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Abrasive Wear Behavior of Copper-Alumina Composite

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Absract - **This paper presents Abrasive wear behaviour of copper-alumina composite. The abrasive wear experiments were carried out using pin on disc apparatus. The wear behaviour was studied at different grit size, RPM and load. The wear behaviour was predicted through statistical analysis of the measured wear rate at different operating conditions. The effect of grit size on wear rate is more severe as compared to RPM and load. Image analysis and hardness studies were carried out on copper alumina composite. The abraded surfaces were observed under scanning electron microscope to study the morphology of abraded surfaces and operating wear mechanism. The analysis of wear debris particles was also carried out to corroborate the findings of experiment.**

Keywords:- Composite; Abrasive Wear; Matrix; Taguchi Method

1. INTRODUCTION

Metal-matrix composites (MMCs) are advanced materials that combine metallic matrixes along with the hard ceramic or high modulus fibres, particulates, short fibres or soft reinforcement. MMCs have high volume stiffness, specific strength and are lighter than monolithic alloys[1]. MMCs are suitable for applications which require high abrasion resistance, creep resistance, thermal conductivity, and dimensional stability. Thus these advanced materials find important applications in automotive, in tribological applications, for components of railways and components for rocket or aircraft engines[2]. Various super-alloys, as well as alloys and elemental aluminium, magnesium, titanium, and copper, are employed as matrix materials. . The reinforcement may be in the form of particulates, both continuous and discontinuous fibers, and whiskers; concentrations normally range between 10 and 60 vol%. Continuous fiber materials used as a reinforcement include carbon, silicon carbide, boron, aluminium oxide, and the refractory metals. On the other hand, discontinuous reinforcements consist primarily of silicon carbide whiskers, chopped fibers of aluminium oxide and carbon, and particulates of silicon carbide and aluminium oxide which are distributed all over the matrix may be homogenously or in-homogenously[3]. Mostly, MMCs are manufactured with the help of diffusion bonding technique, powder metallurgical route, hot pressing and liquid metal infiltration techniques. Generally copper based alumina reinforced composites are prepared by high pressure Die-casting technique, powder forging technique, vapour phase sintering technique etc. [4,5,6] A observation by Jami Winzer and et al [7] showed that Copper alumina composite are particularly suited for wear applications like automobile, aerospace and even bicycle parts due to combination of properties of alumina and copper, but the drawback of the combination of this properties involve relatively low melting point of alumina which limits possible temperatures of application. A study conducted by Y. Sahin [8] on nano Al_2O_3 reinforced copper matrix composite prepared by co-precipitation reveals that as the proportion of alumina increases from 1% to 5%, the hardness was increased markedly, while electrical conductivity presents a reduction tendency. The study also reveals that wear loss decreases firstly and then it increase exhibiting a minimum wear loss at 2% proportion. The wear mechanism observed here was the oxidation wear which is associated abrasive wear or delaminating fatigue. The model reveals that abrasive grain size was the dominant parameter which affects the abrasive wear followed by reinforcement size, while the effect applied load and sliding distance was found to be negligible.

