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Abrasive Wear of Continuous Fibre Reinforced Al And Al-Alloy Metal Matrix Composites

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Abstract

The abrasive wear testing of continuous ceramic fibre reinforced Al and Al-alloy matrix composites is proven difficult due to inherent complexity of the many wear processes, compounded by the possible interplay with microstructural variables in Metal matrix composites. This paper reports the results of abrasive wear tests on specimens of continuous Silicon Carbide (SiC) and high strength Carbon (H.S.C) fibres reinforced Al(1100) and Al(6061) matrix materials, with 50-60% fibre volume fraction, and made by matrix fibre coating and hot-consolidation fabrication process. The test results for fibres parallel to the sliding direction of Al2O3 (alumina) abrasive papers with abrasive grit sizes 85 μm to 250 μm , at sliding speeds of 76, 110, 160 and 180 mm/s, and applied load ranging from 5 to 15 kg for a time (t), show that the test can be applied to continuous fibre reinforced metal matrix composites, and their addition has resulted in a large reduction of abrasion rate by a factor of more than ten for such composite materials. Optical and Scan Electron Microscope (SEM) investigation of abraded surfaces and just below surfaces show that the wear resistance of 55% v/o SiC-Al(6061) were higher than that of 55% v/o SiC-Al(1100) composite materials, indicating that matrix ductility and fibre-matrix interfacial strength affect the abrasive wear behaviour of such composites. The important variables of this test were discussed and its usefulness in comparing wear resistant materials is demonstrated.

Keywords: Metal-Matrix Composites; Fibre-Reinforced; Abrasive Wear; Alumina; Scanning Electron Microscope.

1. Introduction

In recent years, commercially pure aluminum and Al-alloy based metal matrix composites (MMC) are gaining wide spread acceptance in several interesting applications such as pistons, connecting rods, microwave filters, vibrator components, contactors, impellers and space structures. These composites possess excellent wear resistance in addition to other superior mechanical properties such as strength, modulus and hardness when compared with conventional alloys, [1-8]. Of all the aluminum alloys, 6061 is quite a popular choice as a matrix material to prepare MMCs owing to its better formability characteristics. MMCs offer considerable potential for enhanced wear resistance, because the hard ceramic reinforcements impede the removal of material from abrading surfaces. Their effect is closely dependent on type and shape of reinforcement, [2, 4, 9-13]. Reinforcement of the Al matrix with discontinuous SiC and H.S.C fibres is more effective than Al2O3 fibres for the improvement of wear resistance due to the high hardness of SiC reinforcement, [2, 10, 11]. However, understanding of their wear characteristics is still far from complete. This is due in part to the inherent complexity of many wear processes, the problem is compounded by a possible interplay with microstructural variables in MMC's, such as fibre content, size, orientation, fibre matrix interfacial strength, etc., which greatly influence wear behaviour when sliding surfaces occur. This brings asperities into repeated contact and possibly tearing some of them away from parent body forming fragments of wear debris, [11, 12]. The rate at which material is removed from the body being considered is described by the basic relationship, [1, 10, 13],

$$V = \frac{KW}{H} S \tag{1}$$

Where V is the volume removed, W is the applied load, S is the sliding distance, H is the hardness of the body, and K is a constant called the dimensionless wear resistance. From this simple relationship MMC's are expected to resist wear better than the corresponding unreinforced matrix, because hard fibre reinforcement normally increases strength and hardness. Recent studies pertinent to wear of MMC's with hard reinforcement [2, 3, 11-14] have reported improved wear resistance for Aluminium in both lubricated and dry conditions, after reinforcement with Al2O3 (Silicon Carbide or Alumina) whiskers or particles. These workers found that the 20% v/o SiCp-Al(2014) composite gave a wear rate lower than that of

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unreinforced matrix, corresponding to a decrease in, K, from 10^{-3} to 10^{-4}. Furthermore, they found that the size and the fibre matrix interfacial strength had a strong effect. Some workers, [4], reported a decrease in wear rate accompanied by an increase in coefficient of friction in their comparison of MMC's with that of unreiforced matrices. The limited published data available, [1-15], indicate that fibres offer little or no improvement in wear resistance than do particles of the same material and size. The literature also indicates that the focus has been centered on processing of MMCs and characterization of mechanical properties of MMCs, and little or no information is available pertinent to the abrasive wear behaviour of continuous fibre reinforced aluminium matrix materials.

In this paper, tests on the abrasive wear behaviour of Al (1100) and Al (6061) matrix materials reinforced with 55-60% v/o of continuous Silicon Carbide (SiC) and high strength Carbon (H.S.C) fibres were carried out, by using results of a collaborative program of study on the abrasive wear behaviour of such composites. The abrasive wear testing was carried out using an abrasive wear tester apparatus Al2O3 (alumina) grit papers. Optical and Scan Electron Microscope (SEM) investigation of worn surfaces were also carried out to understand the mechanism of wear in continuous fibre reinforced composites, a discussion of the variables which may control the usefulness of the test is included.

