	7.23
2			20	0.7520	1.03	5.15
3			25	1.3325	1.82	7.30
4			30	1.3013	1.78	5.94
1	0.40		15	0.9201	1.26	8.40
2			20	1.2041	1.65	8.25
3			25	3.0156	4.13	16.52
4			30	6.0950	8.35	27.83
1	0.43		15	0.9028	1.24	8.24
2			20	1.8643	2.55	12.77
3			25	4.8050	6.58	26.33
4			30	5.6005	7.67	25.57

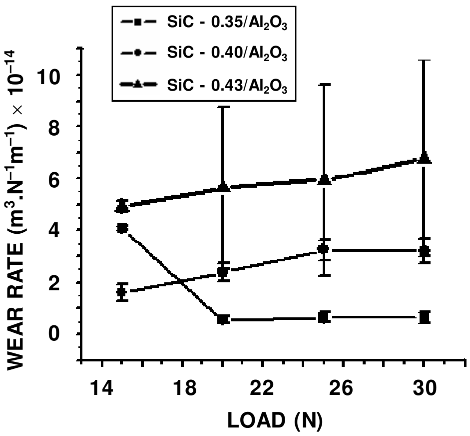


Fig. 1 – Variation in wear rate of SiC_p/Al_2O_3 composite pins as a function of load at different SiC volume fractions under non-lubricated condition

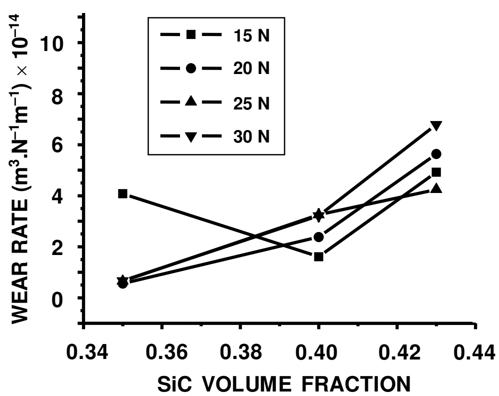


Fig. 2 – Variation in wear rate of SiC_p/Al_2O_3 composite pins as a function of SiC volume fraction at different loads under non-lubricated condition

loads, there are only small differences in the wear rate, however, significant variations in the wear rate are observed under 25 and 30 N loads for different SiC volume fractions of the composite, which is an indication of distinct wear mechanisms. The observation goes well with the literature,[19] which depicts that as the load is increased, the wear rates get increased in non-lubricated conditions. The dependence of wear rate of the disc with SiC particle size at different loads is shown in Fig. 5 and it reveals that the wear rate decreases with increasing SiC particle size. This behaviour can be related to the mechanical properties and, to a lesser extent, to the thermal properties of the particles.

The maximum depth around the center of the wear scar is measured from the traces with the help of stylus surface profilometer and results are plotted in Fig. 6. The results show that the wear depth varies between 0.16 and 0.24 μm for 20 N load, between 0.29 and 0.40 μm for 25 N load, and between 0.29 and 0.45 μm for 30 N load under the present experimental conditions. Except under certain conditions, a uniform increase in wear depth is observed. At lower load of 15 N lower depth is measured, while at higher loads (25 and 30 N) the profilometer traces

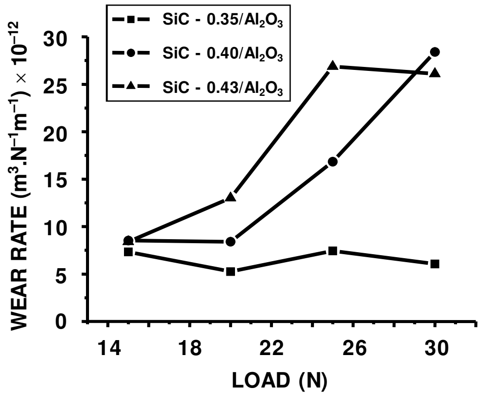


Fig. 3 – Variation in wear rate of disc (CI) as a function of load at different SiC volume fractions under non-lubricated condition