A study conducted by D.P.Mondal and etal [9] has shown that abrasive wear is always less in composite material. Abrasive wear has been defined as displacement of materials caused by hard particles where this hard particles are forced against and moving along solid surface. Wear resistance is not an intrinsic property of a material. A statistical study conducted by S.C.Tjong and etal [10] using pin-on-disk method where samples of copper and its composite reinforced with TiB2 particles prepared by HIP technique shows that Pure copper exhibits a high abrasive wear loss because of its softness whereas the addition of reinforcing particle to copper leads to a dramatic improvement in its wear resistance. A statistical study is conducted by R.L.Deuis and etal.[11] reveals that composites characterised by hardness greater than the abrasive particles and a reinforcement phase of high fracture toughness and a low mean free path compared to the abrasive grit dimension exhibits high abrasive wear resistance. A statistical study by S. Kumara and etal [12] on abrasive wear rate of AA7075 Alluminium alloy matrix composites which are reinforced with SiC particles and mathematical model was developed. This study shows that particle size, reinforcement volume fraction, load, sliding speed and abrasive size also affect on wear rate. It has been shown that composites having large reinforcement size and high volume fraction showed improved wear resistance, while in case of high load the dominant wear mechanism is particle pull out. It has also been shown that when the abrasive size is more than the size of the reinforcement, it results in fracture and micro-cutting of reinforcement.The experimental results of the statistical study conducted by Y. Sahin [13] using Taguchi method shows that abrasive grain size is major parameter among the other control factors on abrasive wear, which is followed by weight fraction of the reinforcement. However, the applied load had a much lower effect while sliding distance was not significant. Similar results were also proved by statistical analysis using central composite design method by Ege Anıl Diler and et al [14] for Silicon carbide reinforced aluminium composite showing fraction of reinforcing particle has maximum effect on wear followed by reinforcement particle size and matrix particle size. Abrasive wear analysis using factorial experiment design done by Esteban Fernández and etal. [15]It has been shown that addition of reinforcement particles improved wear resistance. Increasing the hardness of the reinforcement also results in improved wear resistance. Wear analysis conducted by B.K. Prasad [16]and et al for zinc based alloy reinforced with SiC particles states that size of abrasive particle plays a significant role in wear. A statistical study conducted by Tejas Umale et al [17] showed that the abrasive wear volume loss was increased with increasing load, sliding distance and sliding speed, with load as a dominating factor among the three. A statistical study done by Yusuf Sahin [18] on abrasive wear behaviour of SiC/2014 Aluminium composite reveals that in case of composite samples which are prepared by powder metallurgy route the effect of grain size is more as compared to hardness on wear behaviour of a composite material due to the production method of powder metallurgy, particle size of reinforcement and testing conditions. Axen and etal [19] have studied the abrasion resistance of alumina fibre reinforced aluminium using a pin-on-drum abrasion wear tester and they concluded that fibre reinforcement significantly improved the abrasion resistance in milder abrasive situations, i.e., small and soft abrasives and low applied loads. However, in severe abrasive situations, the abrasion resistance of the composites was equal to or, in some cases, even lower than the unreinforced materials. Statistical analysis conducted by A.A. Cerit and et al [20] also showed that wear resistance of Metal Matrix Composite is enhanced by addition of reinforcement particle, as well as the hardness of a composite is decreased by decreasing reinforcement size and increases with increase in fraction of reinforcing phase. The statistical study conducted by A.Fathy and etal [21] has been shown that in case of $Cu\text{-}Al_2O_3$ nano-composite powders by increasing alumina contents there is increase in compression strengths, hardness and wear resistance. However, increasing alumina contents decreased density. The wear rates of the nano-composites increased with increasing applied loads or sliding speed. Sapate et al. [22] analyzed dry sliding wear behaviour of copper matrix composites reinforced with pre-coated SiCp particles and using dimensional analysis the sliding wear behaviour of Cu-SiC composites, the correlation between wear resistance and deformation and interface parameter was established. Zhang and et al [23] have conducted single point scratch test and reported that alumina particulate reinforcements in a 6061 aluminium matrix increased coefficient of friction. A statistical study conducted by N. Axen and et al [24] and a model is given for multiphase materials which are subjected to sliding friction. This model reveals that the friction occurring during wear not only depends on proportion, size and hardness of the composite but also depends substantially on that of the individual constituents i.e., reinforcement and matrix materials. A statistical study conducted by Dmitri Kopeliovich [25] has shown that hardness of alumina is extremely high. Due to such high hardness alumina ceramics have excellent wear resistance and alumina particles dispersed throughout a relatively soft matrix (metal or polymer) not only increase the material hardness and strength but also improve its tribological behavior. Additionally hard alumina particles in a metal matrix composite decrease the probability of seizure between the sliding counterparts due to the abrasive effect of the particles polishing the surface of the counter part. A statistical study conducted by Mohan and etal [26] revealed that the when graphite particles are incorporated as secondary reinforcement particles in the aluminium matrix ,it reduces slightly 1% the mechanical properties, but it enhances the wear resistance of the material by forming the protective layer between the pin and the counter face which helps in reducing the wear volume loss of a composite material. This study further reveals that in the case of graphite reinforced composite wear resistance can be substantially increased without loosening of properties when it is compared with Al/SiCp composite material. A statistical study conducted by S. Basavarajappa [1] on dry sliding wear behaviour aluminium composite which is reinforced with 10% SiC particles with the help of TAGUCHI Method and the weight loss model of aluminium composite was developed in terms of abrasive grain size, reinforcement size, sliding distance and applied load. The study conducted by Y. Sahin [27] during examining the tribological behaviour of metal matrix and its composite reveals that desired testing parameters are either determined based on experiment or by use of the handbook. However it does not give optimal testing parameter for particular situation. Thus, several mathematical models based on statistical regression techniques have been developed to select appropriate testing conditions.

TAGUCHI technique is a powerful tool to design high quality system and can be simplified by expending the application of traditional experimental designs to the use of orthogonal array. It provides systematic approach to optimize designs for cost, quality and performance. It is a multi step-process having certain sequence of experiments for an improved understanding of process performance. It consists of three main phases:-

(1)Planning phase
(2) Conducting phase
(3)Analysis interpretation phase

The data collected from all the experiments in the set are analysed in order to determine the effect of various design parameter. The TAGUCHI method has lead to limited number of applications in the worldwide industries.