2. Experimental

The MMC's utilized in this work were manufactured by a process called hot-consolidation of matrix coated fibre for producing continuous fibre reinforced MMC's. The process involves coating continuous fibres, (SiC, and H.S.C, table 1, [16-18]), with sufficient material by drawing a preheated continuous fibre strands through the molten metal of commercially pure aluminium (Al (1100) or Al (6061) alloy, tables 2 and 3, [15]), and using a device that controls the thickness and smoothness of the coating, such that during hot-consolidation of the laid up coated fibres into a composite preform, the coatings deformed and bonded together to form the matrix composite(s). The coating thicknesses, therefore, determine the volume fractions of fibre in the finished MMC, fibre volume fraction (v/o) of 40% to 60% of unidirectional specimens were obtained from this process. Detailed information of the processing conditions can be found in [16]. The type and geometry of the test specimens were dictated by the size and quantity of the fabricated materials plates produced. Using a diamond saw, specimens with dimensions 20 x 10 x 3 mm were then cut from unidirectional material plates.

from at least eight measurements determined on each face that was tested in the wear apparatus. Summary of the hardness values of the composite materials studied are listed in table 4. The mechanical properties of the composites are also shown in table 4, refs. [15-18].

Table 1. Properties of the selected continuous fibre reinforcement, [16-18].

Properties	High strength carbon fibre(H.S.C)	Silicon Carbide fibre (SiC)
Fibre Diameter, μm	7-30	12-20
Density, Mg/ m^3	1.75-1.9	2.5
Young's Modulus, GPa	230-270	190-200
Poisson's Ratio (ν)	0.2	0.25
Tensile Strength, GPa	3-4.8	2.5
Failure Strain, %	1.1	-
Thermal Expansivity, $10^{-6}K^{-1}$	(-0.4)-(-1.2)	4.5
Thermal Conductivity, $Wm^{-1}K^{-1}$	24	-

Table 2. Chemical composition of Al (1100) and Al (6061) matrix materials by weight percentage, [15].

Alloy	Si	Mg	Cu	Ti	Fe	Mn	V	Cr	Zn	Be	Other elements
Al(1100)	0.25	0.05	0.05	---	0.04	0.05	0.05	---	---	---	0.03
Al(6061)	0.76	0.92	0.22	0.1	0.28	0.04	0.01	0.07	0.06	0.003	0.45

Table 3. Mechanical properties of Al (1100) and Al (6061) matrix materials, [15].

Material	E (GPa)	σtensile (MPa)	σyield (MPa)	Strain to failure (%)	Poisson ratio (ν)
Al(1100)	69	90	34	50-70	0.33
Al(6061)	72	310	275	12	0.33

Table 4. The mechanical properties of composites, [15-18].

Material	Tensile Modulus (GPa EII)	Strain To failure (%)	Tensile Strength (σ_{II})(MPa)	Hardness (HV)
unreinforced Al(1100)	35	35	90	54
55% v/o SiC-Al(1100)	126	0.7-0.95	897-1026	92
55 % v/o H.S.C-Al(1100)	165	0.55-0.76	780-856	77
unreinforced Al(6061)	275(at P.S of 0.2%)	12	310	130
55 % v/o SiC-Al(6061)	119-214	0.23	1270-1500	284
55% v/o H.S.C-Al(6061)	102-156	0.2	629-1123	225

Abrasive wear behaviour of the composites was examined by using an abrasive wear tester, schematically shown in Figure 1. The tests were carried out in normal atmospheric conditions (25 ºC, and 40-60% humidity) by applying a load (P) ranging from 5 to 15 kg for a time (t). Abrasive tests were carried out against Al2O3 (alumina) abrasive papers with abrasive grit sizes 85 μm to 250 μm , for a total distance of 33 m at sliding speeds of 76, 110, 160 and 180 mm/s. During the abrasive wear tests, it was ensured that the samples always encountered fresh abrasive particles by allowing the abrasive papers to move perpendicular to the sliding direction. Wear loss of the sample was determined at an interval of 5.5 m, by measuring the weight loss of the composites using an electronic balancing device giving readings up to ±0.1mg. The volumetric wear loss of composites was determined using weight loss divided by density. The volumetric wear rate of composites was obtained using volumetric wear loss divided by sliding distance. Four specimens for every composite material were tested and the average volumetric wear was obtained. After performing the wear tests, worn surfaces and subsurfaces of the composites were examined by JEOL JSM T330 Scan Electron Microscope (SEM) and optical microscope.

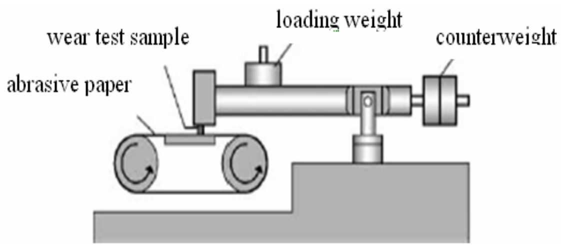


Figure 1. Schematic diagram of abrasive wear testing apparatus.

