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Statistical Analysis on Wear Behavior of Aluminum Alloy2024–Silicon Carbide–Fly Ash Metal Matrix Composites

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Abstract

Aluminum and its alloys entered a main role in the engineering sectors because of their applicable characteristics for indispensable applications. To enhance requisite belongings for the components, the composition of variant metal/nonmetal with light metal alloys is essential in the manufacturing industries. To enhance the wear resistance with significant strength property of the aluminum alloy 2024, the reinforcement SiC and fly ash (FA) were added with the designation Al2024 + 10% SiC; Al2024 + 5% SiC + 5% FA; and Al2024 + 10% FA via stir-casting technique. The wear resistance property of the composites was tested in pin-on-disc with a dry-sliding wear test procedure. The experiment trials were designed in Box–Behnken design (BBD) by differing the wear test parameters like % of reinforcement, sliding distance (m), and load (N). The wear tests on casted samples were carried out at the constant velocity of 2 m/sec, such that the corresponding wear rate for the experiment trials was recorded. Analysis of variance (ANOVA) determined that the Al2024 + 5% SiC + 5% FA, sliding distance 700 m, and load 30 N is the favorable to improve the wear-resisting property of the aluminum alloy hybrid composites. The distance of the composites traveled implies a significant contribution to wear rate with the follow of reinforcement composition rate and external load. The dynamic components are fabricated as hybrid composites directed to operate with this limit of wear-generating parameters.

Keywords

Aluminum alloy, Silicon carbide, Metal matrix composite, Fly ash

Introduction

Aluminum alloys are important to light metal alloys mostly used in industries because of their favorable characteristics for the engineering components. To enrich aluminum alloy properties to the situation of utilization, aluminum alloy-based composites have been developed in industries in numerous categories. SiC, Al_2O_3, B_4C, organic materials, natural ingredients, and the like are added to aluminum alloy as reinforcements. When different reinforcements (continuous, discontinuous whiskers, etc.) are mixed with light metal alloys, the base metal mechanical, chemical, and thermal characteristics have been improved significantly.

Composites have two phases: matrix (continuous phase) and reinforcement (discontinuous phase). The ceramic metals or polymers are used as matrix compounds and for the reinforcement phase fibers and particles are used. The harder phase discontinuous reinforcements are preferred to improve the wear resistance, and the soft reinforcements like Gr and Mo have self-lubricating characteristics, and reduce the wear rate of the contacting surfaces. The composite belongings are based on the matrix and reinforcements, the matrix grips the reinforcements to extract the preferred geometrical surface on the components. At high temperatures, the composite elements do not retort with other elements; it leads to the early failure of the composites. The fabrication of composites with advanced materials is under the name of metal matrix composites (MMCs). To enhance wear resistance in addition to the mechanical and thermal characteristics of the composites, the MMCs have been preferred scientifically in the industries [1].

The sliding contact mechanical parts lose their life cycle spell and lead to high energy consumption because of the friction phenomena addressed at the contacting surface of the contacting elements. The aluminum alloys with series 1xxx-7xxx enroll better utilization in engineering sectors. From the pin-on-disc wear test observation, it has been noticed that the Al2024 alloy reveals better results on wear loss compared with Al2021 and Al2014 [2]. The composition of SiC, B_4C, and Al_2O_3 improves the mechanical properties of the composites; however, the SiC enhances better results on the wear resistance of the composites [3]. The nano-reinforcement materials such as nano-graphite, titanium diboride (TiB_2), and silicon nitride (Si_3N_4) are suitable for the composites preparation. The nano-graphite and TiB_2 reinforcements are improving the wear resistance property of matrix AA2219 [4]. The hybrid metal matrix composite (HMMC) Al7075/B_4C (8 wt.%)/FA (2 wt.%) behaves with deep plowing grooves, fine debris, and shallow defects are present in the worn-out surface of the HMMC; however, it has remarkable wear resistance capacity under the variable load conditions [5].