The aim of the present study was to investigate the wear behaviour of copper alumina composite produced by

2. EXPERIMENT

2.1 Material:

$Cu\text{-}Al_2O_3$ composite was prepared by Powder Metallurgical route. The process included compaction of well mixed copper and alumina powders followed by sintering. Samples received from this process were in cylindrical form with diameter of 10mm and height of 20 mm, and were used for metallography, image analysis, hardness and abrasive wear sliding.

The specimens were subjected to metallography and image analysis which included polishing them on emery papers upto 1200 grit SiC, followed by fine polishing on wheel polishing machine. The polished samples were etched with a mixture of ethanol (100ml), conc. hydrochloric acid (25 ml), ferric chloride (10 grams), to observe the microstructure under Optical Microscope as well as SEM. The volume fraction of dispersed Al_2O_3 particles were measured using Leco Image Analysis Software. An average of ten readings, taken at different locations over the entire micro-structure was reported as

compaction and sintering (powder metallurgy route) based on TAGUCHI method under various testing conditions. Furthermore the analysis of variance were employed to investigate the testing characteristics of copper alumina composite. Table 1 shows the parameters chosen for the experiment.

percentage volume fraction which was found to be approximately 10.04%.

2.2 Metallography and Hardness:

The specimens were well polished using emery paper of different grit size 800, 1000, 1200 likewise and etched with a solution of mixture of ethanol (100ml), conc. hydrochloric acid (25 ml), ferric chloride (10 grams). Then the specimen was observed on optical Microscope as well as Scanning Electron Microscope (SEM). Figure 1 shows the micro-structure of $Cu\text{-}Al_2O_3$ composite in an Optical microscope. The micrograph shows reinforcement alumina particles in copper matrix along with some porosities. Figure 2 shows the micro-structure of $Cu\text{-}Al_2O_3$ composite in SEM. The reinforcement alumina particles appear as black grains in a bright copper matrix along with some blurred region which represents the porosities. Hardness was measured using Vickers Micro-Hardness tester at a load of 100 grams. Five readings were recorded and the result was displayed as the average of these five readings.

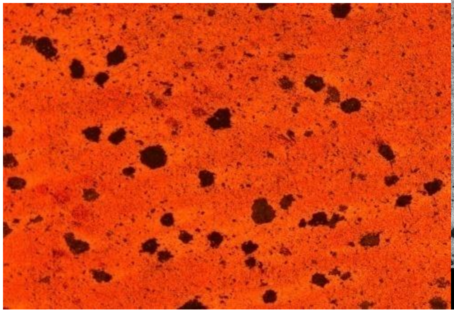

Figure 1 a. Optical Micro-structure of $Cu\text{-}Al_2O_3$

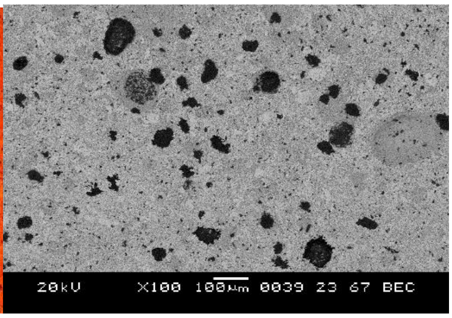

Figure 1 b. SEM micro-structure of $Cu\text{-}Al_2O_3$

2.3 Experiment Design:

The present work is based on the sliding abrasive wear analysis of $Cu\text{-}Al_2O_3$ composite using Statistical Taguchi analysis. The prime aim is to find out the influence of testing parameters on $Cu\text{-}Al_2O_3$ composite. The assigned codes and levels are shown in Table 2. It depicts that the experiment plan has four levels. Apart from the effect of parameters on the weight loss of $Cu\text{-}Al_2O_3$ composite, the effect of their interaction parameters were also studied. An orthogonal array of L16 was prepared depicting the plan (4^{-3}) was selected indicating three independent parameters were varied at four different levels. After the computation of observed data, the results were transformed into signal-to-noise (S/N) ratio. With the help of Taguchi method, we can find the mean deviation from the desired values. There are basically three categories in which Taguchi method can be applied, i.e., lower-the-better, nominal the best and larger-the better. As we are computing wear loss, it should be as minimum as possible, hence we select smaller-the – better method for computation of S/N ratio. In addition, statistical analysis of variance was performed to see which test parameters have considerable effect on weight loss of $Cu\text{-}Al_2O_3$ composite. Hence, with the help of S/N ratio and ANOVA analysis an optimal level of each testing parameter could be predicted with 95% confidence. Finally, a confirmation experiment was conducted to verify the optimal testing parameters.