3. Results and Discussion

The results generated are of enormous amount and only typical results were represented to illustrate the effectiveness of this form of abrasive wear testing. Results of abrasive wear tests conducted on SiC and H.S.C continuous fibre reinforced and unreinforced Al(1100) and Al(6061) matrix materials are shown in Figures (2-8). Figure 2 shows the effect of time on wear volume of a given composite material. The values recorded in this figure with the values of the test conditions load, sliding speed, and materials hardness were used to calculate the dimensionless wear coefficient (K). Figures 3 to 5 clearly indicate that the wear volumes in the abrasion tests were directly proportional to the time of the test, load applied and speed of sliding. It is evident from these results of the abrasive wear tests that, among the investigated composite materials, minimum wear rate was obtained for SiC and H.S.C continuous fibre reinforced Al(6061) alloy matrix composite. When compared to Al(1100) matrix composites, the wear rate of SiC-Al(6061) alloy matrix composite was about twelve times lower against the alumina abrasive grit size 85 μm and six times lower against 250 μm abrasive. The abrasive wear rate of the reinforced and unreinforced matrix materials also increased with increasing the abrasive Al2O3 particle size (Figure 5). This is in agreement to the observations of previous works [12, 20, 25]. For coarser Al2O3 abrasive particles, the test load is carried by fewer particles in a certain area, which causes a higher contact stress on the tip of coarse abrasive particles than that of fine abrasive particles for the same applied load, (Figure 4.). Accordingly, the increase of wear rate with increased size of abrasive Al2O3 particles is possibly due to the increased depth of penetration causing much damage to intact fibres leading to an increase in the amount of material removal during abrasion tests, [3, 11, 14, 22, 28].

Figure 6 shows that the wear rates are inversely proportional to the hardness of the composite material, and the values of wear coefficient are independent of the hardness of the MMC's under abrasive or abrading particles, as shown in Figure 7. These results indicate that the improvement in wear rates of such composites is accompanied by an increase in fibre matrix interfacial strength and hardness of the composite material, which can be attributed to the fibres remaining intact when struck by asperities or abrading particles. Under such conditions the material would have been ploughed out in the unreiforced material. For reasons of comparison, previous work by, [2, 20-26], on the abrasion rates of two Al-alloy composites reported that the presence of dispersed hard ceramic discontinuous reinforcement has resulted in a decrease of the abrasion rate of these alloys by a factor of five. These results were in close agreement with the results obtained in this research work. The results of abrasion rate presented in Figure 8, show that the presence of continuous ceramic fibre reinforced Al and Al-alloy has also resulted in a large reduction of abrasion rate by a factor of six for SiC-Al(1100) and by a factor of more than ten for SiC-Al(6061) composite materials.

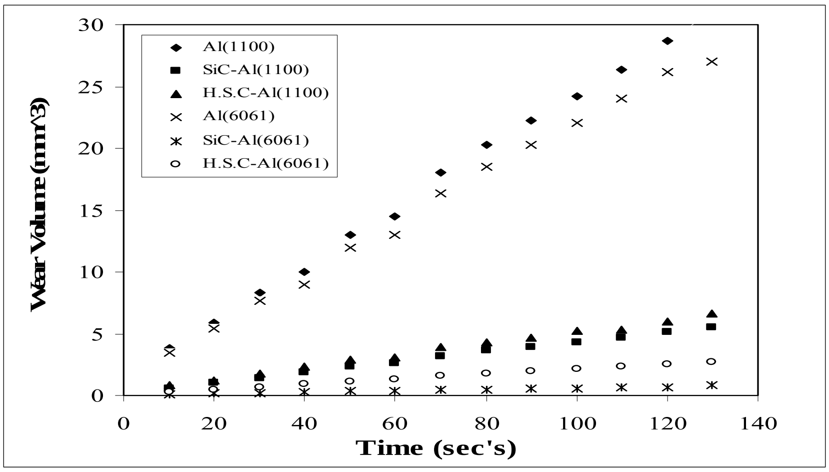


Figure 2. Typical plots of wear volumes versus time to determine wear rates for continuous fibres reinforced and unreinforced Al-matrix composites, with sliding speed 180 mm/s

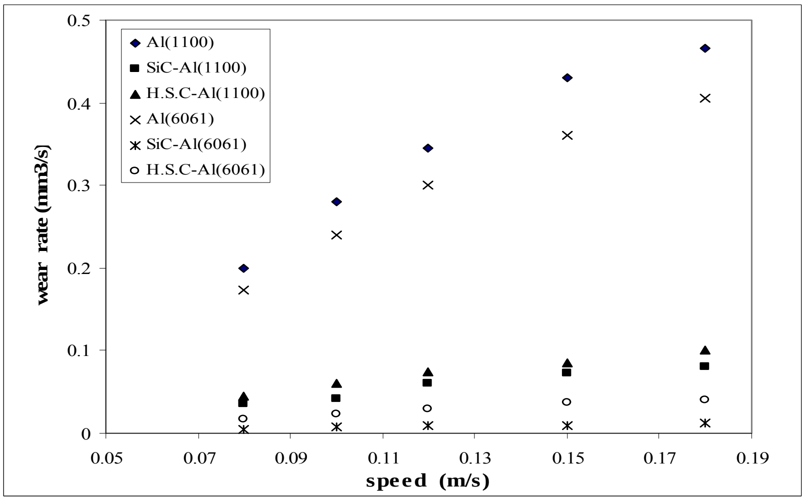


Figure 3. Plots of wear rates versus sliding speed for both continuous fibres Al and Al-alloy matrix composites. With test parameters of; Al2O3 abrasive grit size (250), load 12 kg.