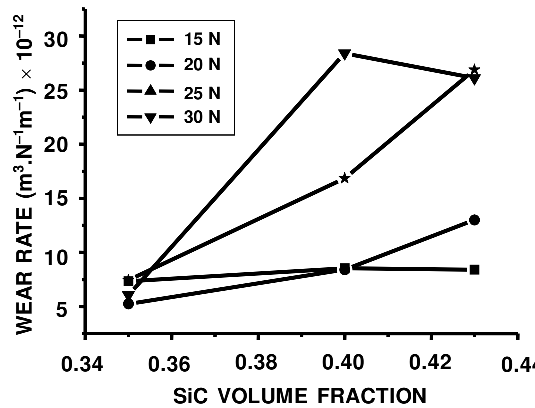


Fig. 4 – Variation in wear rate of disc (CI) as a function of SiC volume fraction at different loads under non-lubricated condition

indicate that more material within larger scar depth and width is removed from the worn surface of the disc (CI). It is clear from the above observations that the severity of wear rate increases with varying loads and SiC volume fractions under non-lubricating condition.

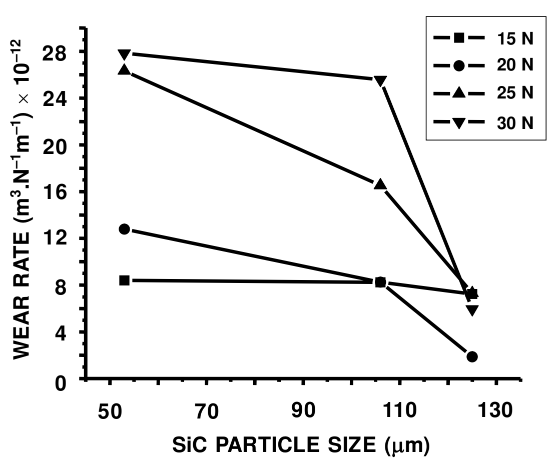


Fig. 5 – Variation in wear rate of disc (CI) as a function of SiC particle size at different loads under non-lubricated condition

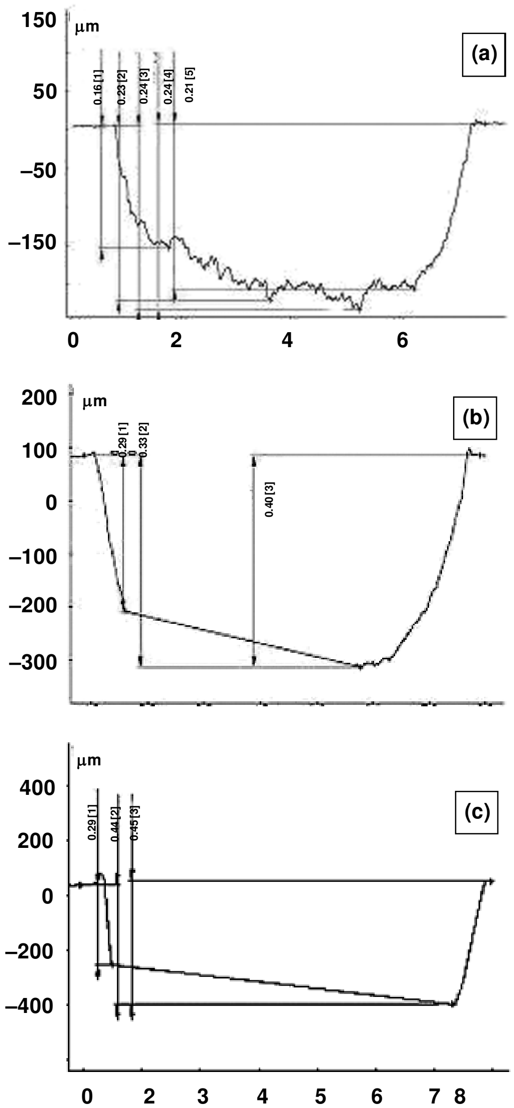


Fig. 6 – Surface profile characteristics of worn pit of SiC_p/Al_2O_3 composite, as traced by stylus profilometer, for applied loads of (a) 20 N (b) 25 N (c) 30 N under dry condition