Parameters	Code	Level 1	Level 2	Level 3	Level 4
RPM	A	150	300	450	600
Load (kg)	B	1	2	3	4
Grit Size	C	320	220	150	80

Table 1. Control factors and their levels

2.4 Abrasion Wear Testing:

All the testing samples were polished on emery papers upto 1200 grit size. Then there surface were cleaned with ethyl alcohol and weighed initially before subjecting them to wear testing using electronic digital balance to the accuracy of 0.1 mg. Abrasive papers of different grit sizes were fixed on the disk according to the conditions in a set of experiment. The cleaned sample was then fixed tightly on the holder. Other test parameters such as load and sliding velocity (RPM) were set as mentioned in a particular set and sample was made to slide on the abrasive paper for a fixed time of 5 minutes. After the completion of test the sample was taken out of the holder, its surface was cleaned with alcohol again and then its final weight was recorded. Debris was collected carefully for further SEM analysis and the sample was preserved for viewing the worn-out surfaces

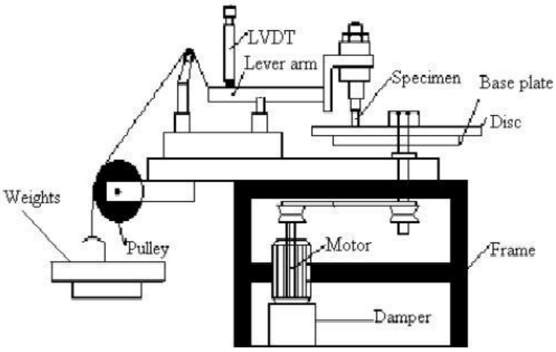

Fig. 2 Schematic of Pin-on-disk Wear Testing Apparatus.

2.5 SEM analysis of worn-out debris and worn-out surfaces:

The worn-out specimen was ultrasonically cleaned and was subjected to SEM analysis. Analysis of the worn-out surface helps us in understanding the wear mechanism, whereas, the analysis of worn-out debris helped us in understanding and determine the amount of reinforcement phase (Al_2O_3 particles) and matrix material (copper) is worn-out during each run. For wear debris analysis, the debris were initially mounted on a stab with carbon tape. The debris adhere to the bare side of carbon tape and hence we are enable to run our testing successfully. Samples were grounded by carbon tape, making it conductive and hence, further enabling us to study size, shape and morphology of worn-out particles.

3. RESULTS AND DISCUSSION:

3.1 Analysis of Control Factors.

The influence of each control factor on the weight loss was studied with a so-called S/N ratio response table. Calculations were done with the help of software minitab 15. Table 2 shows the calculated S/N ratio for the corresponding weight loss. Considering smaller the better case, for wear the calculations for S/N ratio were made. The left side of the table shows selected control parameters with their different levels, whereas the right side of the table shows weight loss and the calculated S/N ratio values. Table 3 shows the corresponding S/N ratio of every control parameter at its each corresponding level and also shows how the values change, when levels of every parameter changes from 1 to 4. The interactions of the parameters were also studied as their analysis also proves as a useful data to study the process under consideration. The control factor which has the maximum effect on the wear was determined from the difference of S/N ratio values. Higher the difference between the S/N ratio values of a particular parameter, greater is its influence on wear of material.

Exp. No	A	B	C	A x B	A x C	B x C	$W_{initial}$	W_{final}	Weight loss	S/N ratio
1	2	2	2	1	1	1	4.8161	4.4135	0.4026	0.790252
2	3	2	3	4	1	4	4.8982	4.1892	0.7036	0.305348
3	4	2	4	3	1	3	4.5959	2.1982	2.3977	-0.75958
4	1	3	2	3	2	4	4.8128	4.5283	0.2845	1.091835
5	2	3	1	4	2	3	4.8982	4.1892	0.709	0.298707
6	3	3	4	1	2	2	4.8219	1.5401	3.2818	-1.03222
7	4	3	3	2	2	1	4.1341	2.4745	1.6596	-0.44000
8	1	1	3	4	3	2	4.9152	3.529	1.3862	-0.28365

9	2	1	4	3	3	1	4.3988	1.376	3.0288	-0.96254
10	3	1	1	2	3	4	4.6042	4.2269	0.3773	0.846626
11	4	1	2	1	3	3	4.7836	4.4453	0.3383	0.941396
12	1	4	4	1	4	4	4.7532	4.5374	0.2158	1.331897
13	2	4	3	2	4	3	4.7957	4.3794	0.4163	0.761187
14	3	4	2	3	4	2	4.1216	3.7734	0.3482	0.916342
15	4	4	1	4	4	1	4.8667	4.2206	0.6461	0.379401
16	1	2	1	2	1	2	4.5943	4.3478	0.2465	1.216366

Table 2: Calculation of S/N ratio for each experiments.

