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Examination of Wear Properties in Dry-Sliding States of SIC Strengthened Al-Alloy Metal Matrix Composites by Using Taguchi Optimization Approach

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Abstract

The current work study is focused on fabrication of aluminum alloy AlMg0.7Si-SiC metal matrix composites and inspection of wear performances using taguchi optimization approach. AlMg0.7Si-SiC matrix composites are manufactured by liquid processing stir casting technique in a top loading electric resistance furnace. The AMCs are fabricated (having 37µm SiC particle size) in four different wt. fractions (0 wt%, 3.5 wt%, 7 wt% and 10.5 wt%). The experimental runs to analyze the wear performance are executed in accordance with L_9 taguchi design of experiment approach to obtain the wear data in a controlled manner. Effect of three control variables, viz,. % wt. of SiC, Load (N) and Sliding distance (m) on the wear rate and frictional force of the casted composites in unlubricated dry slippery conditions is examined by using pin-on-disc wear and friction monitor apparatus. ANOVA is also carried out to inspect the effect of three control factors on the dry slippery wear performance of the composites. Taguchi analysis revealed that % wt. SiC, Load (N), and Sliding distance (m) remarkably influenced the dry sliding wear performance of the casted composites. The optimal level of three control variables for minimum wear rate are also obtained on the basis of 'smaller the better'. The optical microscopic analysis and hardness testing of the casted composites is also carried out in this work.

Keywords: Aluminum metal matrix composites (AMC's), AA6063, stir casting, SiC, wear, taguchi method, and anova

INTRODUCTION

Metal matrix composites produced by addition of hard and tough ceramic particles such as titanium carbide, silicon carbide, aluminum oxide etc. into al-alloys attain excellent mechanical properties as compared to monolithic al-alloys. MMCs reinforced with ceramic agents have a broad range of applications in ship building, automotive sector, architectural components, defense applications etc. These fabricated composite materials possess light weight and acquired better hardness which makes it as wear resistant structural material and in load carrying applications. MMCs are fabricated to conquer these shortcomings and to encounter the world-wide desire for light weight materials escorted by elevated specific strength, high wear resistant and better stiffness properties [1-2]. The properties of aluminum alloy like low density, light weight, easy manufacturing method and good mechanical properties favored it as matrix material in MMC's [3]. For the manufacturing of metal matrix composites several type of fabrication techniques are available but normally stir casting process [4-6], pressure infiltration method [7] and powder metallurgy technique [4-12] are employed. The well known liquid metallurgy Stir casting process is the most recognized and appropriate technique used in the processing of AMC's [13]. Most of the researchers have produced composites by varying the weight fraction of SiC in the range of 0% to 30% [8-12]. The silicon carbide particles are known to be very tough and brittle elements possess properties like high strength, good toughness, high hardness number, and excellent wear resistant and elevated temperature properties and are used as reinforcing agent for many aluminum and its alloys series.

The wear examinations are performed by varying the different variables such as normal applied load, wt. % reinforcement, sliding velocity, sliding distance, sliding time and temperature etc. The abrasive wear analysis of Al/SiC composite produced by altering the vol. fraction and particle size from 5% to 20% and 10, 27, 43µm respectively showed that the wear rates reduces with the addition in vol. fraction but increased with increase in particle size [8-9] The wear performance investigation of AA6061/SiC composite when subjected to normal applied load and temperature showed that wear rate reduces with addition in load applied [14]. The dry sliding wear examination of al-alloy-matrix reinforced with silicon carbide whiskers (from 0% to 16%) revealed that the wear rates of the fabricated composite gradually reduces with the addition in vol. % of silicon carbide whiskers into the matrix alloy [15]. The effect of hardness on the wear performance of AA7075/20 vol. % Al_2O_3 composite matrix showed that the resistance to wear of the composite material is greatly increased by the introduction of 20 vol. % of reinforcement particles [16]. In this experimental work AA6063/SiC composites have been prepared by utilizing enhanced dual step liquid processing stir casting process and examination of their wear performances have been made in accordance with taguchi orthogonal array with three process variables viz. normal load, sliding distance and wt. % SiC. A tribometer with counter face rotating disc and load lever arrangement is employed for wear examination. The experimental results are studied for optimum combination of control variables for minimum wear. ANOVA is also performed to examine the impact of control variables on the wear performance of the composite material. The impact of reinforcement agents on the microstructural and microhardness properties of the processed composite material is also studied.

