Dry Sliding Wear Behaviour of Al-Based Composite Prepared with Novel In-Situ Ceramic Composite Developed from Colliery Waste Using Taguchi Method

Venkata Siva S. B, G. Srinivasa Rao, and K. L. Sahoo

***Abstract*—**The present investigation is carried to relate the influence of wear parameters like sliding speed, applied load and sliding distance on the dry sliding wear of aluminium metal matrix composite (Al-CS) prepared with thermally treated colliery shale material, a waste from coal mines. The design of experiment approach is employed to acquire data in controlled way using Taguchi method. A pin-on-disc apparatus is used to conduct the dry sliding wear test. For comparison purpose similar tests are conducted on the composites made of Al-Al_2O_3 and Al-Al_2O_3SiC. Regression equations are obtained using experimental data, relating operating variables such as sliding speed, applied load and sliding distance on weight loss, coefficient of friction and cumulative wear of the composite. The morphology of the newly developed in-situ ceramic composite and the presence of carbon in the form of graphite has helped to improve the wear resistance of the newly developed Al-CS composite.

***Keywords*—** dry sliding wear, Taguchi method, colliery shale material, in-situ ceramic composite

I. Introduction

THE advantage of AMC's over monolithic alloys is in its good abrasion resistance and has found applications in aerospace and automobile industries [1-5]. Therefore, it is thought to study the wear behaviour of the Al-based composites prepared by using the newly developed novel ceramic composite. Wear behaviour of this developed AMC is then compared with the AMC's prepared using Al_2O_3/Al_2O_3-SiC having similar vol% of the particulates.

The authors, therefore, have developed an in-situ ceramic composite prepared from shale material which is a waste obtained from coal mines. By special thermal treatment of colliery shale material, a novel in-situ ceramic composite comprising of (Al_2O_3-SiC-C) has been developed. The novel ceramic composite has been added to Al-melt and a new AMC has been developed. Thus, the method has dispensed with conventional reinforcing agents such as Al_2O_3/SiC and makes the process cost effective [6].

Many authors have studied the wear properties of AMCs using mathematical models [7-14]. They have found that volume fraction of reinforcement, sliding speed, applied load, sliding distance (major variables) affect appreciably the wear rate of the composites. Different wear mechanisms are operative for composites at different speed and applied load. Mild wear, mixing and oxidative wear, de-lamination wear and severe wear are observed under combination of different speed and load [15-17]. Therefore in the present investigation the variables taken are sliding speed, applied load and sliding distance.

Design of experiments (DOE) is thought to be a very useful technique to predict the behaviour of the composite. In DOE, factors are varied simultaneously with-in a close range of-variables and the results obtained are analyzed to form response surface in the form of regression equation which quantify the main effect of the variables as well as their interactions at different levels. After checking the validity of the equation, the equation can be used profitably for optimization purpose as well as for predictions of the wear behaviour of materials at their different combinations within the range of variation of variables.

II. Experimental

A. Preparation of AMC by stir casting

Al is melted in a bottom poured vertical furnace at 800^{0}C in argon atmosphere. Three AMCs are prepared by using measured quantity of preheated (≈600^{0}C) ceramic particles i.e. CS/Al_2O_3/Al_2O_3-SiC ceramic particles are added to the vortex of the melt, as described elsewhere [6]. The composites Al-CS, Al- Al_2O_3 and Al- Al_2O_3-SiC are cast in to preheated (≈400^{0}C) metallic mould in to the shape of rod having diameter of 30 mm and a length of 30 cm.

Venkata Siva S. B is with Mechanical Engineering Department, Gandhi Institute of Engineering & Technology, Gunupur-765022, Odisha, India. (Phone: 91-9692464540; Fax: 06857-250232, E-mail: bvenkatasiva@in.com)

G. Srinivasa Rao is with Mechanical Engineering Department, R. V. R & J. C College of Engineering, Guntur-522019, A.P, India. (Corresponding author's E-mail: gsraorvr@gmail.com)

K. L. Sahoo is with CSIR - National Metallurgical Laboratory, Jamshedpur- 831007, Jharkhand, India. (E-mail: klsahoo@gmail.com)

B. Mechanical Characterization

The optical, physical and mechanical properties are determined using microscope, universal testing machine, hardness testing machine etc., for all the composites.

C. Wear Test

The samples used for wear test are shown in Fig.1. Wear tests are carried out on a pin-on-disc type machine. Pin specimens are rubbed on a disc of EN 31series hardened to 62 HRC. The wear tests have been conducted under the three normal loads (L) 2kg, 4kg and 6kg and at sliding speeds (V) of 1.0, 1.2 and 1.4 m/s. The tests are carried out for a total sliding distance (S) of 2.4 km and intermittently the reading are also taken at a sliding distance of 1.8 km and 2.1 km. The worn surfaces of pin materials are examined by SEM.

