Dry Sliding Wear behaviour of cast Al/Al$_2$0$_3$/Gr hybrid nano-composite using response surface methodology

I. Manivannan[1], S. Ranganathan[2], S. Gopalakannan[3], S. Suresh[4]

[1]Department of Mechanical Engineering, Motilal Nehru Government polytechnic college, Puducherry, 605008, India.Tel.: +91 9443483684.
[2]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha University, Chennai-602 105, Tamilnadu, India. Tel.: +91 9787415094.
[3]Department of Mechanical Engineering, Adhiparasakthi Engineering College, Melmaruvathur 603 319,TamilNadu, India. Tel.: +91 9944949026.
[4]Department of Mechanical Engineering, University College of Engineering, Nagercoil, Tamilnadu, India, Pin: 629 004. Tel.: +91 9443494576.

E-mail: i.manivannan72@gmail.com.,ranganathan@saveetha.com

Abstract. The newly engineered metal matrix nanocomposite (MMNC) of Al 6061 reinforced with 1.2 wt % Al203 and 0.5 wt % Gr (Al-1.2Al203-0.5Gr) hybrid nanocomposite was prepared by ultrasonic assisted stir casting method. A three-level central composite design test was developed using response surface methodology; parameters such as load, velocity and sliding distance were varied in the range of 10-30 N, 0.4-1.1 m/s and 500–1500 m, respectively. Dry sliding wear tests were performed as per the experimental design using a pin-on disc setup at room temperature. Analysis of variance (Anova) was applied to investigate the influence of process parameters and their interactions viz., Load, velocity, sliding distance on wear, and coefficient of friction (COF). The aim of the study was to identify the process parameters that significantly affect the output features. Further, a mathematical model has been formulated by applying response surface method in order to estimate the tribology characteristics such as wear and COF of the hybrid nanocomposites.

1. Introduction

The Al/Al203/Gr hybrid nanocomposites find wide application in advanced engineered materials due to its tribological applications. When the reinforcement particles are of micro size they improve the strength of the materials, but the ductility of the micro composites weakens when the percentage of reinforcement increases. For less quantity of particulates the mechanical and tribological properties of nano particle dispersion strengthened metal matrix composites are far superior to those of their micro particle composites. Aluminum composites reinforced with nano-particles, strengthen the metal matrix and maintain good ductility compared to micro particles [1-4]. The scope of Al-Al203-Gr nano-composites is of great interest for tribological applications in automotive, aerospace industries including engine valves, cylinder liners. The usage of aluminum hybrid self-lubricating nanocomposite components leads to reduce the oil consumption, power loss and maintenance cost [5]. The present work is envisaged to develop a mathematical model and analyze the effects of tribology parameters on the performance characteristics of MMNC using response surface methodology (RSM)[6-10]. Accordingly, the quantitative mathematical models have been carried out to study influence of process parameters viz., load, velocity and sliding distance and their interactions on wear and coefficient of friction (COF) by using RSM.

2. Experimental Details

2.1 Ultrasonic assisted stir casting method.

The material used in the present investigation for the preparation ofAl-1.2Al$_2$0$_3$-0.5Gr hybrid nanocompositeconsists of Aluminium 6061 as the base matrix alloy. Its chemical composition (%)

isMg-0.5, Fe- 0.17, Si- 0.2, Cu-0.2, Cr-0.3, Ag-0.4 and Al6061 remaining balance. Nano-Al_2O_3 particles supplied by US Research Nano materials, Inc. USA, with an average size of 50 *nm* and graphite ≤ 20 *μm* supplied by Sigma Aldrich are used for hybrid nano-composite fabrication.The hybrid nanocomposites were cast using ultrasonic assisted stir casting method as it ensures uniform distribution of the reinforcement[9].

2.2 Design of Experiments.

In the present study the experiments were designed based on central composite design (CCD) of response surface method.The factorial portion of CCD is a full factorialdesign with all combination of the factors at two levels (high, +1, and low, -1). The "face-centered CCD" involves 20 experimental observations at three independent input variables [4]. The experimental design layout that was adopted in this study in the actual form is shown in Table 1.