The nanohybrid composites Al6061-10TiB2, Al6061-10TiB2-2Gr, and Al6061-10TiB2-4Gr fabricated through powder metallurgy process (PMP) have the improvement in their hardness and resisting properties according to the percentage of reinforcement composition [6]. The MMC of AZ61/ZrO_2/SiC fabricated with the friction stir consolidation (FSC) technique embraces good mechanical properties. Under the wear test conditions of 350 m sliding distance, 240 rpm speed, and 20 N load loss the material due to the friction erosion only 0.008 mg/m, which reveals a significant result of the test parameters. The optimal status specimen while involved in thermogravimetric analysis (TGA), the weight loss concerning temperature, and time was acceptable range, which means the MMC fabricated through FSC enroll is fit for the high-temperature environment services [7]. The aluminum composite LM25/SiC/Cu compresses the wear loss due to the particle size of the reinforcement present in the composites. To maintain accuracy on the wear test observations, the pin-on-disc equipment was used at the ASTM G99-95 (2010) standard test procedures. The wear test apparatus has a rotating disc counterpart, which is made from EN-31 steel with a hardness of 62 HRC [8].

Different mechanisms are involved in the wear behavior of whichever materials, like adhesion, abrasion, thermal softening, oxidation, and melting. Scanning electron microscopy (SEM) images are valuable evidence to identify the wear failures on the rubbed surfaces. The aluminum alloy 6021 was accounted for by the abrasive wear behavior on its crashed regions [9]. The wear behavior test observations of the composite Al–Al_2O_3–TiO_2 define that the lubricating characteristics of the TiO_2 reinforcement minimize the wear rate compared to addressing Al_2O_3 reinforcement. The base metal has a high intensity of wear behaviors compared to composites [10].

The discontinuous reinforcement composite Al6061-T6 + SiC + Al_2O_3 with 15% reinforcement implies superior behavior on wear resistance characteristics. Both the ductile and brittle fractures are indicated in the worn-out surface [11]. The liquid metallurgical routes of gravity die-casting, stir casting, and stir-squeeze casting are used to fabricate aluminum alloy A356 and composite (A356 + 20% of SiC) castings. The hardness of the stir-squeeze cast Al356 + 20% SiC composites ensures it's about 11%–27.5% compared to other fabrication methods of casting. The ultimate tensile strength improvement of the composite is revealed in the range of 9.96% to 22.65% concerning other castings, similarly the squeeze cast composite records a low wear rate during the tribological testing with a load range of 10–40 N [12].

The squeezing pressure dissipates a large amount of heat during the solidification duration of the liquid forging casting process. It reveals better hardness as well as ductility on the squeeze castings. The Al–Si–Cu alloy castings produced at the optimal squeeze pressure enhance remarkable tensile and wear resistance properties [13]. The composite of AA6026 + La_2O_3 fabricated in the stir-casting method derives a remarkable range of wear resistance because of the particulate reinforcement in the composites. The A6063 + Al_2O_3 + B_4C fabricated in a stir-casting route with a stability composition of 5% of Al_2O_3 defines that the increment of B_4C improves the mechanical and tribological characteristics of the composites [14, 15].

The study of stir-squeeze cast composites A356 + 2.5% SiC with 5% and 10% FA exhibits notable improvement in tensile properties and wear resistance characteristics. The 10% FA composite exhibits a low-level wear rate at the tribological test parameters of 10 N load and 1000 m sliding distance. This property enhancement in these composites is suitable for the components used in the environment of sliding contact in the automotive and other engineering sectors [16]. Mg is a light metal alloy with minimal hardness and wear resistance properties. Hence, there is a need to enhance these properties in Mg to enrich its serviceability in the engineering sectors. The composition of SiC at the right percentage with Mg as reinforcement eliminates this limitation. The ball milling method was followed to prepare the alloying components, and then the milled powder composition was produced as a green compact in the hydraulic press with a load of MPa. The green compacts were sintered in the furnace at the hotness of 550°C for about 2 hours. The MMC Mg + SiC synthesized PMP with 2% reinforcement addresses better results on hardness and wear resistance [17].

The aluminum composite Al 6061/6% Al_2O_3/4% SiC attains better wear resistance compared to composites Al 6061/12% Al_2O_3/8% SiC and Al 6061/18% Al_2O_3/12% SiC. The low wear rate recorded in composites with the addition of SiC remarkably in the automobile components [18]. The aluminum-based hybrid composite with groundnut shell ash and B_4C as reinforcement fabricated in the liquid forging process accomplices the mechanical properties and tribological property improvement. The low-cost composites produce a better result with Al-2.5 GSA-7.5 B_4C for industrial applications [19].