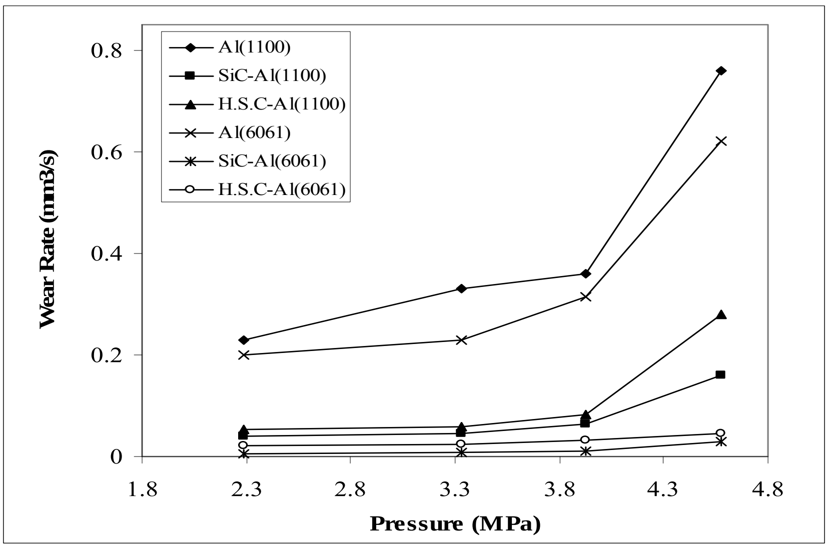


Figure 4. Typical plots of wear rates versus pressure on specimen for both continuous fibres Al and Al-alloy matrix composites. With test parameters of; Al2O3 abrasive grit size (250 μm), sliding speed 180 mm/s.

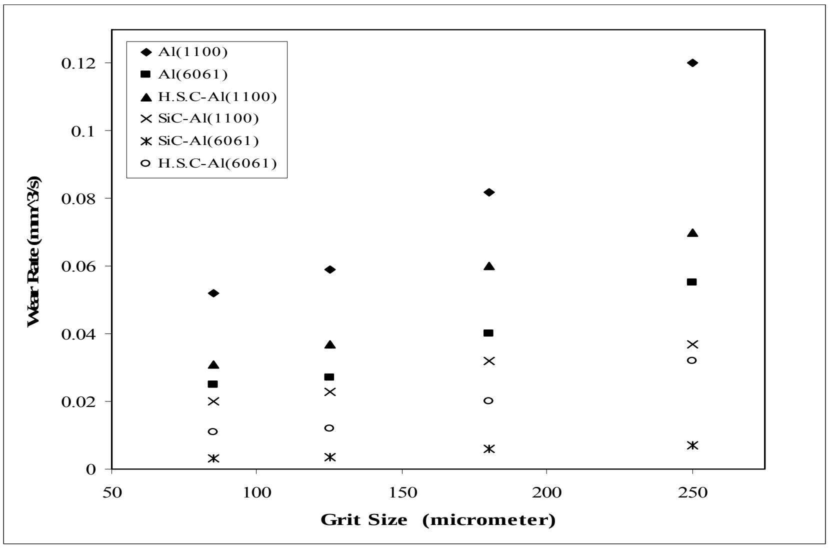


Figure 5. Typical plots of the effect of grit size on wear rates for both continuous fibres Al and Al-alloy matrix composite with test parameters of; load 10 kg, sliding speed 160 mm/s.

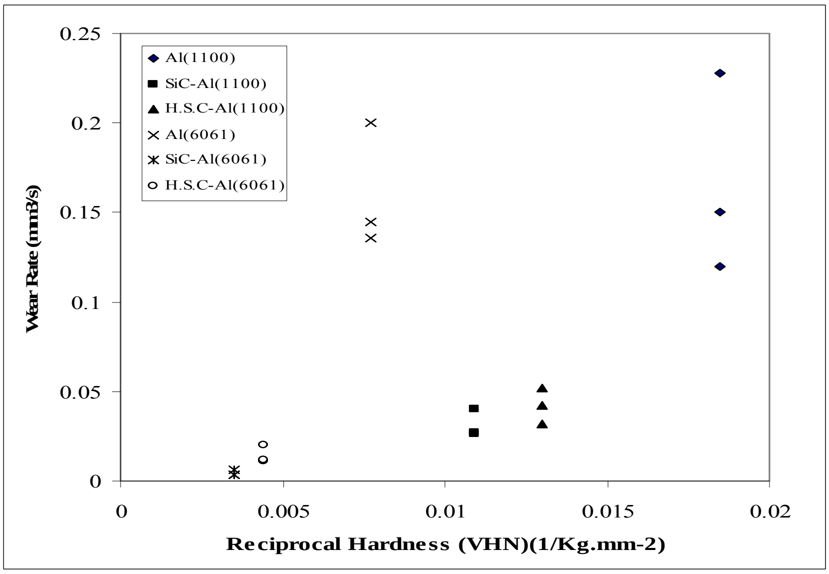


Figure 6. Plots of wear rates versus reciprocal hardness for both Al and Al-alloy matrix composites. With test parameters of; Al2O3 abrasive grit size (250, 180 and 85 μm), load 10 kg, and sliding speed 180 mm/s.