The influence of varying loads (15, 20, 25 and 30 N) and time on the frictional behaviour of SiC_p/Al_2O_3 against gray cast iron as counter body is illustrated in Table III. It is recorded that the steady state coefficient of friction varies in the range of 0.33-0.45 for 15 to 30 N load and is strongly dependent on normal load as well as sliding time. A distinct difference in frictional behaviour is also noted as the load increases from 15 to 30 N. Initially, coefficient of friction increases and gets stabilized at 0.33 for 15 N load. After 200 s, coefficient of friction decreases slightly and reaches a steady state value for the rest of the testing period. For 20 N load, a little higher steady state coefficient of friction of 0.40 is measured. At the higher load of 30 N, coefficient of friction initially increases to a higher value of 0.38 within the sliding time and gets stabilized, and a steep increase of coefficient of friction to 0.45 is observed and then a steady state is maintained for the entire test duration. The

Table III : Details of coefficient of friction of SiC_p/Al_2O_3 composites

Label	SiC volume fraction	Coefficient of friction under loads:			
		15 N	20 N	25 N	30 N
B1	0.35	0.33	0.34	0.35	0.38
B2	0.40	0.28	0.30	0.37	0.39
B3	0.43	0.35	0.39	0.43	0.44

variation of coefficient of friction of SiC_p/Al_2O_3 ceramic matrix composites as a function of SiC volume fraction at different loads is shown in Fig. 7.

The influence of mechanical properties and the thermal residual stresses on the wear behaviour seems to be determinant in the materials. The wear rate of ceramics is controlled by hardness and especially by its fracture toughness. Generally, a material with high hardness and high fracture toughness should wear at a lower rate than a material that is less hard or one that has lower fracture toughness. The fracture toughness is considered to be a primary parameter to relate to the wear loss.[20] During the friction process, microcracks develop in the specimens due to localized structural damage. Thus higher fracture toughness of low volume fraction of SiC_p/Al_2O_3 ceramic composite materials will limit the crack propagation and the material removal compared with lower fracture toughness of higher volume fraction of SiC_p/Al_2O_3 composite materials (Table IV).

The composition, properties and metallurgical structure of the materials determine their wear rates under different conditions of operation. Properties of particular significance are hardness, fracture toughness and modulus of elasticity. Table IV gives the details of mechanical data as a function of SiC volume fraction for particulate reinforced Al_2O_3 matrix composites.

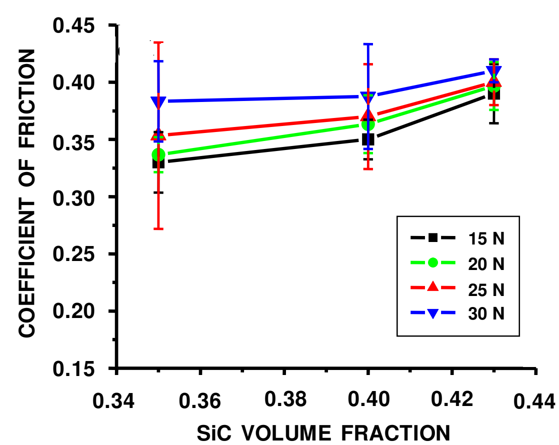


Fig. 7 – Variation of coefficient of friction of SiC_p/Al_2O_3 composite as a function of SiC volume fraction for different loads under non-lubricated condition

Table IV : Details of mechanical data of SiC_p/Al_2O_3 ceramic matrix composites

Label	Volume fraction	Density ($kg.m^{-3}$)	Porosity	Hardness (GPa)	Fracture toughness ($MPa.m^{1/2}$)	Young's modulus (MPa)
B1	0.35	3250	0.1043	8.84	5.61	207.11
B2	0.40	3280	0.0874	8.25	4.64	213.63
B3	0.43	3310	0.0947	8.92	4.01	262.00

Figure 8 shows the variation of wear rate of the disc (gray cast iron) as a function of hardness at different load conditions. The wear rate of the disc increases with increasing hardness. Figure 9 shows the wear rate as a function of fracture toughness for different load conditions. Fracture toughness is often listed as a desired property of a pump seal, bearing material. In this case, the dependence of wear rate is approximately inversely proportional to fracture toughness. Figure 10 shows the wear rate as a function of Young's modulus for different load conditions; the wear rate of the counterface (CI) increases as the Young's modulus increases.