MATERIALS AND METHODS

Materials

In this experimental work wrought AA6063 (AlMg0.7Si) used as base metal alloy available in size 50mmx6mm rectangular strips for casting composite material and was purchased from Atco Aluminum strips Pvt. Ltd., New Delhi. Magnesium (0.45-0.9%) and Silicon (0.2-0.6%) are the principal alloying elements in AA6063 and that is why it is known as Mg-Si alloy. The other alloying elements are iron (0.35%), copper (0.1%), manganese (0.1%), zinc (0.1%), titanium (0.1%), and chromium (0.1%) in very small percentages by wt. percentage. Silicon carbide (SiC) in particle form (having particle size 400mesh) was used as reinforcement agent for the fabrication of composite material. Silicon carbide is made up of two elements silicon and carbon and is very hard and tough material and is used as an abrasive in many applications. SiC is used in many fields such as in automobile industry for making parts requiring high endurance like in car brakes, clutches and electronic industry for making LEDs and detectors. SiC is widely used in semiconductor electronic parts that operate at elevated temperature range.

Development of AA6063 composites

The enhanced dual-step liquid processing Stir casting method has been utilized for the development of AA6063/SiC matrix composites investigated by Fatile et al. [17] and Alaneme & Aluko [18]. A top loading digitally controlled electric resistance furnace was used for the melting of weighed amount of matrix alloy. The matrix alloy (AA6063) into a graphite crucible inside the furnace was melted upto temperature 810 ^{o}C to ensure the complete melting of alloy matrix. At this stage preheated (in another muffle furnace) SiC particles at temperature 900 ^{o}C were incorporated with a uniform rate into the molten melt in the form of small capsules wrapped in aluminum foil and dynamic stirring at 450rpm was carried out to form a fine vortex as reported by Hashim et al. [19] and Sevik & Kurnaz [20]. To enhance the wettability of the slurry mixture magnesium metal powder (1% by wt.) was mixed into the molten slurry during vortex stirring. Mechanical stirring of the molten slurry was employed using a SS impeller comprises four blades covered with alumina for 15 minutes at an average speed of 450 rpm to ensure a complete mixing of the reinforcement SiC particles into the melt. Two step stirring procedure was employed to ensure a thorough mixing and to overcome problems of agglomeration of reinforcement particles into the molten slurry. The composite slurry at this stage was reheated at temperature 750±30 ^{o}C as the temperature lowers down during stirring. At this time mechanical torque was again applied by stirrer and the composite slurry was rotated for 5 minutes at the same average speed. The Composite samples of different wt. % (3.5%, 7%, 10.5%) were obtained by pouring the mixture slurry into preheated (at 250 deg. Celsius) cast iron mould at a pouring temperature of 720 ^{o}C and let to cool at room temperature.

Wear examinations

The wear examinations on composite specimens (3.5%, 7% & 10.5%) were conducted in dry sliding states on pin-on-disc wear and friction monitor machine [DUCOM (TR-20LE)]. The test set up was consist of a rotating disc made of material EN-31 steel with hardness value of 62HRC and has 100mm diameter and10mm thickness (in fig. 1 (b)) The rectangular pin type test samples (in fig. 1(a)) of size 32 x 6 x 6 mm were pressed against the counter rotating disc. A loading lever was swiveled close to the load sensor for placing the dead weights. The samples to be examined were fine polished to make flat face before the start of wear examination and gripped against the rotating counter face disc. The composite specimens were subjected to dry sliding wear tests at room temperature in accordance taguchi L_9 orthogonal array design matrix as shown in table 3. To acquire error free data the samples and the rotating disc were polished after each run. The LVDT arrangement with accuracy of 1µm during the wear test continuously acquired the wear data in terms of displacement of the specimens in micrometer (µm). The wear displacement sensor permits for acquiring direct readings of the deflection due to load lever, which are analogous to the wear of the specimen. The wear behavior is usually expressed in terms of wear volume or weight loss and the wear rate was calculated from height loss measurements by using the formula:

Wear rate (mm^3/m) = Height loss (mm) x Cross sectional area of specimen (mm^2) / Sliding distance (m)