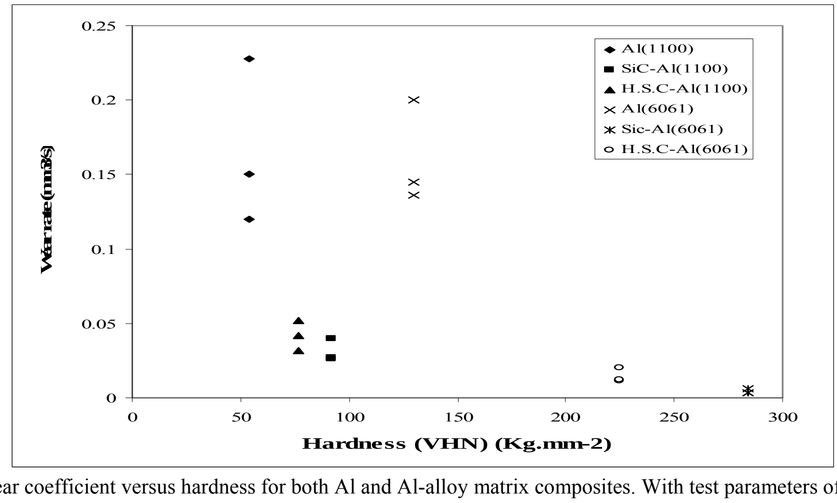


Figure 7. Plots of wear coefficient versus hardness for both Al and Al-alloy matrix composites. With test parameters of; Al2O3 abrasive grit size (250, 180 and 85 μm), load 10 kg, and sliding speed 180 mm/s.

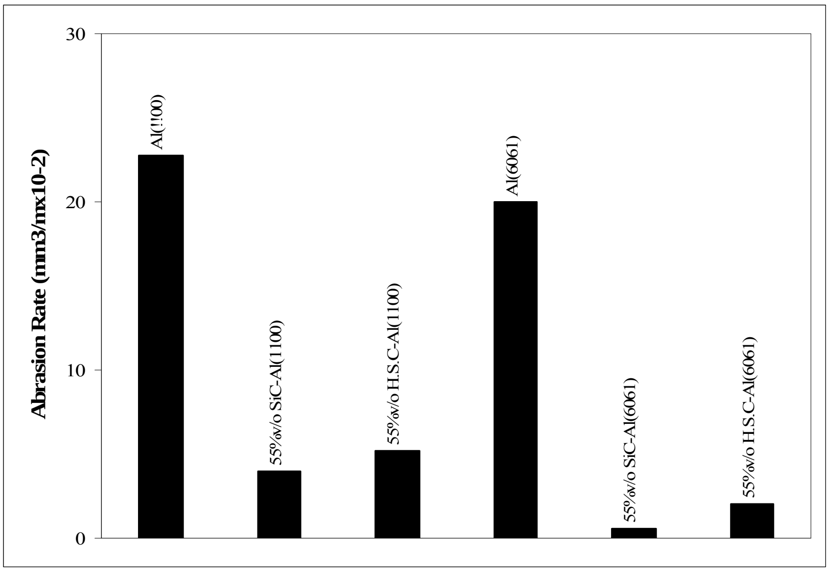
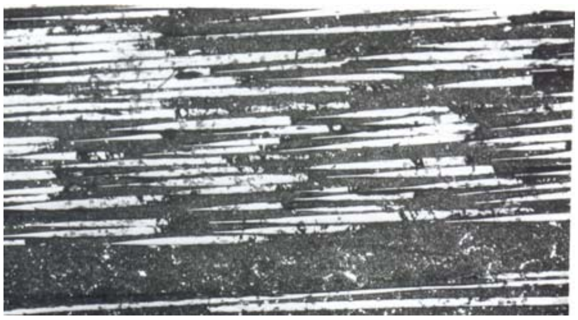


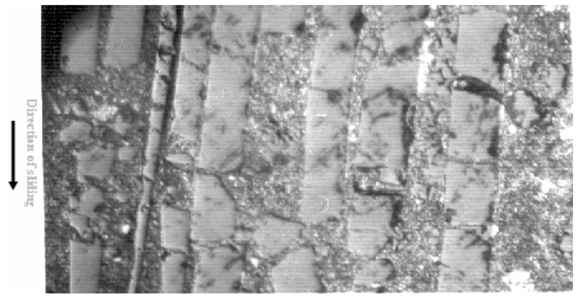
Figure 8. An overall view of, the low stress abrasive wear rates of both continuous fibres Al and Al-alloy matrix composites.

Furthermore, the evidence presented in these Figures (2-8) suggest that under the conditions of these abrasive tests, the simple archard's hypothesis may be used in estimating or predicting the wear rates of composite materials undergoing abrasive wear during service, [25-28]. However, since wear mechanisms in industrial environments are rarely simple, it is possible to assess a group of materials under the same conditions of abrasive wear so that a judgment can be made on the possible relative behaviour of those materials under service conditions, [27-33]. Figure (7) shows the validity of the archard's equation because of its independence of the material type and depends only on the wear operating mechanism and the size of the abrasive particles used. As might be expected, the value shown in Figure 7, for SiC-Al(6061) composite material is K=1.2×10^{-4} using abrasive grit size of 125 μm ; whereas the two extremes of the grit size 250 μm and 85 μm give values of K equal to 6×10^{-4} and about $1.\times10^{-4}$, respectively, which may suggest that another coefficient could be inserted into the wear coefficients to give a relationship that includes the size of the abrading particle in the archard's equation.