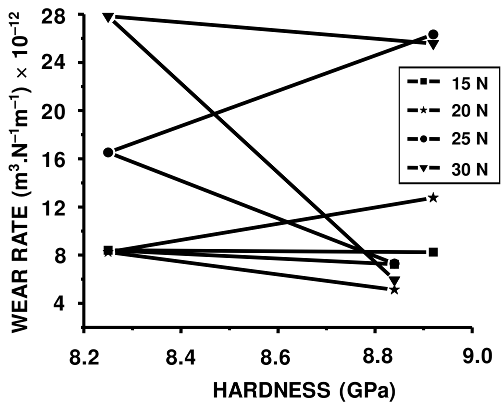


Fig. 8 – Variation of wear rate of CI as a function of hardness for different loads under non-lubricated condition

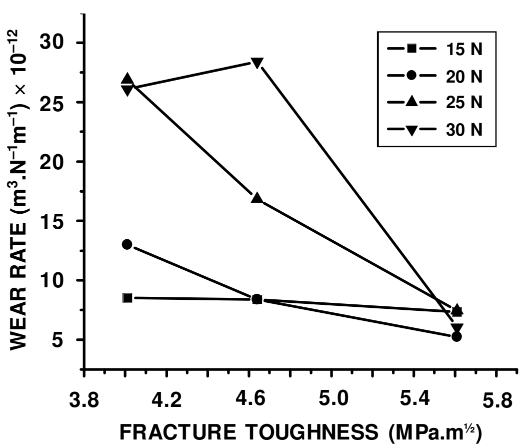


Fig. 9 – Variation of wear rate of CI as a function of fracture toughness for different loads under non-lubricated condition

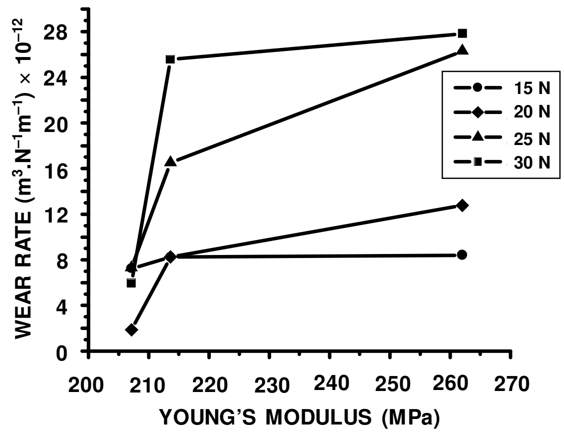


Fig. 10 – Variation of wear rate of CI as a function of Young's modulus for different loads under non-lubricated condition

The growth surface characteristics of Al_2O_3 matrices grown from Al-Si-Mg-Zn alloys have been reported. The external growth surface of ceramic matrix grown from an Al-Si-Mg-Zn alloy was used to form the composite matrix; the external surface of the composite was converted by a thin layer of ZnO.[21] No $ZnAl_2O_4$ was observed. For these composites, the thin metal layer separating the ZnO film from the interconnected Al_2O_3 was significantly thinner and its complete continuity was more difficult to ascertain. These composites typically contained a refined microstructure with 1-3 μm wide channels. The ceramic matrix growth rate from Al-Si-Mg-Zn complex commercial alloy exhibited lower activation energy for temperatures between 1050° and 1200°C. This lower activation energy was associated with a dissolution precipitation process controlled by the oxygen transport rate through ZnO surface layer on these composites. This activation energy consisted that for the oxidation of Zn, where similar processes are believed to occur in a ZnO layer exposed to a steep O_2 gradient. The growth temperature also affected the matrix microstructure, with higher growth temperatures increasing the ceramic content and slightly refining the microstructure.