To investigate proper experiment designing is important, the experiment variables considered from the experience and other non-recognized data direct an invalid experiment trial process. Taguchi method DOE and RSM-based randomized experiment design are favored to obtain healthier results in research studies. Taguchi L_{27} orthogonal array produces inherent compositions with experiment input variables in tribological behavior analysis of LM26/SiC/B_4C composites [20]. The statistical optimization techniques Taguchi method, RSM, genetic algorithm (GA), grey relational analysis (GRA), artificial neural network (ANN), fuzzy logic, and the like have been in the drive to analyze the different process parameters to optimize the solution of the process with less calculation duration and cost consumption.

The introduction of FA as reinforcement with light metal alloys is of limited importance in deriving the quality characteristics of the composites. The fabrication of composites with less weight and production cost is essential for the interest of industries. FA is a reasonably priced reinforcement and in large-scale availability ensures the attention of the composites, component producers. It is the by-product of the combustion of coal in thermal power plants. Nowadays about 900 million tons of FA have been produced for the various applications of civilians [21, 22, 23, 24, 25].

From the previous articles, it has been observed that mostly Taguchi-based optimization analysis is used for the characteristics analysis of aluminum alloy-based composites. RSM-based Box–Behnken is an experiment design method to achieve better results with the potential interactions between parameters and also time-saving by reducing the number of trials. In this study, the most available reinforcement elements SiC of size 45–70 μm and C-type FA of 40–100 μm are used to fabricate the Al2024/SiC/FA composites in liquid metallurgical route of stir-casting method. The variant wt.% of composition with aluminum matrix and the tribological behavior of the composites have been analyzed in the statistical optimization approach of RSM. The RSM, Box–Behnken design (BBD) method is followed to design the wear test experiments with 12 trials. The fabricated composites are involved in the wear test experiment observation, the results of the experiment observation were analyzed in Design Expert software 11. The improvement of wear resistance because of the SiC and FA reinforcements with the Al2024 will be found through experimental and statistical analysis. The variation between the optimal functional parameters setting wear rate and predicted wear rate has been evaluated to justify the result of optimal process parameter setting out of the assigned factor levels.

Materials and Methods

Material

Aluminum alloy grade 2024 is used as a matrix component to fabricate the composites. The materials available in the market of silicon carbide (SiC) of size 45–70 μm and FA of C-type with size 40–100 μm are considered as reinforcement to enhance the characteristics of the composites [26].

Stir-Casting Process

The stir-casting process is a simple method to produce composites with limited cost of manufacturing. The liquid phase of the matrix and reinforcement phases are mixed using the stirrer rotation speed of the stirrer blades. The electric prime mover, which is integrated with the stirrer spindle, regulates the speed of the rotating blades to the desired level. The blades are arranged in single steps or in multiple steps to expand the mixing action in the molten metal. The desired quantity of powder from SiC and FA was preheated at about 300°C for 3 hours. The aluminum alloy 2024 is melted in the induction furnace at 750°C, the argon gas is supplied inside the molten metal for degassing process. Now, the preheated reinforcements were transferred to the crucible and the liquid state of the composite was stirred at 300 rpm for 10 minutes. The vortex flow of reinforcement with the stirrer speed 300 rpm improves the inclusion of the reinforcements with the matrix. The Mg is added to the composite to increase the wettability of the composites. The vortex rotation of the stirrer blade and the dispersion of the reinforcement were achieved. The molten temperature was maintained above 700°C to maintain the fluidity of the molten metal. The liquid phase of composite material is transferred to the metal mold and solidified until gains in the solid phase. The same procedure was followed to fabricate other samples with the desired weight percentage of composites.

Wear Test

The composites fabricated in the stir-casting process are machined for the wear test samples as per the ASTM G99-95 were followed to conduct the wear test. The wear test specimens were preferred with the dimension of ϕ10 × 25 mm. The tribological wear test input factors are type of composite, sliding distance (SD), and load. These experiment input variables are preferred based on the earlier research works and industrial practice for the aluminum

TABLE 1 Wear test parameters and levels (constant velocity: 2 m/sec).

Factors	Code	Level 1	Level 2	Level 3
Composite (%)	A	Al2024/10% SiC	Al2024/5% SiC/5% FA	Al2024/10% FA
Sliding distance (m)	B	400	700	1000
Load (N)	C	20	30	40

alloy composites. The velocity of the disc is considered 2 m/sec to the 12 wear test experiments (Table 1).