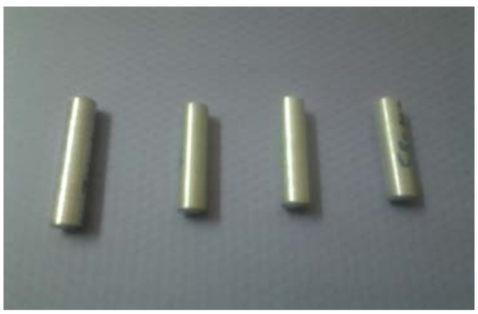


Fig. 1 Samples used for wear test

D. Experimental Design

The experiments are conducted as per central composite face centered (CCF) design for three factors. The CCF design consists of 15 runs which includes 2^3 (8) fractional factorial portion, 6 axial points and a centre point. Each experiment is replicated twice and a total of 30 experiments are performed to analyze the influence of various factors on the response.

TABLE I. DESIGN MATRIX

Exp. NO.	S	V	L
1	-1	-1	-1
2	-1	-1	+1
3	-1	+1	-1
4	-1	+1	+1
5	+1	-1	-1
6	+1	-1	+1
7	+1	+1	-1
8	+1	+1	+1
9	-1	0	0
10	+1	0	0
11	0	-1	0
12	0	+1	0
13	0	0	-1
14	0	0	+1
15	0	0	0

TABLE II
LEVEL OF CONTROL FACTORS

Factor symbol	Factor	Level 1 (Low)	Level 2 (Medium)	Level3 (High)
S	Sliding distance (km)	1.8	2.1	2.4
V	Sliding speed (m/sec)	1	1.2	1.4
L	Load (kg)	2	4	6

The proposed model of the corresponding design matrix is shown in Table 1. In Table 2, the values for the levels are given in coded form such as '-1' indicates level '1' of the factor, '0' indicates level '2' of the factor, '+1' indicates level '3' of the factor. Experiments are conducted randomly to avoid biasness.

III. RESULTS AND DISCUSSION

A. Characterization of AMC Composites

The properties of three as cast AMCs are shown in Table 3. Among the three, Al-CS composite has the least density, thereby showing higher specific strength. Higher specific strength properties promise superiority of Al-CS composite over the other two composites. The advantage of the developed novel composite is thus established. Presence of free carbon in the form of graphite in Al-CS composite is expected to improve the wear resistance [18-19].

TABLE III
DIFFERENT PROPERTIES OF AL-CS, AL-AL2O3 AND AL-AL2O3-SIC COMPOSITES

Material	Avg. Vol. Fraction(%)	Density (kg/m^3)	Brinell hardness (HB)	Ultimate tensile strength (MPa)
Al – CS	15	2770.62	37.1	92
Al – Al_2O_3	15	2886.87	31.8	80
Al - Al_2O_3 – SiC	15	2854.00	31.8	62

B. Quantitative analysis of test results obtain from design of experiments

Table 4 shows the 2nd order design matrix with responses for all the three composites. Here three responses such as weight loss, coefficient of friction and wear are given for each treatment combination. The insignificant coefficients are eliminated by taking backward option in SPSS. The parameter estimates and analysis of variance for the model are given in table below. By treating the data of table 4 regression equations are formed for the three composites as shown in equations (1-9).

The parameter estimates and analysis of variance for the three responses for Al-CS composite is given in **table 5** below.

Similar analysis is made for the other two composites i.e. $Al\text{-}Al_2O_3$ and $Al\text{-}Al_2O_3SiC$ for comparison purpose. Regression equations for weight loss (WL), coefficient of friction (CF) and cumulative wear (WR) for the three composites are formed are shown in equations 6 – 14.

$$W.L._{Al\text{-}CS}=0.029+0.004\,S+0.003V+0.010L-0.005S^2+0.006\,V^2-0.005\,L^2-0.001SXL+0.001VXL \quad (1)$$

$$W.L_{(Al\text{-}Alumina)}.=0.037+0.003\,S+0.004V+0.008L-.008S^2+0.006\,V^2-0.005\,L^2 \quad (R\text{-}square=0.909) \quad (2)$$

$$W.L_{(Al\text{-}AluminaSic)}.=0.036+0.004S+0.004V+0.007L-0.012S^2+0.006\,V^2 \quad (R\text{-}square=0.827) \quad (3)$$