The microstructures of the SiC_p/Al_2O_3 ceramic matrix composites with different volume fractions at 30 N load are shown in Fig. 11. The worn surfaces of the SiC_p/Al_2O_3 composite pins were generally smooth, although closer inspection revealed differential wear between the grains with particulate wear debris, built up in the recesses. Loosely attached wear debris was present scattered over the surface.

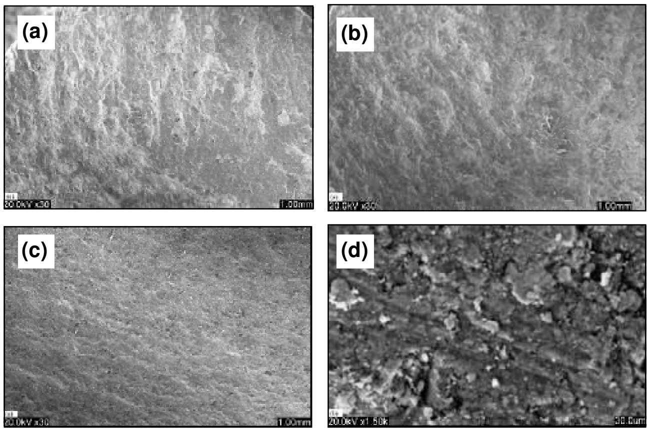


Fig. 11 – SEM images of wear tracks on the composite pin surface after dry sliding on gray cast iron under 30 N load for sample: (a) Al_2O_3-35%SiC (b) Al_2O_3-40%SiC (c) Al_2O_3-43%SiC and (d) Al_2O_3-43%SiC at higher magnification

Fine scale abrasive grooves were also present, the extent of which increased with SiC content. The diameter of the grooves was difficult to measure, and therefore, comparison in size with the SiC volume fractions. In addition to these widespread abrasive grooves, occasional regions of more substantial microgrooving were also present (Fig. 11d).

The wear rate of SiC_p/Al_2O_3 ceramic matrix composite pins fabricated in the present work was found to be in the range of 0.55×10^{-14} to 6.78×10^{-14} $m^3.N^{-1}.m^{-1}$ against gray cast iron under 15-30 N loads for SiC volume fractions in the range of 0.35-0.43. It may be noted that the 0.43 volume fraction composite materials possess larger wear resistance than the coarser particulates at 30 N load.

Scanning electron microscopic observation of the surface of the composite pins reveals low wear rate and coefficient of friction in the composite with SiC volume fraction 0.35, particularly at 30 N load and under non-lubricating conditions owing to the formation of surface film that is rich in gray cast iron. This ceramics holds good for wear components such as cutting tools, pump seal. The low weight, self lubricating properties as well as the ease of microstructure control of this material holds prospects for bearings to suit a wide range of wear resistance applications in varied environments. EDS of the pin (Fig. 12) shows that it contained a substantial proportion of Fe and a small amount of C, both from the counterface. The worn composite specimens generally exhibited the same feature. At low loads, worn surfaces were smooth in all cases.

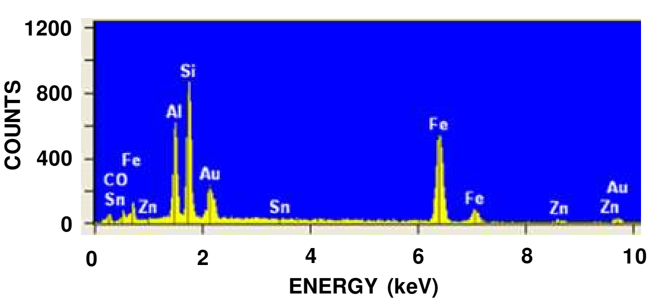


Fig. 12 – EDS spectra of Al_2O_3-43%SiC pin surface after dry sliding on gray CI for 30 N