The DUCON pin-on-disc apparatus (Model ED-201) is used to conduct the wear test on stir-cast composites. The EN-31 steel disc with 62 HRC, specimen holder, load carrier, and lubrication supply unit are assembled to perform the wear test efficiently. The initial weight of the specimen was measured using an electronic weighing machine with 1×10^{-4} g least count. To conduct the wear test, the specimen was held in the pin holder in the direction perpendicular to the rotating disc. Figure 1 shows the pin-on-disc apparatus with its accessories and test specimens.

The assigned value of the load is placed on the arm integrated with the strain gauge. The specimen was pressed on the counter disc at the time of the desired rpm, and the track distance was maintained by increasing the speed of the counter rotation. After the track distance of rotation of the specimen, it is unloaded from the holder and cleaned and the weight is lost by measuring in the weighing machine. Also, the wear loss induced in the specimen in the geometrical dimension was measured from the data acquisition system available with the pin-on-disc. The length reduction in the specimen due to the frictional force induced at the contact surface of the test piece and the rotating counter disc was counted from the data acquisition system with the unit "μm" [27, 28]. The experiment trials repeated for 12 samples, and two samples were tested for each trial parameter setting such that the average value for the two trials is given in Table 2 for the corresponding functional parameters.

TABLE 2 Average value of wear for each trial parameter and level setting

	Factors			Response
Ex. no.	A: Composite %	B: Distance (m)	C: Load (N)	Average value of wear (μm)
1	1	700	40	138.85
2	3	700	20	79.68
3	2	1000	20	132.87
4	3	700	40	164.87
5	1	400	30	48.62
6	3	400	30	63.56
7	1	700	20	68.75
8	2	1000	40	205.62
9	1	1000	30	160.24
10	3	1000	30	180.36
11	2	400	20	48.65
12	2	400	40	92.68

Discussions on Results

The observed experiment results were imported to the experiment array table available in the Design Expert 11 software. By assigning RSM statistical analysis; the optimal parameters to reduce the wear rate in the specimen were determined. The experiment results and predicted values are related to the mean value of the composition, hence the R^2 value is 0.968. It means that the model formed in the statistical calculation is significant and it produces optimal results for each level of the parameter settings. Figure 2 declares the scarcity of the predicted values concerning the mean value of the experiment results.

FIGURE 1 (a) Pin-on-disc apparatus and (b) wear test specimens.

(a) Pin-on-disk apparatus (b) Wear test specimens

FIGURE 2 Predicted values vs. experimental values.