$$CF_{Al\text{-}CS}=0.087-0.044\,S+0.068V^2+0.052L^2-0.033SXV+0.059VXL \quad (4)$$

$$CF_{(Al\text{-}Alumina)}.=0.109-0.101\,S+0.098V^2+0.l04L^2 \quad (R\text{-}square=0.801) \quad (5)$$

$$CF_{(Al\text{-}AluminaSic)}.=0.241-0.052S-0.096S^2+0.076L^2-0.056\,SXV+0.091SXL \quad (R\text{-}square=0.811) \quad (6)$$

$$WR_{Al\text{-}CS}=568+112.5V+275L-106.5S^2 \quad (7)$$

$$WR_{(Al\text{-}Alumina)}=614+44S+75V+376L+53V^2-85SXL+72.5VXL \quad (R\text{-}square=0.989) \quad (8)$$

$$WR_{(Al\text{-}AluminaSic)}=668.143+115.5V+373.5L-250.357SXS+189.643VXV+71.875VXL \quad (R\text{-}square=0.950) \quad (9)$$

The analysis of the equation (1) reveals that .004, .003 and .01 are the three coefficients attached to S, V and L which represent main effects of the individual variable. It can be observed that the effect of load is three fold in comparison to the other two variables in the range of variation of variables. The coefficient attached to S^2 is negative indicating that abrasion rate decreases with increasing the sliding distance. At higher distance de-lamination of the particles from the matrix cause debris accumulating at the tip of the abrading pin which increases the coefficient of friction and thereby decrease the erosion rate. Similar trend is also observed at higher load (vide coefficient to L^2), showing influence of work hardening on the decrement of the abrasion rate. Thus while increasing load causes individually positive effect but the square term indicates negative coefficient indicating the enhancement of work hardening with increasing load causing decrease in erosion slightly. However, the overall effect of L and L^2 shows net amount of abrasion, taking in to account of work hardening. There is strong interaction between s and L, V and L as marked by two coefficients attached to them in the equation. From the foregoing discussion it is apparent that combined effect of l and s will decrease the erosion rate due to de-lamination and work hardening, but the effect of V and L combindly will contribute positively to the erosion. Thus regression equation not only describes the quantitative effect of parameters but also helps to understand different mechanisms operating at different levels. Similar trend is observed for the other two composites (vide equations 2 & 3). Similar observations are made for the other responses as shown in equations 4 to 9.

Three dimensional plots of the response surfaces at 2kg load for the three composites are shown in Figs.2a-c. These figures give pictorial views and depict behaviour of the material at different test conditions. Depicted surfaces may help the operator to predict performance of the material within the stipulated time for particular operating conditions.

TABLE IV. EXPERIMENTAL RESULTS OF 2ND ORDER DESIGN

Exp. no	S	V	L	Weight loss (g)			coefficient of friction			Wear (microns)		
				CS	Alumina Sic	Alumina	CS	Alumina sic	Alumina	CS	Aluminasic	Alumina
1	-1	-1	-1	.0080	.0130	.0160	.2816	.2750	.4500	100	220	180
2	-1	-1	+1	.0280	.0320	.0290	.1350	.1600	.4100	680	710	1000
3	-1	+1	-1	.0120	.0200	.0190	.2500	.4500	.4900	250	180	170
4	-1	+1	+1	.0380	.0390	.0390	.3915	.2000	.4100	750	1200	1200
5	+1	-1	-1	.0200	.0280	.0250	.2350	.1100	.2000	155	140	420
6	+1	-1	+1	.0350	.0350	.0360	.0800	.3500	.1500	550	780	820
7	+1	+1	-1	.0230	.0260	.0250	.1250	.0550	.2250	280	400	430
8	+1	+1	+1	.0420	.0430	.0470	.1500	.1750	.1500	900	1085	1200
9	-1	0	0	.0190	.0220	.0270	.0637	.2000	.0600	350	480	550
10	+1	0	0	.0290	.0300	.0300	.0916	.0750	.0850	600	500	670
11	0	-1	0	.0300	.0330	.0330	.1400	.1600	.2000	410	860	540
12	0	+1	0	.0390	.0540	.0530	.1750	.3500	.2168	840	1000	710
13	0	0	-1	.0130	.0270	.0240	.1550	.3700	.2295	205	200	220
14	0	0	+1	.0350	.0360	.0400	.1275	.2500	.2000	860	1100	960
15	0	0	0	.0320	.0400	.0360	.0994	.2250	.1785	525	560	670

TABLE V. PARAMETER ESTIMATES AND VARIANCE ANALYSIS OF AL-CS COMPOSITE FOR THE THREE RESPONSES

a) For Weight loss (R-square=0.98)