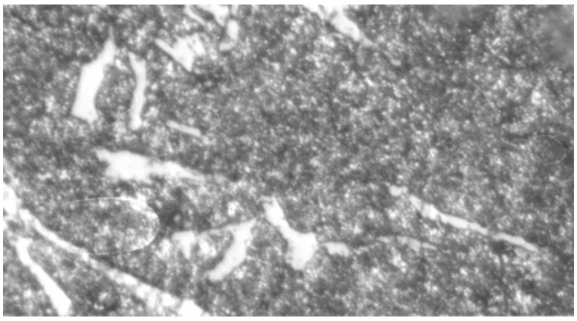
The limited published data available, [4, 17, 20, 22, 24], suggest that fibres do not dramatically offer greater improvement in wear resistance than do particles of the same material and diameter [6, 33]. To the contrary, in this work, improvements in wear resistance were evident when high interfacial bond strength exists, as in SiC-Al (6061) composite material. Therefore, it can be said that wear performance is a consequence of enhanced resistance to fibre fracture and excavation which is quite evident in Figure 9 (a, b and c), for SiC-Al (6061) composite showing intact fibres after being struck by the abrading particles. It is also apparent that the diameter and volume of fibre reinforcement, relative to the size of the abrading particles, is of considerable importance, [9-13, 20]. Improvements in wear resistance were observed for fine abrading particles (85 μm grit size), but less obvious when they were larger. This behaviour can be seen from the SEM micrographs of abraded surfaces in Figure 10 (a, and b).



(a)

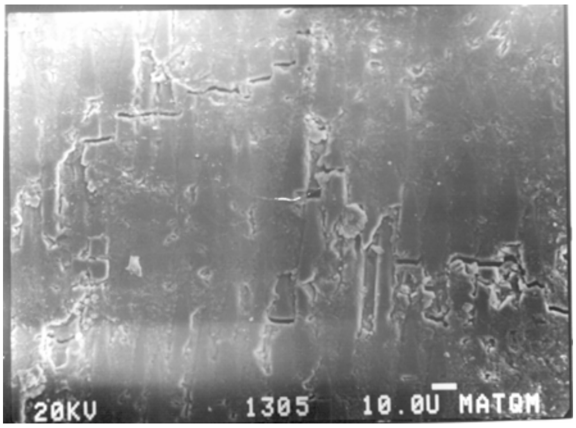


(b)

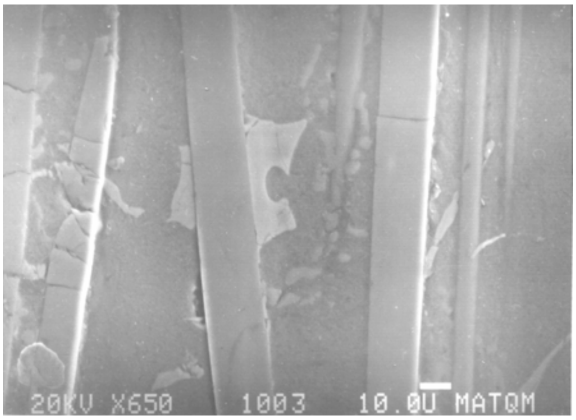


(c)

Figure 9. (a). Mag (252X), (b). Mag (500X), (c). Mag(252X) Optical and SEM micrographs of worn surfaces for SiC-Al(6061), H.S.C-Al(6061) composite materials and Al(6061) matrix material, respectively, with test parameters of; Al2O3 abrasive grit size 250 μm, load 12 kg, time of abrasion 20 seconds.



(a)



(b)

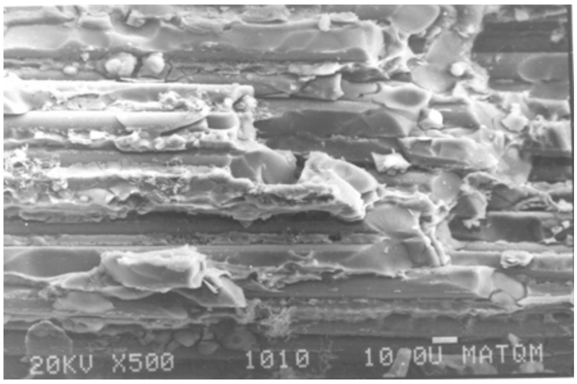
Figure 10 (a, b). SEM micrographs of abraded surfaces for Sic-Al(1100) and Sic-Al(6061) composite materials, respectively, showing fractured but intact fibres, with test parameters of; Al_2O_3 abrasive grit size 85 µm, load 7 kg, time of abrasion 10 seconds, at high magnification.

with regular furrows probably caused by the ploughing of the weaker interfacial bond strength composite such as SiC-Al(1100) composite material, as in Figure 11(a and b). However, this ploughing has been significantly reduced by the presence of broken but intact fibres just below the surface of the abraded composites, as shown in Figure 12

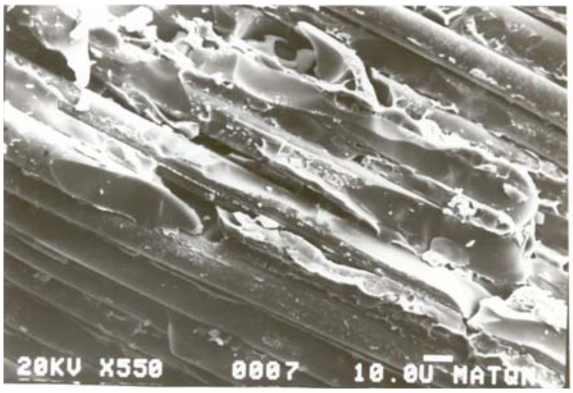
This figure shows the unreinforced matrix after abrasion with finer particles, and b), hence, protecting the aluminium alloy matrix from further abrasion providing that the fibre-interface is strong enough. It is also evident that the role of the Al-alloy matrix should not be underestimated because it provides support to hard fibre phase and imparts ductility to the composites, [24]. This may explain the reason for the high resistance to abrasion of the SiC-Al (6061) compared with that of SiC-Al (1100) composite materials. With larger abrading particles, however, both matrix and fibres became slightly ploughed, as in Figures 9(b), 11(b), and 12(b), were fibres became cracked and in some cases fractured under the higher load to which they are subjected particularly with larger abrading particles, hence becoming excavated along with a physically deformed matrix.