Wang and Hsu[22] studied the wear mechanisms of ceramic materials in non-lubricated sliding contact. They found that the difference in surface roughness correlated well with difference in wear rate in each material. Brittle fracture and surface cracks were observed on the wear track where debris was generated. Kim *et al.*[23] studied the wear of a number of ceramic materials – Al_2O_3, TiO_2, SiC and Si_3N_4 – bearing steel in non-lubricated rolling contact. They found that steady state wear occured after 104 to 105 cycles. In steady state wear the wear volume was proportional to the number of revolutions. They showed that although alumina and silicon carbide were harder than silicon nitride the wear loss of silicon nitride was lower than any other ceramic material and bearing steel combination in non-lubricated rolling contact. As load was increased the wear rate increased in a non-lubricated bearing.[19] Eventually a point was reached where the wear rate increased drastically. This increase is usually due to high temperatures which soften the material. Wang and Hsu,[24] in their study of wear and wear transition of alumina ceramics, found the time-dependent wear transitions phenomena of alumina. When the normal load was increased without changing any other parameters, an abrupt increase in wear scar diameter occurred in shorter time. The time dependent wear transitions usually did occur at certain loads and speeds which were close to but not exceeding the critical fracture criteria of the materials.

Jayaram and Biswas[25] reported wear rate and coefficient of friction of Al_2O_3-SiC-(Al, Si) composites prepared by melt oxidation process. The test was performed by pin-on-disc technique against EN 24 steel under dry and wet conditions. The applied normal pressure was in between 1 and 10 MPa and linear sliding velocities varied between 1 and 15 $m.s^{-1}$. The reported wear rate and coefficient of friction were in the range of 5.85×10^{-14}-12.30×10^{-14} $m^3.m^{-1}$, and 0.22-0.32 respectively as a function of SiC particle size. Subsequently, Gomes *et al.*[26] studied wear resistance of silicon nitride ceramic pins sliding against gray cast iron. The above mentioned work reported the wear rate in the range between 1.79×10^{-6} and 18.3×10^{-6} $mm^3.N^{-1}.m^{-1}$ and friction coefficient in the range between 0.51 and 0.74 at room temperature. In another work, Westergard *et al.*[27] reported the wear rate of Si_3N_4-SiC composites intended for face seal applications, measured by cylinder-on-disc equipment, to be in the range of 10^4-10^5 $\mu m^3.N^{-1}.m^{-1}$ and coefficient of friction in the range of 0.41-0.9.

In the present work the wear rate of SiC_p/Al_2O_3 ceramic matrix composite pins was found to be in the range of 0.55×10^{-14} to 6.78×10^{-14} $m^3.N^{-1}.m^{-1}$ and the coefficient of friction was in the range of 0.33-0.45. However, the cost of production of the former process[27] was higher apart from affecting mass production.

Figure 13 shows a hollow cylinder fabricated in the present work. Under non-lubricating condition the

Fig. 13 – SiC_p/Al_2O_3 ceramic matrix composite hollow cylinder fabricated in the present work (inside diameter = 30 mm, outer diameter = 40 mm, thickness = 5 mm)

SiC_p/Al_2O_3 performs very good wear resistance under all critical load conditions. If the porosity of the composites could be brought down then the effect would be much better. This low temperature (range 950°-980°C) ceramic matrix composite holds a great promise for tribological applications in varied environments because of low weight with high mechanical properties, good resistance to corrosion and high temperature.

Conclusions

In the present work it was observed that the DIMOX process can be successfully applied to fabricate bulk SiC_p/Al_2O_3 ceramic matrix composites at a rather low temperature. The composites thus obtained were evaluated for wear resistance. The wear behaviour of these composites in contact with gray cast iron was very much dependent on experimental parameters, namely reinforcement, load and time. The optimized composite exhibited wear rate in the range of 0.55×10^{-14} to 6.78×10^{-14} $m^3.N^{-1}.m^{-1}$ and coefficient of friction between 0.33 and 0.45 under 15-30 N loads for SiC volume fractions in between 0.35 and 0.43. The wear rate increased with SiC volume fraction and load. The effects of SiC volume fraction and load on wear rate were more significant for long sliding time. A distinct transition in friction and wear behaviour was observed. The microstructures revealed the differential wear between the grains with particulate wear debris, built up in the recesses. In addition to the widespread fine scale abrasive grooves, occasional regions of more substantial microgrooving were also present in the microstructure. The good wear resistance of the fabricated composite is highly promising for tribological applications.