Variable	PE	SE	t	Sig.
Intercept	0.029	0.001	31.653	0.000
s	0.004	0.001	8.046	0.000
v	0.003	0.001	6.034	0.001
l	0.010	0.001	18.651	0.000
s x s	-0.005	0.001	-4.430	0.004
v x v	0.006	0.001	5.306	0.002
l x l	-0.005	0.001	-4.430	0.004
s x l	-0.001	0.001	-2.453	0.050
v x l	0.001	0.001	2.044	0.087

Source	df	SS	MS	F-value	Sig.
Model	8	0.002	0.000	64.774	0.000
Error	6	0.000	0.000		
Total	14	0.002			

b) For CF (R-square=0.819)

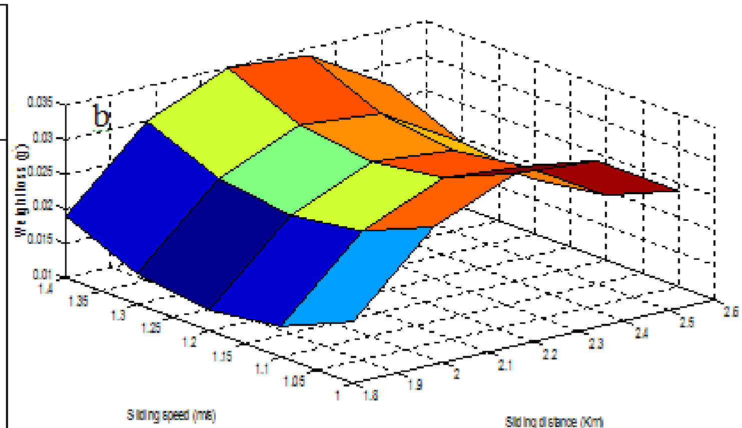
Variable	PE	SE	T	Sig.
Intercept	0.087	0.024	3.653	0.005
s	-0.044	0.015	-2.974	0.016
vxv	0.068	0.028	2.435	0.038
lxl	0.052	0.028	1.855	0.097
sxv	-0.033	0.017	-2.001	0.076
vxl	0.059	0.017	3.536	0.006

Source	df	SS	MS	F-value	Sig.
Model	5	0.089	0.018	8.162	0.004
Error	9	0.020	0.002		
Total	14	0.109			

C) For Wear (R-square=0.902)

Variable	PE	SE	T	Sig.
Intercept	568	0.024	3.653	0.005
v	112.5	0.015	-2.974	0.016
l	275	0.028	2.435	0.038
sxs	-106.5	0.028	1.855	0.097

Source	df	SS	MS	F-value	Sig.
Model	3	920620	306873.33	33.749	0.000
Error	11	100020	9092.727		
Total	14	1020640			



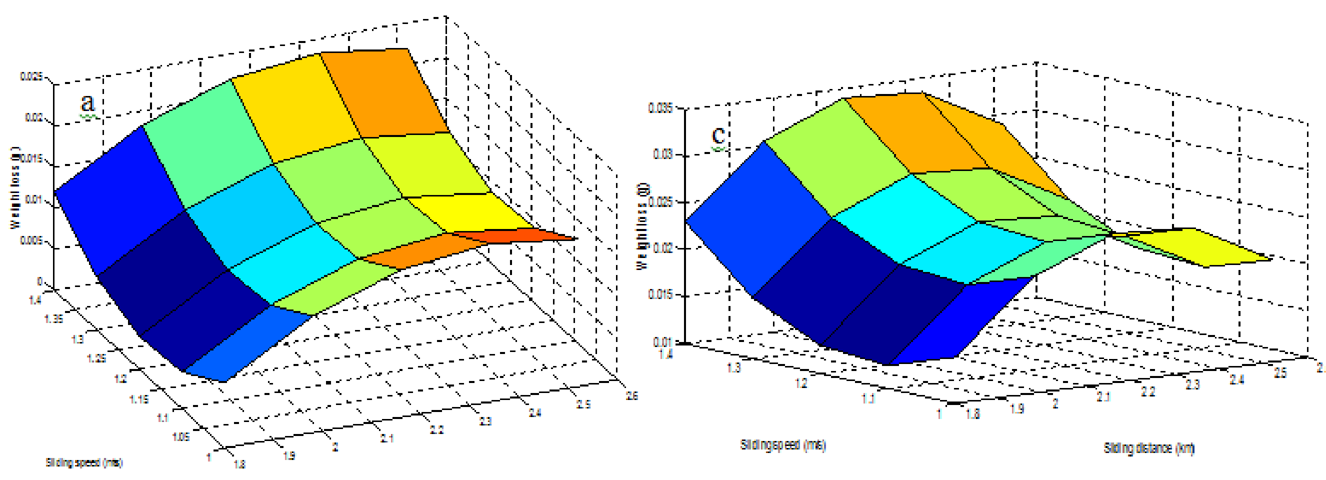


Fig.2 a, b & c show 3d plots at 2kg load for Al-CS, Al-Al2O3SiC and Al-Al2O3 composites