Table. 1 Design matrix and experimental results

Ex.No	Load(N)	Sliding speed(*m/sec*)	Sliding distance(*m*)	Specific wear rate(SWR)10^{-7}*g/Nm*	Coefficient of Friction(CO*F*)
1	10	0.4	500	3.41	0.293
8	30	1.1	1500	1.06	0.211
12	20	1.33	1000	0.86	0.243
5	10	0.4	1500	2.75	0.273
15	20	0.75	1000	1.55	0.252
17	20	0.75	1000	1.55	0.253
16	20	0.75	1000	1.54	0.254
4	30	1.1	500	0.72	0.233
9	10	0.75	1000	2.11	0.272
20	20	0.75	1000	1.55	0.252
10	40	0.75	1000	0.85	0.221
19	20	0.75	1000	1.55	0.252
3	10	1.1	500	1.42	0.276
7	10	1.1	1500	1.08	0.257
18	20	0.75	1000	1.56	0.252
13	20	0.75	200	1.74	0.265
14	20	0.75	1900	1.93	0.241
2	30	0.4	500	1.82	0.243
11	20	0.16	1000	2.05	0.252
6	30	0.4	1500	1.43	0.224

3. Experimental Procedure.

The wear behaviour of the Al-1.2Al_2O_3-0.5Gr hybrid nano-composites samples under dry sliding condition were investigated using a pin-on-disc wear test machine (TR-20-PHM-M1 DUCOM), according to ASTM G99 standard. The wear tests were performed using cast hybrid nanocomposite pins on a hard steel disc of 62HRC under dry sliding condition. The conventional grinding and polishing techniques were used for surface preparation of cylindrical pin and disc surface. The sample of cylindrical pin and disc surface were polished down to 0.15μm with emery papers of 1000 and 1200 grid size. The applied load for the nano-composite pins were of 10–30 N. The sliding distance of 500, 1000 and 1500 m was employed, with sliding speed of 0.4, 0.75, 1.1 m/s. The dimensions of the wear test pins are of diameter 10 *mm* and height 20 *mm*. The sliding path on the disc surface was 25 mm diameter. After each test acetone is used to clean the pin and disc to remove the traces. An electronic balance of 0.1 *mg* accuracy was used to find the weight of

pins. By weighing the pin before and after each wear test, loss of wear of the pin was calculated. The computer system connected with the pin-on-disc wear test machine was used to record the friction co-efficient between the specimen and rotating disc.

4. Results and Discussion

Mathematical Model for Specific Wear and Friction**.** The fit summary results of quadratic and linear models are given in ANOVA Table 2.

Table 2 The ANOVA table for the fitted models

Source	Sum of squares	df	Mean square	F value		Prob>F
For SWR						
Model	9.705	9	1.078	5.697	0.005	significant
Residual	1.892	10	0.189			
Lack of Fit 1.891	5		0.378	2768.757	1.345e-08	Not significant
Pure Error	0.0006	5	0.00013			
Cor Total	11.598	19				
Std. Dev.	0.435			R^2		0.836
Mean	1.7805			Adjusted R^2		0.689
C.V. %	24.434			Predicted R^2		0.237
				Adeq Precision		8.687
For COF						
Model	0.0056	6	0.0009	42.359	8.5648e-08	significant
Residual	0.0002	13	2.212e-05			
Lack of Fit	0.0002	8	3.534e-05	36.565	0.0005	Not significant
Pure Error	4.83e-06	5	9.66e-07			
Cor Total	` 0.005	19				
Std. Dev.	0.0047			R^2		0.951
Mean	0.27985			Adjusted R^2		0.928
C.V. %	1.680			Predicted R^2		0.797
				Adeq Precision		25.40

When the R^2 approaches unity, the better the response model fits the actual data [6]. It exists the less the difference between the predicted and actual data. Further the value of adequate precision (AP) in this model, which compares the range of the predicted value at the design point to the average prediction error, is well above 4. The values obtained are as follows: $R^2 = 0.8368$ and AP= 8.6872 for specific wear rate; $R^2 = 0.9513$ and AP= 25.4047 for COF. The response equations for Specific wear rateand COF are:

Specific wear rate:

SWR=$1.83481 + -0.401196 * A + -0.660605 * B + -0.209617 * C + 0.2425 * AB + 0.06 * AC + 0.075 * BC + -0.151433 * A^2 + 0.0253437 * B^2 + 0.0465569 * C^2$

Coefficient of friction:

COF = $0.27985 + -0.0176567 * A + -0.00534526 * B + -0.00674647 * C + -0.00375 * AB + -0.00275 * AC + -0.00475 * BC$

4.1 Effect of dry sliding parameters on wear

It can be noted from the fig.1.that the wear decreases with increase in sliding speed for Al-1.2Al$_2$O$_3$-0.5Gr hybrid nanocomposites. The decrease of wear with increase of sliding speed may be because of the increased effectiveness of the mechanical mixed layer (MML) in Al-1.2Al$_2$O$_3$-0.5Gr hybrid nanocomposites. That is, at high sliding speed may result in quick formation of MML and there by the wear gets reduced. It can be noticed that the wear decreases with increase in load. The decrease of wear with increase of load in Al-1.2Al$_2$O$_3$-0.5Gr hybrid composites nanocomposites may be due to the increased effect of the MML. It can be observed from the fig.2. that the wear increases with sliding distance due to the weakened tribolayer. Similar results have been reported on wear rates of composite, which showed a drastic increase with the sliding distance and shortly after the removal of tribolayer the composite seized against the steel counterface [10].
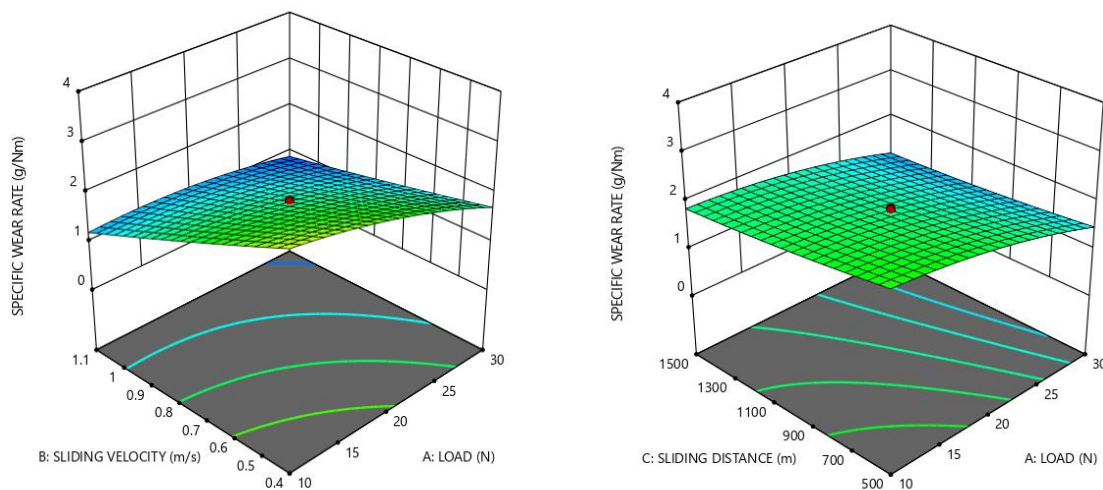

Figure.1 SWR versus sliding velocity and load **Figure.2** SWR versus sliding distance and load

The Al-1.2Al$_2$O$_3$-0.5Gr hybrid nanocomposites exhibit improved wear properties owing to the synchronized effect of enhanced strength and formation of a tribolayer predominantly consisting of Al$_2$O$_3$ and graphite particulates[7,8].

4.2 Effect of dry sliding parameters on friction

Friction coefficient is influenced by load and sliding speed. The surface plot of the effect of load and sliding speed on friction coefficient of Al-1.2Al$_2$O$_3$-0.5Gr hybrid nanocomposites is shown in Fig. 3&4. Sliding distance is not affecting the friction coefficient of composites. As the sliding

between the composite and the disc surface is separated by the tribolayer, friction coefficient is independent of the disc surface. This is true as long as a stable tribolayer exists at contact surfaces even for longer sliding distances. Thus, a stable tribolayer may exist for sliding distances considered in the present investigation, as a result of which the friction coefficient is not influenced by the sliding distance. Friction may get reduced with increase in sliding speed due to the quick formation of tribolayer at contact surfaces resulting in decrease of friction coefficient.
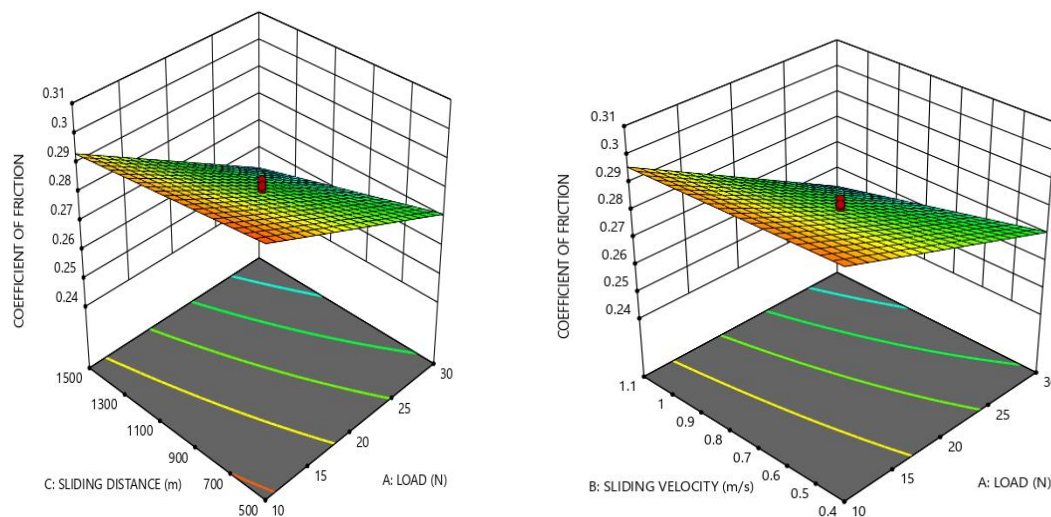