References

1. R. A. Signorelli and J. A. Dicarlo, *J. Metal*, **6**, 41-43 (1985).
2. S. T. Buljan, A. E. Pasto and H. J. Kim, *Ceram. Bull.*, **68**, 387-394 (1989).
3. L. D. Maloney, *Design News*, March 12 (1989).
4. S. Ashley, *Mech. Eng. CIME*, July, 44-49 (1991).
5. M. W. Barsoum, *Fundamentals of Ceramics* (series in Materials Science & Engineering), 2nd edition, Taylor & Francis, UK (2003).
6. A. G. Evans, *Mater. Sci. Eng.*, **71**, 3-21 (1985).
7. R. W. Rice, *J. Phys. Chem. Solids*, **45**, 1033-1050 (1984).
8. K. J. Bowman, S. K. El-Rahaiby and J. B. Wachtman (Eds), *Handbook on Discontinuously Reinforced Ceramic Matrix Composites*, Purdue University Press, West Lafayette, Indiana, USA (1995).
9. M. S. Newkirk, A. W. Urquhart and H. R. Zwicker, *J. Mater. Res.*, **1**, 81-89 (1986).
10. M. S. Newkirk, H. D. Lesher, D. R. White, C. R. Kennedy, A. W. Urquhart and T. D. Claar, "Preparation of LANXIDE™ Ceramic Matrix Composites: Matrix Formation by the Directed Oxidation of Molten Metals", pp. 879-885 in: *Ceramic Eng. Sci. Proc.*, Ed. W. Smothers, John Wiley & Sons, Inc., New Jersey, USA (1987).
11. V. Constantine, L. Scheed and J. Masounave, *J. Tribol.*, **121**, 787-794 (1999).
12. M. Roy, B. Venkataraman, V. V. Bhanuprasad, Y. R. Mahajan and G. Sundarajan, *Metall. Trans. A*, **23**, 2833-2847 (1992).
13. S. Santhosh Kumar, M. Devaiah, V. Seshu Bai and T. Rajasekharan, *Ceram. Int.*, **38**, 1139-1147 (2012).
14. S. M. Pickard, E. Manor, H. Ni, A. G. Evans and R. Mehrabian, *Acta Metall. Mater.*, **40**, 177-184 (1992).
15. ASTM G99, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, USA.
16. ASTM E399-90, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, USA.
17. ASTM E92, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, USA.
18. B. Basu, T. Venkateswaran and D. Sarkar, *J. Euro. Ceram. Soc.*, **25**, 1603-1610 (2005).
19. R. G. Bayer, *Mechanical Wear Prediction and Prevention*, Marcel Dekker Inc., New York, USA (1994).
20. G. R. Evans and D. B. Marshall, "Wear Mechanisms in Ceramics", pp. 439-452 in: *Fundamentals of Friction and Wear of Materials*, Eds. D. A. Rigney, American Society of Metals, Metals Park, Ohio, USA (1981).
21. A. S. Nagelberg, A. S. Fareed and D. J. Landini, "Production of Ceramic Matrix Composites for Elevated Temperature Applications using the DIMOX™ Process," pp. 128-142 in: *Processing and Fabrication of Advanced Materials for High Temperature Applications*, Eds. V. A. Ravi and T. S. Srinivas, The Minerals, Metals and Materials Society, Pennsylvania, USA (1992).
22. Y. Wang and S. M. Hsu, *Wear*, **195**, 25-46 (1996).
23. S. S. Kim, K. Kato, K. Hokkirigawa and H. Abe, *Trans. ASME*, **108**, 522-526 (1986).
24. Y. Wang and S. M. Hsu, *Wear*, **195**, 90-99 (1996).
25. V. Jayaram and S. K. Biswas, *Wear*, **225-229**, 1322-1326 (1999).
26. J. R. Gomes, A. S. Miranda, J. M. Vieira and R. F. Silva, *Wear*, **250**, 293-298 (2001).
27. R. Westergard, A. Ahlin, N. Axen and S. Hogmarks, *Proc. Instn. Mech. Engrs.*, **212**, 381-387 (1998).