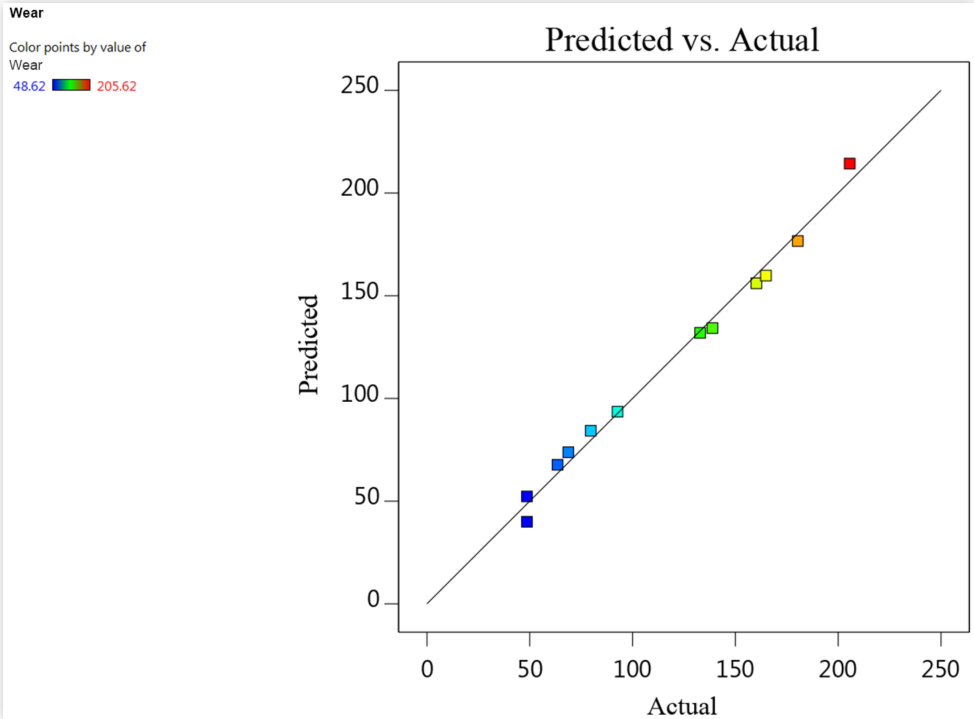


Table 3 gives the information related to the ANOVA calculation related to the input variables and output responses of the wear test experiments. A linear equation was developed for the parameter interaction, however, which alias to the quadratic equation. Hence the quadratic equation was preferred to advance the result with the interaction of square values of the input variables.

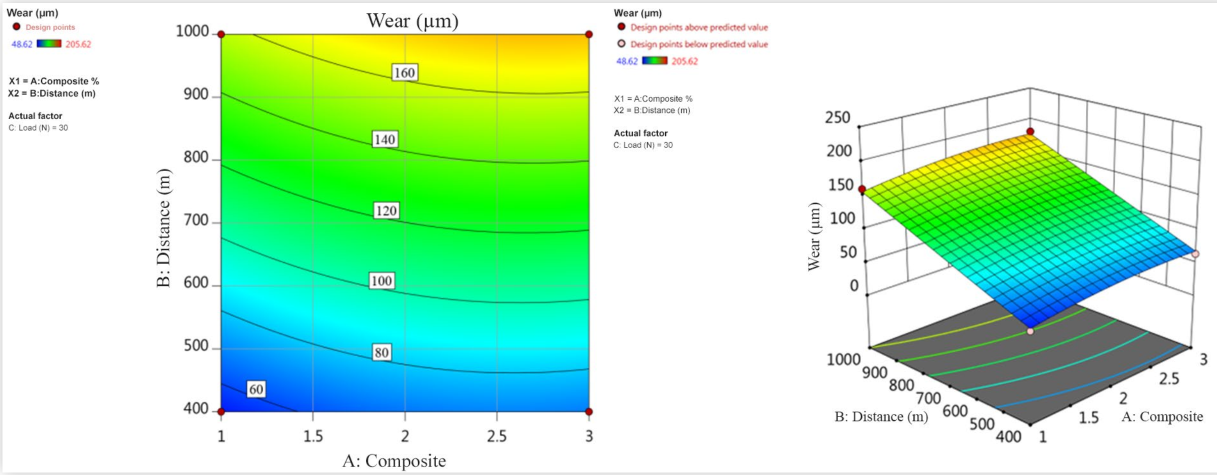
The regression model has an F-value of 40.10, which indicates that the model generated is significant for all ranges of assigned input variables. A p-value less than 0.05 represents a significant effect of each input factor on the results. The p-value larger than one defines that the equation terms are not significant. The fit statistics is mentioned as R^2 value is 0.9907; it means there is less chance to generate noise factors in this analysis. The agreement of predicted R^2 (0.8518) with adjusted R^2 (0.9666) leads better solution on statistical analysis of the problem. **The wear rate on aluminum-based nanocomposites is mostly influenced by the load and percentage of SiC; however, the SD influences the wear rate of the part comparing other parameters** [29, 30].

Figure 3 represents the variation of wear rate concerning composite type and SD. In the contour plot, the variation of response with the interaction of two input factors is given as 2D. This is the possibility to avoid the maximum wear rate by assigning the composite with 5%–10% of SiC and FA reinforcement with the base metal Al2024, such that the SD is at a level of 400 to 600 m. The modulation of composites is described in the surface plot in the third-dimensional axis. The three types of composites maintain a low-level wear rate with a SD

TABLE 3 ANOVA for wear.