Level	A (RPM)	B	C
1	8.3911	8.4721	6.8528
2	2.2190	3.8809	9.3496
3	2.5902	-0.2042	0.8572
4	0.3030	1.3546	-3.5561
Differ	8.0881	8.6763	12.9057
Rank	3	2	1

Table 3: S/N response table for parameters and their interactions for Cu-Al_2O_3 composite.

Table 3 shows the sorting of control parameters and their interactions according to their corresponding difference in S/N ratio values. From Table 3 it can be seen that abrasive particle grain size (C.) has the greatest influence on wear of Cu-Al_2O_3 composite consequently followed by load (B). As per interaction of parameters is concerned, the interaction between abrasive particle grain size and load(B×C) shows its maximum influence on wear. Fig. 4(a) and (b)shows the main effects and their interaction plots for the weight loss of the MMCs for S/N ratio and mean value, respectively. The greater is the S/N ratio, the smaller is the variance of weight loss around the desired value. Optimal wear conditions were found out from the response graphs. These graphs shows the change in the S/N ratio values and mean values when the levels of each parameter was subsequently increased.

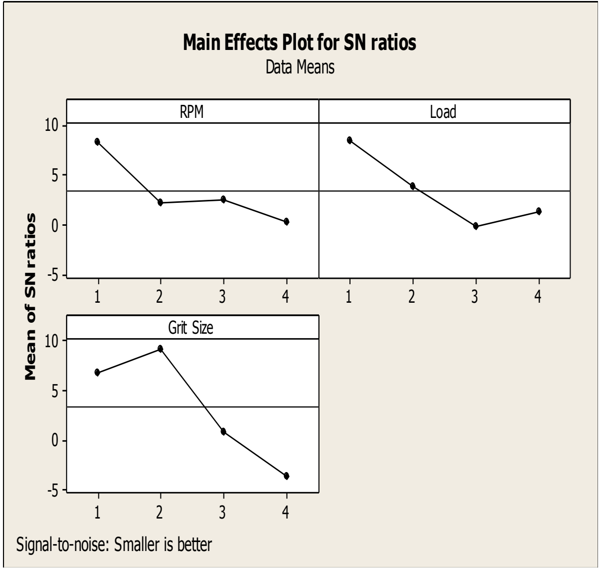

Fig 4a. Weight loss plot with respect to S/N ratio

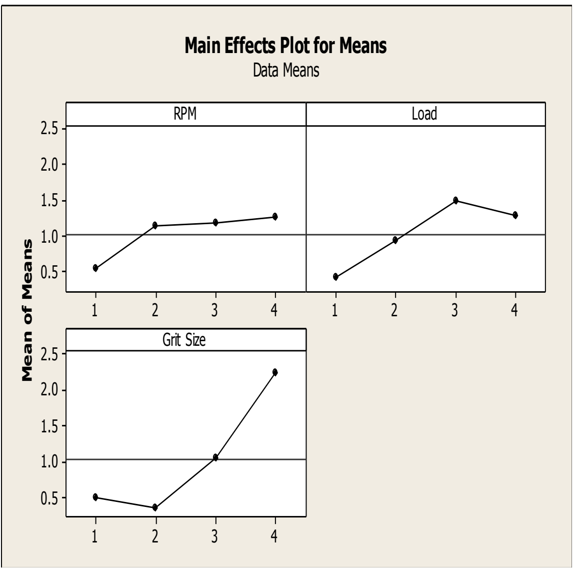

Fig 4b. Weight loss plot with respect to mean

It is clear that grain size of the abrasive medium, has the maximum effect on wear, subsequently followed by load. The weight loss increased as the grain size was increased from 45 µm(320 mesh) to 177 µm(80-mesh). This phenomenon may be occurring, since the penetration power of the particles increase as their size goes on increasing. In addition, it was also observed that weight loss also increased as the applied load and sliding speed was increased. However, this is in opposition to Rabinowicz's classical theory [28], which states that applied load and hardness of the material has the maximum effect on wear. Similar results were observed by by Esteban Fernandez et al. [15] and Spuzic et al [29] while they were studying the effect of material and sliding speed by fractional design of experiments. However, work carried out by Hutchings and Wang states that, abrasion grit size has the maximum effect on wear followed by load. Some similar results were obtained by Mondal et al [9] which states that load has the maximum effect on wear as compared to abrasion grit size for cast Al alloy and 10 wt.% Al2O3 composite, which somehow contradicts the present work. Prasad et al [16] showed that the wear rate reduced with sliding distance, whereas it increased with load and concluded that load has the most significant effect on wear.