Specific wear rate ($mm^3/N\text{-}m$) = wear rate / Load applied

Wear Resistance = 1 / wear rate

Figure1(a) Wear test specimens **(b)** An overview of pin-on disc wear apparatus

Microstructural examination

The optical metallurgical microscope made by Dewinter was used to carry out standard metallographic tests on the fabricated al-matrix composite specimens. For microscopic examination the specimens were extracted from the fabricated composites and fine polished against various sizes (400-2000 grit size) water proof emery papers and velvet cloth, while final polishing was done with a tube of 5µm diamond paste. The standard Keller's reagent basically solution of HNO_3 (5ml), HCl (3ml), HF (2ml) and 190ml distilled water was used to reveal the microstructure of the mirror polished composite specimens. The samples were immersed in the solution for 10seconds at room temperature before microscopic examination.

Hardness testing

The microhardness of the unreinforced and reinforced composite specimens was measured at different points to get the average value of hardness. The FIE model MV1-PC Vicker's microhardness tester was used to measure the hardness of the samples. The average micro hardness values were measured at a set load of 0.05kgf for a dwell time of 15 seconds.

Taguchi experimental plan

Taguchi experimental approach was selected for robust and sophisticated design. As compared to traditional designs taguchi method gives an easy, systematic and managed approach by minimizing the experimental time and cost of experiments for the optimization of the design factors [21]. Taguchi experimental plan basically utilizes two important tools (i) S/N (signal to noise) ratio which lessen quality characteristic variation due to unmanageable factors. (ii) Orthogonal array which occupies the design factors for experimentation. The key part is the selection of process parameters in the design of experiment approach. As reported in the literature a number process factors such as normal load applied, sliding speed, wt. % of reinforcement agent, sliding distance and sliding time etc. greatly influenced the wear performance of aluminum centered metal matrix composites. For the optimization of the control variables easy and well organized taguchi approach for three factors and three levels was utilized as shown in table 1 & 2. The L_9 orthogonal array having set of 9 experimental runs was selected to analyze the wear performance of the casted composite specimens as shown in table 3. In this study normal applied load, sliding distance and wt. % SiC were considered as control factors. The wear rate (WR) and frictional force (FF) were selected as response output variables. The experimental examinations were transformed into signal to noise ratio. Here the S/N ratio analysis was carried out using the characteristic smaller-the-better by using equation:

S/N= -10log 1/n $\{\Sigma y^2\}$, where n is the number of experiments and y is data examined.

Analysis of variance (ANOVA)

Analysis of variance was carried out to determine the impact of wear parameters such as normal load applied, sliding distance, wt. % SiC on the wear behavior characterstics like wear rate and frictional force. ANOVA was used to find out statistically significant process variables, which influenced the wear performance of the fabricated composites. The ANOVA results showed that selected process variables are highly significant variables affecting wear behavior of the composite. The percentage contribution of each factor was also determined.

Table 1: Parameters for wear test

Control variables Units	Symbols
Load (L) Newton (N)	A
Sliding distance (SD) Meter (m)	B
Wt. % SiC (% R) %	C

Table 2: Control factors at three levels

Control factors	Level		
	1	2	3
Load (N)	20	30	40
Sliding distance (m)	523	1046	1570
Wt. % SiC (%)	3.5	7	10.5

Table 3: L_9 Taguchi orthogonal array

Sr. No.	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	2
9	3	3	1

RESULTS AND DISCUSSIONS

Microscopic analysis

The optical microscopic images of the various composite specimens are shown in fig. 2 (a), (b) and (c). The microscopic examination was fetched at a magnification power of 100x. The optical images revealed a homogeneous and uniform dispersion of SiC reinforcement particles at all wt. % of SiC reinforcement throughout the aluminum matrix alloy. A uniform SiC particle size was seen right through the al-matrix alloy. The enhanced dual step stir casting technique and selection of suitable process parameters during casting can be imputed to the regular dispersal of SiC reinforcement particles right through the matrix alloy phase. The casting defects such as holes or porosity were not seen during the microscopic analysis. The addition of 10.5 wt. % of SiC reinforcement particles has shown a little amount of agglomeration of particles and was attributed to non homogeneous dispersion of reinforcement particles. The mechanical properties of the composite materials are very much influenced by homogeneous and uniform dispersion of particles into the matrix alloy phase. A sharp increase in the hardness values of resulting composite is attributed to the homogeneous dispersal of SiC particles in the matrix alloy.