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	32,935.34	8	4116.92	40.10	0.0058	Significant
A—Composite %	648.18	1	648.18	6.31	0.0867	
B—Distance (m)	22,639.79	1	22,639.79	220.54	0.0007	
C—Load (N)	9252.76	1	9252.76	90.13	0.0025	
AB	6.71	1	6.71	0.0653	0.8148	
AC	56.93	1	56.93	0.5545	0.5105	
BC	206.21	1	206.21	2.01	0.2514	
A^2	91.40	1	91.40	0.8903	0.4150	
B^2	0.0496	1	0.0496	0.0005	0.9838	
C^2	0.0000	0				
Residual	307.97	3	102.66			
Cor total	33,243.32	11				

FIGURE 3 Contour plot – surface plot (composite vs distance).



range of 400–700 m; however, the SD increased the wear rate on the composites.

Figure 4 represents the variation of wear rate concerning composite type and load applied. The wear rate of the composites is limited up to application load level 25 N for all types of composites. The increasing external load develops wear formation in the composites.

Figure 5 represents the wear rate variation for the SD and load. The maximum wear formed in all types of composites at 1000 m SD with the load application 30–40 N. There is a safety level of process parameters to minimize the wear rate on the composites; such as 400–700 m of SD for the three categories of composites. The ANOVA statistical calculation defines the point of optimal level for the input parameters such as Al2024 + 5% of SiC + 5% of FA composite, 700 m SD, and 30 N load predicts the wear rate 119.797 μm. The confirmation test was conducted for these optimal parameter settings and the actual output result (wear rate: 122.52 μm) correlated with predicted results. The error between actual and predicted results is 2.2% since the predicted values have better agreement with the experiment values. The linear interaction of the input variables' regression model is limited to predicting the solutions. The aliased quadratic model has been considered as a regression equation; in this model, the coded variables are considered to evaluate the optimal response value. The factor that has the larger F-value in ANOVA calculation produces the most significant effect on the response. In this, the SD contributes a significant effect on wear rate with the followers of load and composite category. To anticipate the ideal process parameters that deviate from the assigned level of factors, the RSM-desirability approach is employed in conjunction with ANOVA data (table 3) to obtain optimal process parameter result. In this, 100 solutions are arrived at by interpolating the level of parameters and the best result is shown with the desirability value of 1. The optimal parameters were identified in the desirability approach as Al2024 + 5% of SiC + 5% of FA composite, 440 m SD, and 20 N load with a wear rate of 43.35 μm. The elements present in the composites imply the best role to reduce the wear loss in the composite elements [31, 32]. Figure 6 shows the bar chart for the desirability value of individual factors and overall desirability value.

FIGURE 4 Contour plot – surface plot (composite vs load).

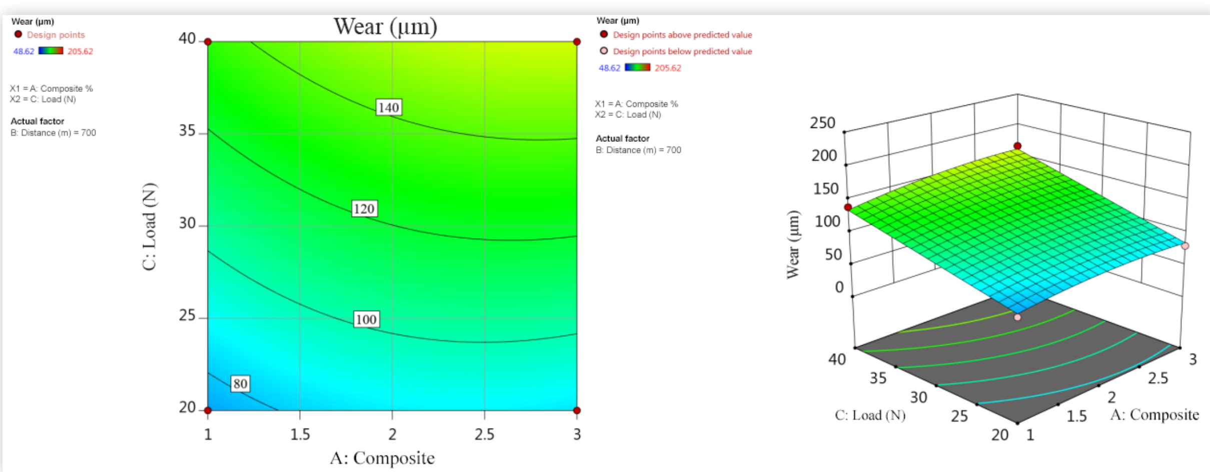


FIGURE 5 Contour plot – surface plot (distance vs load).