4. Conclusions

The experimental results on the abrasive wear behaviour of Al (1100) and Al (6061) matrix materials reinforced with 55% v/o of continuous SiC and H.S.C

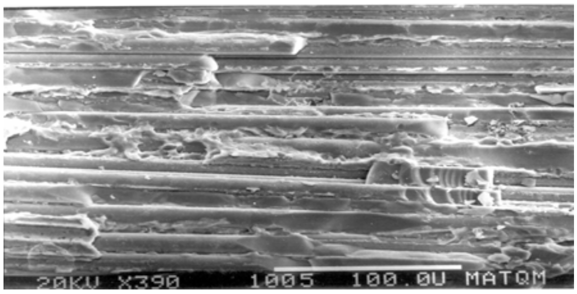


(a)

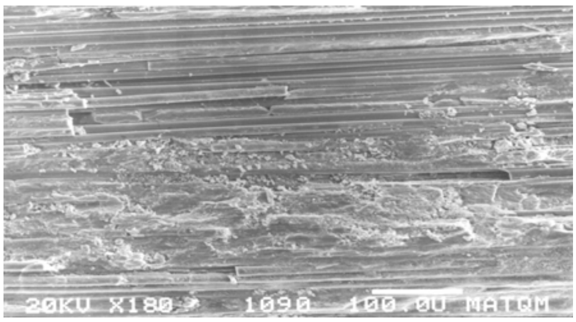


(b)

Figure 11. (a and b) SEM micrographs of abraded subsurfaces for Sic-Al(1100) and C-Al(1100) composite materials, respectively, showing fractured fibre surfaces (due to contact with abrading particles), bare and intact fibre(s) surfaces just below abraded surface, with test parameters of; Al_2O_3 abrasive grit size 85 µm, load 12 kg, time of abrasion 130 seconds, at high magnifications.



(a)



(b)

Figure 12. (a, b) SEM micrographs of abraded subsurfaces for Sic-Al(6061) and C-Al(6061) composite materials, respectively, again showing fractured and intact fibre surfaces, adhered matrix to fibre(s) surfaces just below abraded surface, with test

parameters of; Al_2O_3 abrasive grit size 85 μm, load 12 kg, time of abrasion 120 seconds, at high magnifications.

fibres, show that the wear volumes in the abrasion tests were directly proportional to the time of the test, load applied and speed of sliding. These results and SEM investigations of abraded surfaces clearly show that the presence of continuous ceramic fibres have resulted in a large reduction of abrasion rate in both reinforced metal matrix materials, and this improvement in wear rates of such composites is accompanied by an increase in fibre matrix interfacial strength and hardness of the composite materials, which can be attributed to the fibres remaining intact when struck by asperities or abrading particles.

The obtained values for the wear coefficient (K) of both continuous fibre reinforced Al matrix materials, seem to depend on the exact wear mechanism in operation, fibre-matrix interfacial strength, and matrix ductility used in the abrasive wear tests. From the results obtained, it is possible to use the abrasive wear test apparatus to relate the abrasive wear of continuous fibre reinforced metal matrix composite materials, with test conditions of load, time, speed and hardness. The simple relationship (Archard's hypothesis) can also be used, because it appears to be independent of the material type and depends only on the wear operating mechanism.

References

[1] F.M.Hosking, F.Folgar-Portillo, R.Wunderlin, And R.Mehrabian, in "Composite of Aluminium alloys; Fabrication and Wear Behaviour", J. Mat. Sci., Vol. 17, 1982, 477-98.

[2] K.J.Bhansali and R.Mehrabian, in "Abrasive Wear of Aluminium Matrix Composites", J. Metals, Vol. 32, 1982, 30-40.

[3] Y.M.Pan, M.E.Fine and H.S.Cheng, in "Wear Mechanism of Al-Based Metal Matrix Composites under Rolling and Sliding Contact", in Tribology of Composite Materials, P.K.Rohatgi, B.G.Blau and C.S. Yust (eds) ASM, 1990, 93-101.

[4] I.M.Hutchings in "Abrasive and Erosive wear of MMC's, in Proc. 2nd European Conf. on Adv. Mat., Euromat '91, Cambridge, U.K, T.W.Clyne and P.J.Withers (eds), Inst. Of Metals, 1991, 56-64

[5] J. J. Ahan, and S. Ochiai, "The Effect of Wear Environment Temperature on The Wear Behaviour and Friction Coefficient of SiCw-Al Composite", J. Compos. Mater., Vol 37, 2003, 1083.

[6] K.Akutagawa, H.Ohtsuki, J.Hasegawa and M.Miyazaki in "Reduction of Friction Coefficient of MMC under Dry Conditions" SAE Tech. report 870441, 1987.