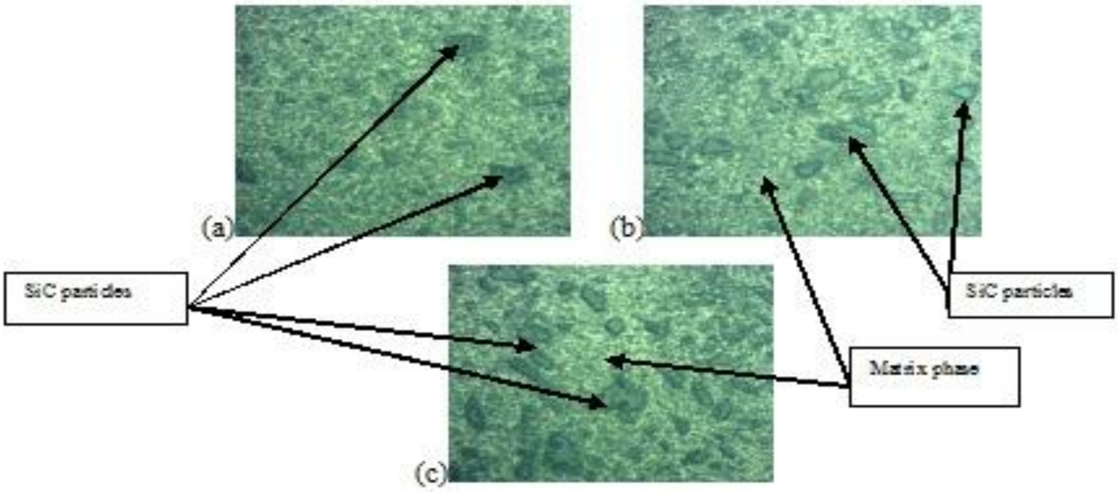

Figure 2: Microscopic images of aluminum matrix composite 6063 reinforced with different wt. % of SiC: (a) 3.5 % (b) 7 % (c) 10.5 %

Microhardness evaluation

Table 4: Vicker's microhardness results for AA6063/SiC composite.

Material	Vicker's Hardness (at load .05Kgf, dwell time= 15sec)
AA6063+0% SiC	54.60
AA6063+3.5% SiC	58.20
AA6063+7% SiC	65.90
AA6063+10.5% SiC	84.10

A graph is plotted between hardness and wt. % SiC as shown in fig. 3 depicts a continuous increase in the microhardness values of the composite specimens. The 10.5 wt. % addition of SiC particles increased the hardness value by 54% as compared to the unreinforced as cast aluminum matrix alloy. The regular and homogeneous dispersion of reinforcement particles into the matrix phase plays a key role in increasing the hardness values of the reinforced composite materials.

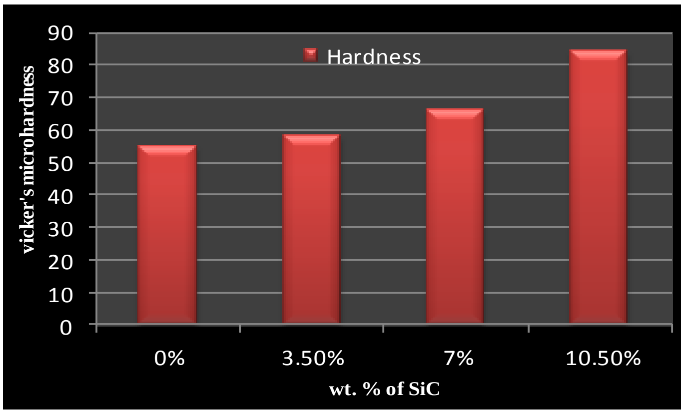

Figure 3: vicker's microhardness versus wt. % SiC

Dry sliding pin-on –disc Wear analysis

The main aim of this study was to minimize the wear rate and frictional force for AA6063-SiC matrix composite using taguchi optimization approach. The taguchi design of experiment was executed using MINITAB 17 software. An experimental layout was drafted using taguchi optimization approach and L_9 orthogonal array by considering all possible set of control parameters and their corresponding levels before analyzing the behavior of composite specimens. The observed wear rate and frictional force data of SiC reinforced AA6063 matrix composite and corresponding S/N ratio is depicted in table 5.