Table 4: Results of the analysis of variance of S/N Ratio for Copper-Alumina Composite

Factors	Degree of freedom	Sum of squares (SS)	Mean square (MS)	Characteristics of F	Contribution (%)
A	3	146.2	48.73	1.35	15.49
B	3	172.5	57.51	1.59	18.28
C	3	408.7	136.23	3.78	43.30
Error	6	216.4	36.07		
Total	15	943.8			100

3.2 ANOVA:

Analysis of Variance(ANOVA) of the design parameters was carried out to examine that which parameter has a significant effect on the quality characteristic. Fischers (F) value for each design parameter was calculated by dividing mean of squared deviations to the mean of squared error. If the value of Fischers (F) value is greater than 4, it is said that the parameter has a significant effect on the quality characteristic. Inspection of the calculated F values, shows that abrasive particle size (C) has very significant effect on wear of Copper-alumina composite, followed by load (B) and subsequently by sliding velocity (A). Additionally the interaction between abrasive particle size and load (B*C) also proved its significant effect on wear followed by interaction between sliding distance and abrasive particle size (A*C). The last column of the Table _ shows percentage of contribution of each control factor on the total variation, depicting the degree of influence on wear. From the inspection of the Table 4, it is clearly evident that abrasive particle size (P= 43.30%) and load (P= 18.28%) has a significant effect on wear of Cu-Al_2O_3composite. While factors like sliding velocity (P=15.49%) has moderate effect on wear. As the matrix chosen for conducting experiments was (4^3) the percentage contribution of interaction parameters could not be calculated accurately. For doing so the number of parameters must be equal to the number of levels in each parameter or should be multiples of each other[3]. The ultimate step was to examine the improvement of the quality characteristic by using an optimal level of the design parameters. The optimal conditions were estimated from the significant factors as shown in Table 5. Factors C (grit size), B(load), A(sliding velocity), B*C(load*grit size) & A*C (sliding velocity*grit size) has the maximum effect on wear and hence would be crucial in predicting the performance at optimal level. Table 6 shows the comparison of predicted values with actual calculated values. It is much evident, from the values that the experimentally calculated values are in good accordance with the predicted values. This proves that the model constructed in the present work, is suitable to predict the wear for the Cu-Al_2O_3 composites.

Control Factors	Notation	Setting
RPM, A	A1	150
Load, B	B1	1
Grit Size, C	C2	220

Table 5: Optimal setting of control factors for weight loss.

Verification Test Results		Predicted Values		Difference
Weight Loss	S/N Ratio	Weight Loss	S/N Ratio	$(S/N)_V - (S/N)_P$
0.0797	21.9708	0.1064	19.4611	2.5097

Table 6. Confirmation test result and comparison with calculated value.

3.3 Worn-out Surfaces and Worn-out Debris

Apart from ANOVA analysis, it can also easily observed that, at lower levels of process parameters wear suffered is relatively less as compared to that at higher levels. Fig 5. Shows the wear tracks of worn-out surface of setup 3 whereas, fig 5(b) shows the wear tracks of worn-out surface of setup 15.Fig 6(a) shows the wear debris of experimental setup 3 , and Fig. 6(b) shows the debris obtained from experimental setup 15. It is clearly evident that wear scars over the worn out surface run more deep in higher levels of experimental setup as compared to those at lower levels. Similarly the wear debris obtained for the higher levels of parameters are also flaky and elongated as compared to those at lower levels indicating severe wear at higher levels. This reflects that as the size of abrasive particle increases, its penetration ability increases and thus causes more wear. Similarly increasing load causes an increase in the force per unit area on the surface to increase causing the more enforcing of surface on the abrasive particles causing deep scars and enhancing wear. It can also be seen as the sliding velocity increases the sliding distance tends to increase within a fixed time, and hence more wear is incurred by the material.

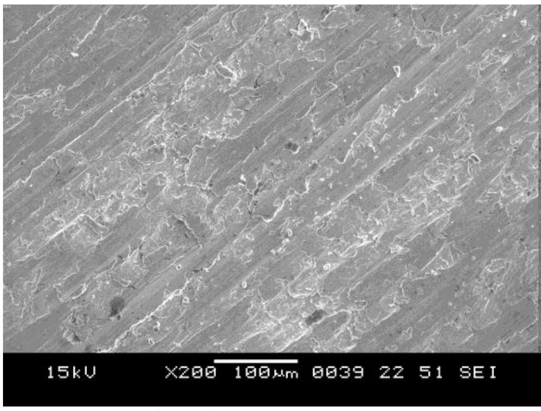

Fig 5(a) Worn out surface of Experiment set 3[higher level]