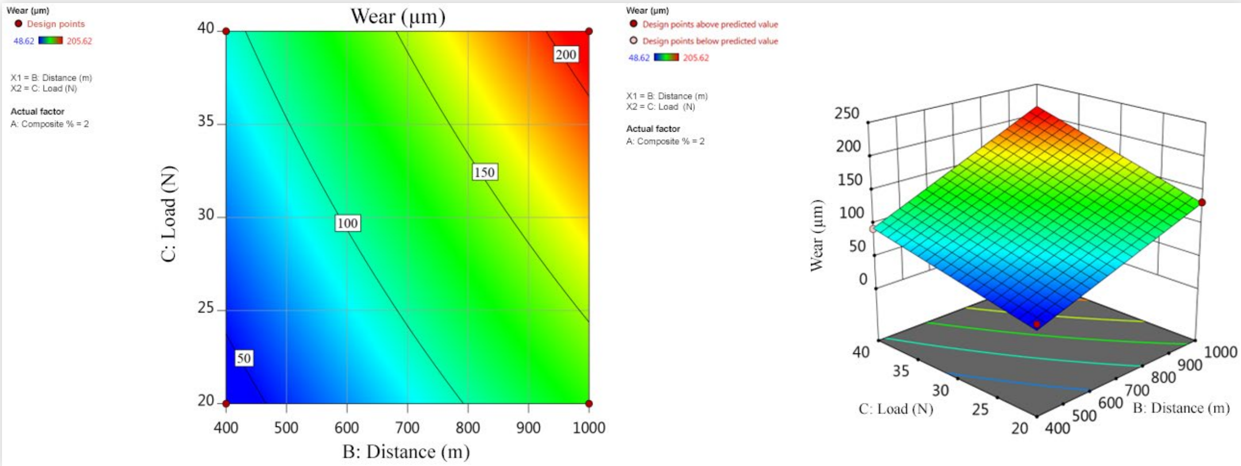
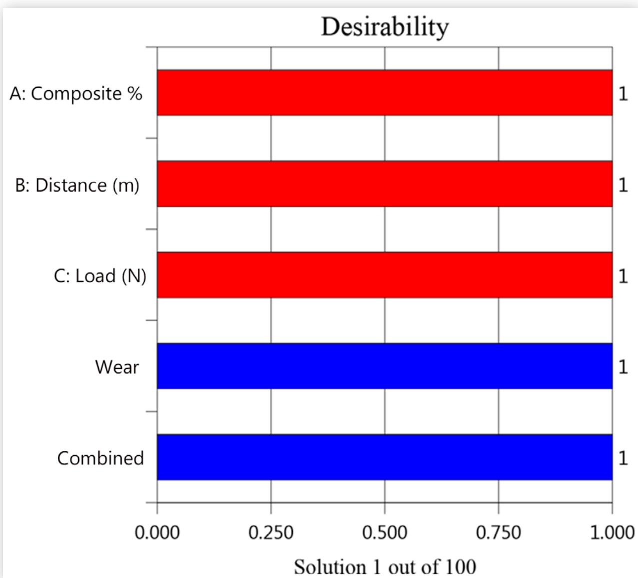


FIGURE 6 Bar chart—desirability.



The desirability value for the individual optimal level of input factors and output responses are one, it means the predicted level of input variables able to produce better results on output responses; however, the multi-objective solution of combined optimal parameters setting also produces better results on wear resistance of the aluminum composites.