IV. Conclusions

1. Design of experiments technique is successfully used to study the dry sliding wear behaviour of AMC prepared from treated colliery waste (Al_2O_3-SiC-C).
2. The variables sliding distance, speed and load are having positive affect and therefore increases the abrasion rate. However the affect of load is three fold when compared to the other two variables.
3. The interactions between variables are complex and have seen to be retarding the erosion rate at higher sliding distance and load due to work hardening.
4. Al-CS composite has shown high wear resistance in comparison to the other two composites at all the test conditions because of in-situ nature of ceramic composite formed by thermal treatment as well as due to presence of free carbon in the form of graphite.

Acknowledgement

The authors are indebted to Management of GIET, Gunupur, Odisha, India, and NML, Jamshedpur, India for providing necessary facilities for carrying out the research work.

References

[1] A.A. Das, M.M. Yacaub, Z. Zantout, A.I. Cleg, Cast Met. 1 (1988) 60–80.

[2] S. Sawla, S. Das, Wear 257 (5/6) (2004) 551–561.

[3] Y. Sahin, Mater. Des. 24 (2003) 95–103. http://dx.doi.org/10.1016/S0261-3069(02)00143-7

[4] Y. Sahin, G. Sur, Surf. Coat. Technol. 179 (2004) 349–355. http://dx.doi.org/10.1016/S0257-8972(03)00802-8

[5] C.Z. Liu, L.Q. Ren, J. Tong, S.M. Green, R.D. Arnell, Wear 253 (2002) 878–884. http://dx.doi.org/10.1016/S0043-1648(02)00172-2

[6] Venkata Siva S. B, K. L.Sahoo, R. I. Ganguly, R. R. Dash, S. K. Singh, B. K. Satpathy, G. Srinivasa Rao: Metall,. Mater. Trans. B, 44 (2013) 800-808. http://dx.doi.org/10.1007/s11663-013-9832-x

[7] J. Esteban Fernandez, M.R. Fernandez, R.V. Diaz, R.T. Navarro, Wear 255 (2003) 38–43. http://dx.doi.org/10.1016/S0043-1648(03)00103-0

[8] S. Spuzic, S.M. Zee, K. Abhay, R. Ghomasch, I. Reid, Wear 212 (1997) 131–139. http://dx.doi.org/10.1016/S0043-1648(97)00089-6

[9] B.K. Prasad, Wear 252 (3/4) (2002) 250–263.

[10] R.L. Deuis, Wear 214 (1998) 112–130. http://dx.doi.org/10.1016/S0043-1648(97)00197-X

[11] S.C. Tjong, K.C. Lau, Mater. Sci. Eng. A82 (2000) 183–186. http://dx.doi.org/10.1016/S0921-5093(99)00752-2

[12] Y. Lee Gun, C.K.H. Dharan, R.O. Ritchie: Wear, 252 (2002) 322–331. http://dx.doi.org/10.1016/S0043-1648(01)00896-1

[13] R. Colaço, R. Vilar: Wear, 254 (2003) 625–634. http://dx.doi.org/10.1016/S0043-1648(03)00185-6

[14] J. Kopac, M. Bahor, M. Sokovic: Int. J. Mach. Tools Manuf., 42 (2) (2002) 707–716. http://dx.doi.org/10.1016/S0890-6955(01)00163-8

[15] D.A. Rigney: Wear, 245 (2000) 1-9. http://dx.doi.org/10.1016/S0043-1648(00)00460-9

[16] S.C. Lim and M.F. Ashby: Acta Metall., 35 (1987) 1–24. http://dx.doi.org/10.1016/0001-6160(87)90209-4

[17] R. Antoniou and C. Subramanian: Scripta Metall., 22 (1988) 809–814 http://dx.doi.org/10.1016/S0036-9748(88)80054-1

[18] Zou X.G., Miyahara H., Yamamoto K. and Ogi K., Materials Science and Technology, 19 (11) (2003) 1519-1526. http://dx.doi.org/10.1179/026708303225007997

[19] Jun D., Yao-hui L., Si-rong Yu and Wenfang L., Wear, 257 (2004) 930– 940 http://dx.doi.org/10.1016/j.wear.2004.05.009