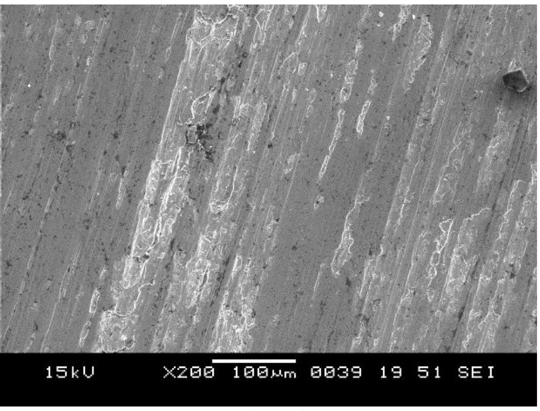

Fig 5(b) Worn out surface of Experiment set 15[lower level]

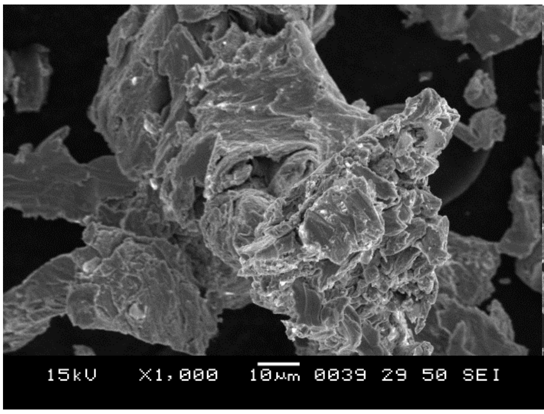

Fig 6(a) Wear debris of Expriment set 3[higher levels]

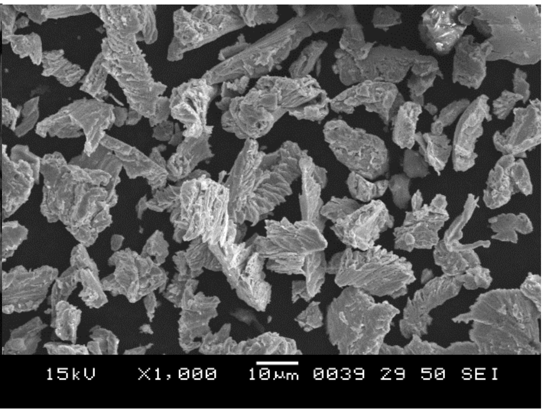

Fig. 6(b) Wear debris of Experiment set 15 [lower levels]

4.CONCLUSIONS

A simple framework for abrasive wear in ductile composite reinforced with hard phase is presented. A statistical method was adopted to investigate the effect of load, grit size and RPM. The following conclusions could be drawn from the results of wear behaviour of copper alumina composite.

1. Comparing the effectivity of grit size, load and RPM on the wear rate of copper alumina composite, the effect of grit size is found to be higher subsequently followed by load and then sliding velocity for Cu-Al_2O_3 composite. Hence, the grit size is the most dominating factor controlling wear behaviour of copper alumina composite.
2. Among interactions, the interaction of grit size and load was also one of the dominating factor contributing wear followed by the interaction between grit size and sliding velocity.
3. The S/N ratio using the optimal testing parameters for wear resistance could be calculated.
4. The SEM analysis of worn out surfaces and wear debris of copper alumina composite helped in identifying proper abrasive wear mechanism of material removed during test conditions.
5. The morphology of the wear debris and the worn out surfaces helped in depicting the shifting of wear mode from mild to severe as we moved from lower levels of testing parameters to higher levels.

REFERENCES

[1] S. Basavarajappa , G. Chandramohan , J. Paulo Davim ,Application of Taguchi techniques to study dry sliding wear behaviour of metal matrix composites,Materials and Design 28 (2007) 1393–1398.

[2] Mr.S.Balu Mahandiran Dr.M.Nataraj, Dry Sliding Wear Behaviour of Al – SiC Composites Using Design of Experiments, Proceedings of the National Conference on Manufacturing Innovation Strategies & Appealing Advancements, MISAA2013

[3] W.D. Callister, Introduction to Materials Science and Engineering.

[4] K. Granat et al, Production and wear properties of copper based MMC strengthened with δ-alumina fibres- , ARCHIVES Of FOUNDRY ENGINEERING ISSN (1897-3310) Volume 11 Special Issue 2/2011 71–74 14/2

[5] Tachai Luangvaranunt et al, Aluminum-4 mass % Copper/Alumina Composites Produced from Aluminum Copper and Rice Husk Ash Silica Powders by Powder Forging, Materials Transactions, Vol. 51, No. 4 (2010) pp. 756 to 761 2010 The Japan Institute of Metals.

[6] Marc. A. Ritland and Dennis W. Readey, Alumina- Copper Composites by Vapor Phase Sintering, Proceedings of the 17th Annual Conference on Composites and Advanced Ceramic Materials, Part 2 of 2: Ceramic Engineering and Science Proceedings, Volume 14, Issue 9/10, Published online 28th March 2008.