[7] S.V. Prasad and P.K. Rohatgi, J. Metals., Nov, 1987, 22.

[8] A. Shashishankar, M. Krishna and C.S. Chandrasekhara Murthy, A study on sliding behaviour of flyash reinforced aluminium 7075 alloy composites. In: E.S. Dwarakadas and C.G. Krishnadas Nair, Editors, Proceedings of the Third International Conference on Advances in Composites. Bangalore, 2002, 583–589.

[9] X.Y. Li and K.N. Tandon, Microstructural characterization of mechanically mixed layer and wear debris in sliding wear of an Al alloy and an Al based composite, Vol. 245, 2000, 148–161.

[10] A. Wang and H.J. Rack, Transition wear behavior of SiC particulate and SiC whisker reinforced 7091 Al metal matrix composite. Mater. Sci. Eng. Vol. 147, 1991, 211–224.

[11] A. Wang and I.M. Hutchings, Wear of alumina fiber: aluminum metal matrix composite by two body abrasion. Mater. Sci. Vol. 5, 1989, 71–76

[12] Lee GY, Dharan CK, Ritchi RO. A physically-based abrasive wear model for composite materials., wear, Vol. 252, 2002, 322-331.

[13] Mondal DP, Das S, Jha AK, Yegnesswaran AH. Abrasive wear of Al alloy-Al O particle reinforced composite: a study on the combined effect of load and size of abrasive. Wear ,Vol. 223, 1998, 131-138.

[14] Sheu S.Y, Lin S.J. Particle size effect on the abrasion wear of 20 vol% SiCp/7075 Al composites. Scripta Mater, 1996; 11: 71-76.

[15] American Society for Metals, "Properties and Selection: Nonferrous alloy and pure metals", Metals Handbook, 9th edition, Vol.2, 1979, 63 and 161.

[16] Ramadan J. Mustafa and Yassin L. Nimir, "A New Process for Manufacturing Continuously Reinforced Aluminium Alloy MMC." Mu'tah Lil-Buhuth wad-Dirasat (Mu'tah Journal for Research and Studies, Vol. 21, No. 2, 2006, 183-205.

[17] M. Wang and W. Bonfield, "Effect of heat treatment on the mechanical properties and failure modes of carbon fibre-aluminium alloy composites", Metal Matrix Composites, 2nd Conference, the Royal Society, U.K., 1989.

[18] Ming Yang, V.D. Scott and R.L.Trumper, "The role of interface on the mechanical behaviour of carbon fibre reinforced aluminium alloy composites". Metal Matrix Composites, 2nd Conference, the Royal Society, U.K, 1989.

[19] J.A. Hawk, R.D. Wilson, J.H. Tylczak and O.N. Dogan, Laboratory abrasive wear tests: investigation of test methods and alloy correlation. Wear 225–229, 1999, 1031–1042.

[20] T. Miyajima and Y. Iwai, Effects of reinforcements on sliding wear behaviour of aluminium matrix composites, Wear, Vol. 225, 2003, 606–616.

[21] J. Zhang and T. Alpas, Transition between mild and severe wear in aluminium alloys. Acta Mater. 45, 1997, 513–528

[22] J.A. Hawk, and D.E. Alman,. Abrasive wear of intermetallic-based alloys and composites. Mater. Sci. and Eng. A 239-240, 1997, 899–906.

[23] A.T. Alpas and J.D. Emburey, Sliding and abrasive wear behavior of an Al 2014–SiC particle reinforced composite. Scripta Metall. , Vol. 24, 1990, 931–935.

[24] Z. Liu, J. Sun and W. Shen, Study of plowing and friction at the surfaces of plastic deformed metals. Tribol. , Vol. 35, 2002, 511–522.

[25] L.J. Yang, Determination of transient wear distance in the adhesive wear of A6061 aluminium alloy reinforced with alumina, in: Proceedings of the Second Asiatrib International Conference, Jeju Island, Korea, October, 2002, 217–218.

[26] Zhang ZF, Zhang LC, Mai YW. Particle effects on friction and wear of aluminium matrix composites, J. Mater Sci.,Vol. 30, 5999-6004.

[27] Bindumahavan PN, Wah HK, Prabhakar O,. Dual particle size (DPS) composites: effect on wear and mechanical properties of particulate metal matrix composites. Wear, Vol.248, 2001, 112-120.

[28] Sahin Y, Ozdin K. The effect of abrasive particle size in the wear of metal matrix composites. In: Numiform 2004 conference, The Ohio State University, Department of Mechanical Engineering, 650 Ackerman Road, Columbus, OH 43202, USA.

[29] Dues RL, Subramanian C, Yellup JM. Abrasive wear of Al alloy composites: a review. Wear, Vol. 201, 1996, 132-144.

[30] Sahin Y. Wear behaviour of aluminium alloy and its composites reinforced by SiC particles using statistical analysis. Mater Des, Vol. 24, 2003, 95-103.

[31] Colaco R, Vilar R. A model for the abrasive wear of metallic matrix particle reinforced materials. Wear, Vol. 254, 2003, 625-634.

[32] Sahin Y. Tribological behaviour of composites and its alloy, Mater Des, Vol. 28, 2007, 1348-1352.

[33] Esteban Fennandez J, Rocio Fennandez M, Vijande Diaz R, Tucho Navarro R. Abrasive wear analysis using factorial experiment design. Wear, Vol. 255, 2003, 38-43.