Figure. 3 COF versus sliding distance and load **Figure. 4** COF versus sliding velocity and load
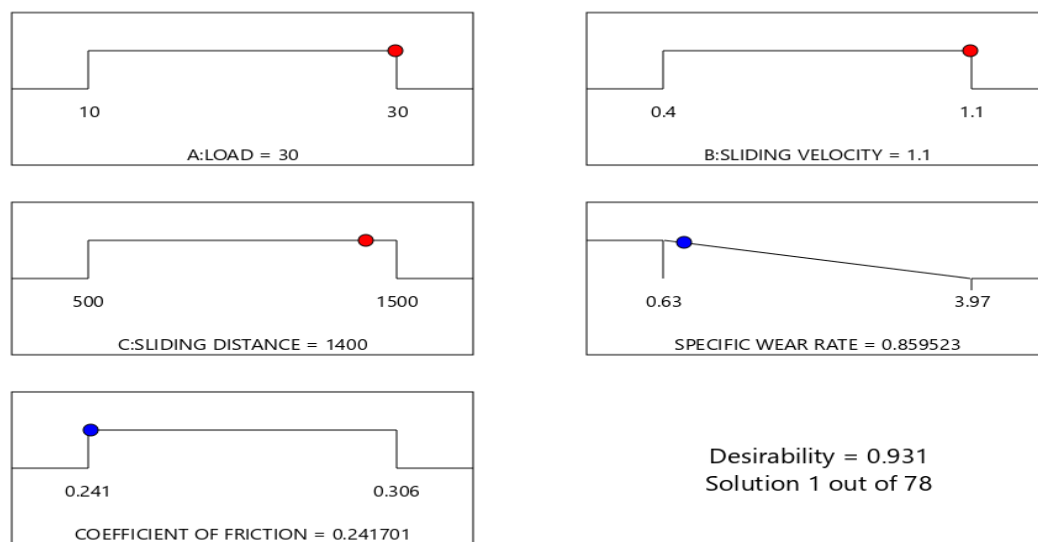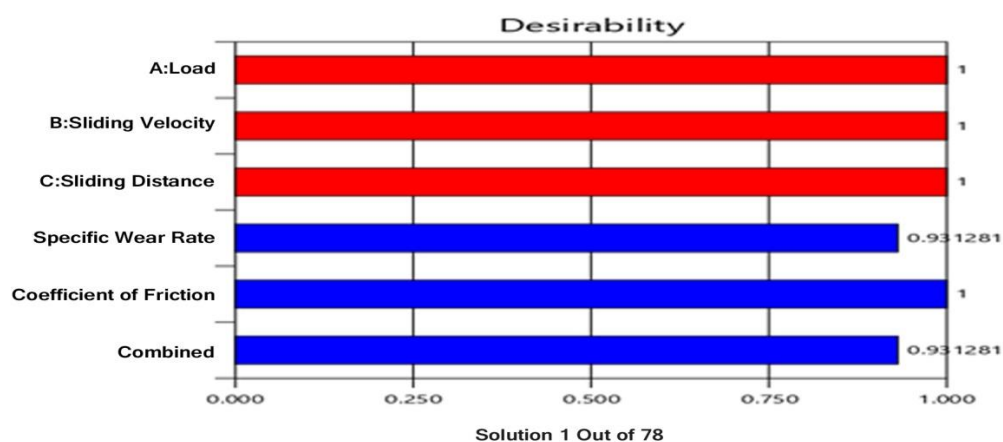
The confirmation experiment was performed by conducting tests with specific dependent variables. In this procedure, the process variables were assigned intermediate values in order to carry out the conformity test runs. It was observed that the percentage errors between the predicted and the experimental values are within the acceptable range. Hence, these models can be used for prediction of wear rate and coefficient of friction at 95% level of confidence [10,11].