[7] Jami Winzer, Ludwig Weiler, Jeanne Pouquet, Jurgen Rodel, Wear behavior of interpenetrating copper alumina composite, Materials & Design, Volume 36, April 2012, Pages 100-107

[8] Y. Sahin – Tribological Behaviour of Metal Matrix's Composite, Materials and Design 28 (2007) 1348–1352.

[9] D.P. Mondal , S. Das, A.K. Jha, A.H. Yegneswaran. - Abrasive wear of Al alloy–Al_2O_3 particle composite: a study on the combined effect of load and size of abrasive, Wear Volume 223, Issues 1–2, December 1998, Pages 131-138.

[10] S.C. Tjong *, K.C. Lau- Abrasive wear behavior of TiB2 particle-reinforced copper matrix composites. Materials Science and Engineering A282 (2000) 183–186.

[11] R.L. Deuis ,C. Subramanian ,J. Yellup - Abrasive wear of aluminium composite-a review, Wear, Volume 201, Issues 1–2, 15 December 1996, Pages 132-144.

[12] S. Kumar , V. Balasubramanian Effect of reinforcement size and volume fraction on the abrasive wear behaviour of AA7075 Al/SiCpP/M composites—A statistical analysis, Tribology International 43 (2010) 414–422.

[13] Y. Sahin, The prediction of wear resistance model for the metal matrix composites, Wear, Volume 258, Issues 11–12, June 2005, Pages 1717-1722.

[14] Ege Anıl Diler , Rasim Ipek, Main and interaction effects of matrix particle size, reinforcement particle size and volume fraction on wear characteristics of Al–SiCp composites using central composite design, Composites: Part B 50 (2013) 371–380.

[15] Esteban Fernández, Madel Roc´ıo Fernández, R. Vijande Diaz, R. Tucho Navarro,Abrasive wear analysis using factorial experiment design, Wear, Volume 255, Issues 1–6, August–September 2003, Pages 38-43

[16] B. K. Prasad", S. Das, A. K. Jha, 0. P. Modi, R. Dasgupta and A. H. Yegneswaran, Factors controlling the abrasive wear response of a zinc-based alloy silicon carbide particle composite, Composites Part A 28A (1997) 301-308.

[17] Tejas Umale, Amarjeet Singh, Y Reddy, R.K. Khatitrkar, S. G. Sapate Abrasive wear behaviour of Copper-SiC and Copper-SiO_2 composites. International Journal of Modern Physics: Conference Series Vol. 22 (2013) 416–423.

[18] Yusuf Sahin - Abrasive wear behaviour of SiC/2014 aluminium composite. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology January 7, 2013 135065011247176.

[19] N. Axen, A Alahelisten, S. Jacobson, Abrasive wear of alumina fibre-reinforced aluminium, Wear, Volume 173, Issues 1-2, April 1994, Pages 95-104.

[20] A.A. CERIT, M.B. KARAMIŞ, F. NAIR AND K. YILDIZLI Effect of Reinforcement Particle Size and Volume Fraction on Wear Behaviour of Metal Matrix Composites- Tribology in industry, Volume 30, No. 3&4, 2008.

[21] A. FathyF. Shehata, M. Abdelhameed, M. Elmahdy, Compressive and wear resistance of nanometric alumina reinforced copper matrix composites-, Materials & Design, Volume 36, April 2012, Pages 100-107.

[22] S.G. Sapate, A. Uttarwar, R.C. Rathod, R.K. Paretkar, "Analyzing dry sliding wear behaviour of copper matrix composites reinforced with pre-coated SiCp particles", Materials and Design 30 (2009) 376–386.

[23] J. Zhang, A.T. Alpas, Wear regimes and transitions in Al_2O_3 particulate-reinforced aluminum alloys, Materials Science and Engineering: A Volume 161, Issue 2, 1 April 1993, Pages 273-284.

[24] N. Axen, I. M. Hutchings and S. Jacobson, A model for the friction of multiphase materials in abrasion, Tribology International Vol. 29, No. 6, pp. W-475, 1996

[25] Dmitri Kopeliovich, Tribological properties of alumina reinforced composites, Subs-Tech (Substances &Technologies), 16th July 2013.

[26] Mohan S, Pathak JP, Gupta RC, Srivatsava S. Wear behavior of graphitic aluminium composite sliding under dry conditions. Wear,2002;93:1245–51.

[27] Y. Sahin, Optimization of testing parameters on the wear behaviour of metal matrix composites based on the Taguchi method, Materials Science and Engineering A 408 (2005) 1–8.

[28] Rabinowicz ED. Friction and wear of materials. New York: Wiley; 1965. 168–174.

[29] S. Spuzic, M. Zec, K. Abhary, R. Ghomashchi, I. Reid, Fractional design of experiments applied to a wear simulation, Wear, Volume 212, Issue 1, 30 November 1997, Pages 131-139.