Table 5: The S/N ratios for wear rate (WR) and frictional force (FF)

Sr. No.	A	B	C	Wear Rate (WR)	Frictional Force (FF)	S/N ratios (WR)	S/N ratios (FF)
1	20	523	3.5	11.030	12.01	-20.8515	-21.5905
2	20	1046	7.0	4.486	3.56	-13.0372	-11.0290
3	20	1570	10.5	2.830	2.15	-9.0357	-6.6488
4	30	523	7.0	9.311	4.15	-19.3799	-12.3610
5	30	1046	10.5	5.194	8.17	-14.3100	-18.2444
6	30	1570	3.5	5.340	13.22	-14.5508	-22.4246
7	40	523	10.5	10.016	17.56	-20.0139	-24.8905
8	40	1046	3.5	7.580	19.05	-17.5934	-25.2879
9	40	1570	7.0	5.427	6.61	-14.6112	-16.4040

The mean of S/N ratio and rank based on delta value for each level of the control parameters is presented in table 6. It is obvious from the response table that rank 1 is given to the factor with highest delta value and rank 2 is given to the factor with second highest delta value and so on. The factor sliding distance in this case has the highest delta value and rank 1 is given to sliding distance. Rank 2 is given to the factor wt. % SiC and rank 3 is given to the factor load applied. From the delta based rank analysis it is apparent that sliding distance is the most significant factor for wear performance of AA6063/SiC composite proceeded by wt. % SiC and load applied. The optimal level for minimum wear can be established as A1B3C3. The main effects plot for S/N ratio for wear rate is shown in fig. 4.

Table 6: Response table for wear rate (smaller-is-better)

Level	A	B	C
1	-14.31	-20.08	-17.67
2	-16.08	-14.98	-15.70
3	-17.43	-12.76	-14.45
Delta	3.12	7.32	3.21
Rank	3	1	2

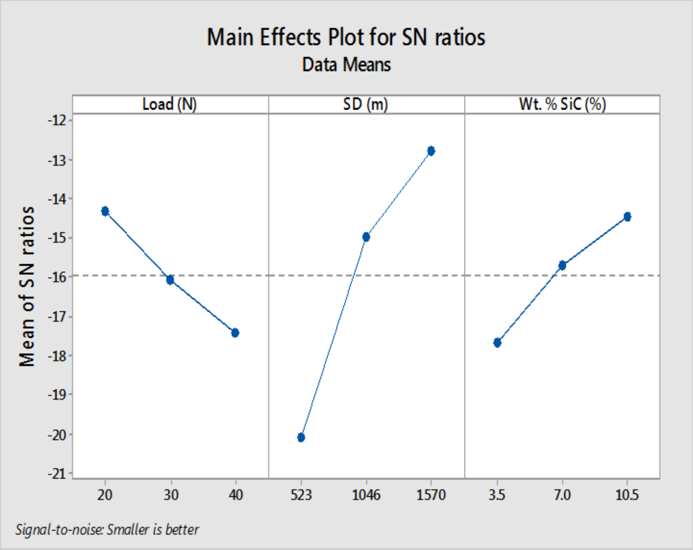

Figure 4: Main effects plot for S/N ratios (wear rate)

From the response table 7 it is evident that wt. % SiC with highest delta value is the most significant factor in minimizing the frictional force followed by applied load and sliding distance. The optimum order for minimum frictional force can be assigned as A1B3C2, ie., the lowest level of load applied, highest level of sliding distance and medium level of wt. % of SiC. The main effects plot for S/N ratio for wear rate is shown in fig. 5.

Table 7: Response table for frictional force (smaller-is-better)

Level	A	B	C
1	-13.09	-19.61	-23.20
2	-17.68	-18.29	-13.26
3	-22.30	-15.16	-16.59
Delta	9.21	4.45	9.94
Rank	2	3	1