4.3 Multiobjective optimization

It is a challenging task in selecting the optimal combination for wear and coefficient of friction due to the presence of a number of process variables. Grey relational analysis was employed to optimise the tribological parameters having multiple responses. An integration of artificial neural networks with genetic algorithms is proposed to optimise the multiobjectives of material selection. Taguchi's signal to noise ratio was used for multiobjective optimisation using grey relational analysis. The desirability function approach is one of the most widely used methods in industry for the optimisation of multiple response processes. An application of combined central composite design and desirability approach to improve the multiple performance characteristics of wear of aluminium metal matrix composite was reported by Ravikumar and Sreebalaji [11]. Design Expert software was used to evaluate the desirability value. Wear rate and coefficient of friction were optimized using a set of data derived from RSM. The optimality solution is to evaluate the input process parameters in minimizing the wear rate and coefficient of friction. The range, goals and optimum values of input parameters and the output characteristics, namely, wear rate and coefficient of friction, are given in Table 3.

Table 3 Range of parameters and response for desirability

Sl.no.	Process parameter	Goal		Lower limit	Upper limit	optimum value
1	Load/N	is in range	10	30	30	
2	Sliding speed/ms^{-1}	is in range	0.4	1.1	1.1	
3	Sliding distance/m	is in range	500	1000	1400	
4	Specific wear rate$10^{-7}$$_{(g/Nm)}$	minimise	0.63	3.97	0.85	
5	Coefficient of friction	minimise	0.241	0.306	0.241	

Figure.5 Ramp function graph of desirability

Figure. 6 Bar graph of desirability

The set of conditions with highest desirability value is selected as optimum condition for the responses. The optimal set of conditions with higher desirability function is given in Table 3. The ramp function graph and bar graph of desirability are shown in Figs. 5 and 6. Factor setting or response prediction for a particular characteristic is indicated by the dot on each ramp. The height of the dot shows the desirability of the response [11]. The overall desirability function of the responses, namely, the wear and coefficient of friction, is shown in the bar graph. The desirability value varies from 0 to 1 depending upon the closeness of the response towards the output. The near optimal region had an overall desirability value of 0.885, indicating the closeness of the target. The optimum parameter set for the current study is as follows: load, 30 N; sliding speed, 1.1 m/ s; sliding distance,1400m and with specific wear rate 0.859 10^{-7} g/Nm; coefficient of friction, 0.241.

5. Conclusion

The influence of process parameters on abrasive wear and coefficient of friction of Al-1.2Al$_2$0$_3$-0.5Gr hybrid nanocomposites was investigated. A mathematical model was developed to predict the wear rate and coefficient of friction of Al-1.2Al$_2$0$_3$-0.5Gr hybrid nanocomposite material incorporating the effects of applied load, sliding distance and sliding speed. The adequacy of the proposed model was then investigated using ANOVA. Confirmation tests were carried out to study that the accuracy of the developed model and the deviation between the actual value and the predicted value are within the acceptable limit. Coefficient of friction decreased with increase in sliding speed and load. The parameters were optimised using desirability based multi response optimisation technique to minimise the wear rate and coefficient of friction. Increase of speed reduces wear by supporting mechanically mixed tribolayer and increase of load decreases wear by the role of MML layer.

References

[1] Suresh S, Moorthi N SV, Vettivel S C, Selvakumar N, and Jinu G R, 2014, *Mater. Sci. Eng. A*, **612**, 16-27.

[2] Cao G, Choi H, Konishi H, Kou S, Lakes R, and Li X, 2008 *J. Mater. Sci*, **43,** 5521-5526.

[3] Baradeswaran A, and ElayaPerumal A, 2014, *Composites: Part B*, **56,** 464-471.

[4] Mosleh-Shirazi S, Akhlaghi F, and Li D.Y, 2016,*Tribol. Int*,**103,** 620-628.

[5] Mahdavi S, and Akhlaghi F, 2011, *Tribol. Lett*, **44**, 1.

[6] Kumar R,Dhiman S, 2013,*Mater. Des*, **50**, 351-359.

[7] Ravindran P, Manisekar K, Narayanasamy P, Selvakumar N, Narayanasamy R, 2012, *Mater. Des*, **39**, 42-54.

[8] Radhika N, Raghu R, 2015, *Tribol. Lett*, **59**:2.

[9] Gopalakannan S, Senthilvelan T, 2013, Int J AdvManufTechnol, **67**:485-493.

[10] Kumar S, Balasubramanian V, 2010, *Tribol. Int*, **43**, 414-422.

[11] Ravikumar K, Sreebalaji VS, 2015, *Tribology - Materials, Surfaces & Interfaces*,**9**,128-136.