Validation Tests

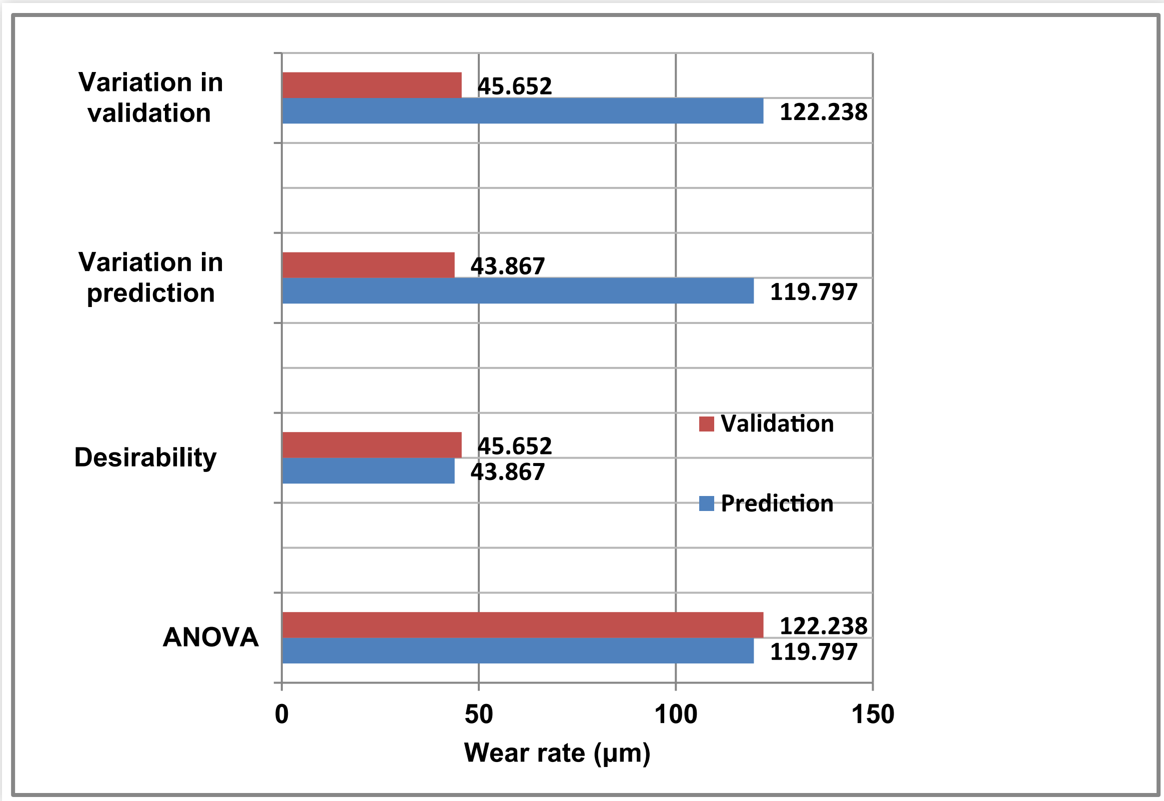
The confirmation test for the predicted optimal parameters level through ANOVA and desirability approach was performed, such that the actual validation experiment values are compared with the predicted response values. The validation test was conducted with two samples for each predicted range of process parameters. The graph represents the variation of predicted and validated response values. The predicted level of input variables in ANOVA statistical calculation is Al2024 + 5% of SiC + 5% of FA composite, 700 m SD, and 30 N load and corresponding wear rate 119.797 µm. Similarly, from the desirability approach, the predicted parameters are Al2024 + 5% of SiC + 5% of FA composite, 440 m SD, and 20 N load with a wear rate of 43.35 µm.

The confirmation test for both optimization approaches predicted the level of parameters performed and the corresponding wear rate is given in Figure 7.

Conclusions

The hybrid aluminum composites with the composition of SiC and FA were fabricated in stir-casting technique. The fabricated composites are Al2024/10% SiC, Al2024/5% SiC/5% FA, and Al2024/10% FA. RSM–Box–Behnken method was followed to design the experiment trials for the wear test with a level of parameters like SD: 400, 700, and 1000 m and load: 20, 30, and 40 N. The velocity was taken as 2 m/sec constantly for the application of 12 trials. For each parameter setting two samples were tested and the corresponding wear rate accumulated as a geometrical variation on test composites. Design Expert Software 11 used to execute the ANOVA calculation and desirability analysis. The Al2024/5% SiC/5% FA composite, 700 m SD, and 20 N load are the optimal parameters predicted in ANOVA, whereas the Al2024/5% SiC/5% FA composite, 440 m SD, and 20 N load are optimal parameters in the desirability approach from 100 solutions of the result. The wear resistance characteristics improved with the addition of reinforcement with Al2024 is 57.66%—84.42 by the ANOVA and desirability approaches compared to the base metal of Al2024. The desirability approach result signifies a 62.653% improvement in wear resistance characteristics of the Al2024/5% SiC/5% FA composite. Among three composites each 5% of SiC and FA reinforcements attain better results on wear loss. This composite is favorable to fabricate lightweight components that need wear resistance.

FIGURE 7 Prediction vs validation.



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