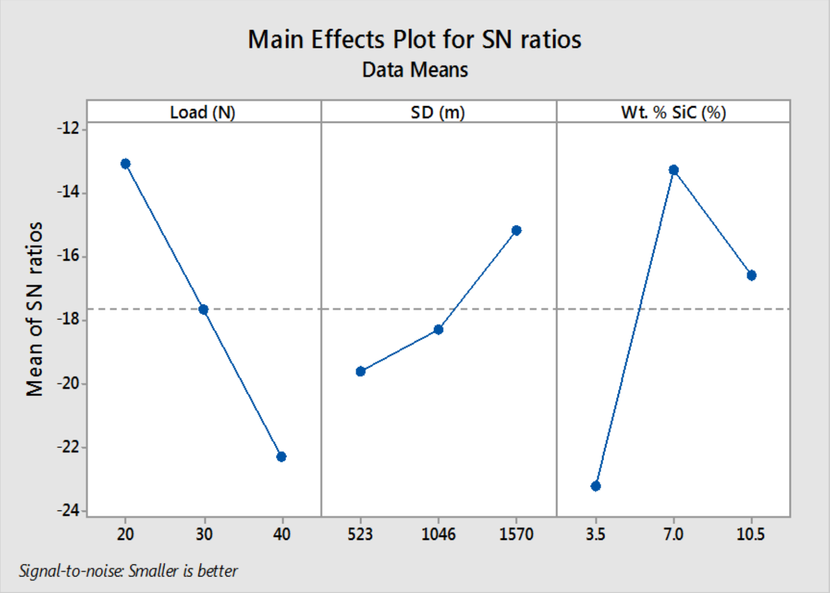

Figure 5: Main effects plot for S/N ratios (frictional force)

Analysis of variance (ANOVA)

ANOVA (analysis of variance) has been performed to establish the process factors that are statistically significant based on experimental data. The main aim of ANOVA is to determine the effect of particular parameters on the output response factor. ANOVA results in table 8 and table 9 showed clearly the effect of each parameter on wear rate and frictional force respectively. The F-test has been carried out to indicate which process factors have a significant impact on wear behavior. Larger F-value designates that alteration of process factor makes a significant change on the behavior characterstics. The F- values in table 8 justified that for minimum wear rate sliding distance (SD) is the most significant factor with 82.34 % contribution followed by wt. % SiC (%R) with 8.37 % contribution and load (L) with 4.88 % contribution. The sliding distance (SD) has the highest impact on wear rate of the casted Al-SiC matrix composites. Table 9 clearly showed that for minimum frictional force the factor wt. % SiC is the most significant factor and contributing 49.31 % towards the output response frictional force under investigation followed by load applied with 37.39 % contribution and sliding distance contributing 8.17 %.

Table 8: ANOVA results for wear rate (x10^{-3}mm^3/m)

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	% Contribution
L	2	3.8023	3.8023	1.9012	4.88	6.04
SD	2	51.7607	51.7607	25.8804	66.44	82.34
% R	2	6.5183	6.5183	3.2592	8.37	10.36
Error	2	0.7791	0.7791	0.3896	1.23	
Total	8	62.8605				100

Table 9: ANOVA results for frictional force

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	% Contribution
L	2	113.78	113.78	56.88	7.32	37.39
SD	2	24.88	24.88	12.940	1.60	8.17
% R	2	150.05	150.05	75.024	9.65	49.31
Error	2	15.54	15.54	7.772	5.10	
Total	8	304.25			100	

CONCLUSIONS

In this investigation, tests were conducted to examine wear performance and frictional force of SiC reinforced AA6063 matrix composite under various levels of applied load, sliding distance and %age reinforcement using taguchi optimization approach. The analysis of variance was also performed to find out the most significant factor which influences the wear performance of the composite material. The experimental investigation reached to the following conclusions. (i) Wear performances of the composite material have been successfully examined by Taguchi optimization approach using software MINITAB 17. The optimal level of control parameters and the significant control parameters influencing the wear performance and frictional force has been determined by this approach. (ii) It was analyzed that factor sliding distance (SD) is the most significant factor influencing the wear rate at a confidence level of 95% and contributing 82.34% towards the response factor under investigation, while factors wt. % SiC (%R) and load applied (L) has very small contribution towards the response factor wear rate. (iii) The ANOVA performed for response factor frictional force showed that the percentage of reinforcement (wt. % SiC) is the highly significant factor which influences the frictional force with 49.31 % contribution followed by 37.39 % contribution of load applied towards the response characteristic. The sliding distance (SD) has a mere contribution towards the response factor under study. (iv) The optical microscopic examination revealed a regular and homogeneous dispersion of SiC reinforcement particles into the matrix alloy for all wt. % variations. (v) The vicker's microhardness examination exhibited that there is a continuous increase in the micro hardness values and the hardness for 10.5 wt. % addition matrix composite is increased (from 54.6HV to 84.1HV) by 54% as compared to the unreinforced al-alloy matrix.

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