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Investigation and Optimization of Tribological Aspects of Babbitt-Ilmenite Composite using Weighted Grey Relation Analysis

A. S. Wadhwa*, A. Chauhan

University Institute of Engineering and Technology, Panjab University, Chandigarh, India

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ABSTRACT

Babbitt-Ilmenite composite prepared via stir casting method with controllable parameters which include percentage weight of Ilmenite, stirring speed and aging time was investigated for its sliding wear characteristics and coefficient of friction (COF) with varying applied load, sliding velocity and sliding distance. Morphological tests were conducted for characterization of the composite and to ascertain the wear mechanism under mild and severe conditions. Taguchi philosophy with analysis of variance (ANOVA) statistical technique was used for multi-objective optimization of the tribological characteristics of the composite. The entropy based grey relation analysis (EGRA) performed for weighted multi-performance optimization of tribological aspects of the composite and hybrid Taguchi grey relation technique (TGRA) confirmed that the percentage weight of Ilmenite, applied load, sliding distance and stirring speed were the significant parameters with regard to multi - criteria optimization with contributions of 44.46%, 23.82%, 11.33%, and 5.66%, respectively. There is an overall improvement in wear resistance and COF at optimal TGRA conditions. Babbitt-Ilmenite composite can be used in steel slide bearing bushings for power, automobile and aerospace.

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1. INTRODUCTION

Metal matrix composites (MMCs) outperform monolithic materials in terms of strength, stiffness, wear resistance and weight reduction [1]. In MMCs a fibrous or particulate reinforcing phase is dispersed in a metallic matrix. The presence of hard phase in the metal matrix protects it from wear [2, 3]. Ceramic reinforced MMCs have higher sliding wear resistance resulting in improved tribological properties of the composite [4, 5]. The applied load is transmitted from the ductile matrix to the hard reinforcements during sliding wear resulting in higher wear resistance of the composite [6]. Solid lubricants like graphite forms protective layer between the counterpart and metal surface and lowers wear rate of the composite [7]. Secondary reinforcements like rice husk ash (RHA), fly ash, bamboo leaf ash (BLA) resulted in developing low-cost hybrid composite with good sliding wear characteristics comparable to single reinforced composite [8]. The addition of ceramic reinforcements decreases the wear rate of composite which remain constant with time and the wear performance of single ceramic reinforced composite is found to be better at elevated temperatures [9]. Wear rate is influenced the most with variation in load, sliding distance and speed conditions [10-12]. Sliding speed indirectly influence the worn morphology of the composite through temperature change leading to formation of mechanically mixed layer which affects the wear rate [13, 14]. Vortex stir casting is the most convenient and economical liquid state method to fabricate metal matrix composites [15-17] and the controllable parameters from the relevant literature survey which affect the tribological properties of the composite include percentage weight of reinforcement (W), stirring speed (S) and aging time (A) [18-23].

1. 1. Grey Relational Analysis (GRA) Several

*Corresponding Author Institutional Email: *aman_wadhwa77@rediffmail.com* (A. S. Wadhwa)

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scholars have utilized Grey relational analysis to optimize control parameters with more than one response by aggregating all performance attributes to a lone distinguishing characteristic called Grey relational grade to be optimized [24-27]. The procedure for grey relational analysis to optimize multi-performance characteristics is as:

1) Data Pre-processing: The responses are normalized from zero (0) to one (1) to reduce the scatter. The two most commonly used criteria for normalizing the sequence are larger is better and smaller is better. The expressions for the two criteria are:

For larger is better:

$$Yij = \frac{Zij - \min(Zij)}{\max(Zij) - \min(Zij)} \quad (1)$$

For smaller is better:

$$Yij = \frac{\max(Zij) - Zij}{\max(Zij) - \min(Zij)} \quad (2)$$

where, Yij refers to normalized value and Zij is the experimental response.

2) Determine Grey relation Coefficient

In order to establish the relationship between ideal and actual normalized response the factor called Grey relational coefficient (ξ) is calculated as:

$$\xi i = \frac{\Delta \min + \varsigma \Delta max}{\Delta i + \varsigma \Delta max} \quad (3)$$

where ς is the distinguish coefficient taken as 0.5 for better stability and moderate distinguish effects [28] and Δi is the difference between 1 and normalized value of i^{th} experiment treated as quality loss from target value. The values of Δ min and Δ max are 0 and 1, respectively.

3) Generation of Grey relation grade (GRG)

The Grey relation grade is then calculated as a weighted average of Grey relation coefficient for all the responses corresponding to one set of test parameters in an orthogonal array.

$$\alpha(i) = \sum_{k=1}^{n} w_k \xi_i(k) \quad (4)$$

where α(i) is the Grey relational grade corresponding to i^{th} experiment, w_k is the weight of k^{th} response, n are the number of performance attributes to be optimized such that $\sum_1^n w_k = 1$.

2. DEVELOPMENT OF BABBITT/ILMENITE COMPOSITE

2. 1. Materials In the process of composite fabrication, ASTM B-23 Grade 2 Babbitt alloy has been utilized as a matrix material. It is the bearing alloy used frequently for high speeds and large loads industrial applications. For the present investigation, it was obtained in form of ingots from Jain Metal Corporation in Ahmedabad, Gujarat. It has density of 7.39 g/cm^3 with melting and pouring temperature of 241°C and 424°C, respectively. Hardness, Tensile strength, Impact strength and fatigue strength of ASTM-23 Grade 2 Babbitt is 24.5 BHN, 77MPa, 3.4 J and 33 MPa, respectively. The 149-micron ball-milled Ilmenite procured from Integral Trading, Rajkot-360005 was utilized to reinforce Tin Babbitt composite. It is blackish grey, weakly magnetic, brittle, and has a high strength-to-weight ratio. It has specific gravity of 4.7 and hardness range of 5.5-6 MHN.

2. 2. Method Babbitt/Ilmenite composite was fabricated by vortex stir casting. The vortex produced by the impeller ensures uniform mixing at relatively low cost. Babbitt ingots were cut and stacked in the crucible. After weighing the alloy and reinforcement, the cut pieces were put in a muffle furnace maintained at 400 °C. Following the melting of the metal matrix, reinforcement was incorporated into the molten state at the desired speed, and the mixture was agitated for a period of five minutes. To ensure an even distribution of reinforcement, the molten material in the furnace was brought up to a temperature of 440°C and swirled again for few seconds. Then the molten material is put in the mold and the casting thus obtained after solidification was machined to proper size and form for tribological test. In order to refine the surface characteristics of the material, the samples were aged at 150 ° C for 2, 8, 24 and 48 hours and allowed to cool at ambient temperature.

3. TESTING

3. 1. Tribological Tests Wear test of the composite samples was performed using Tribometer (Model: TR-20LE-PHM-CHM- 400, Make: Ducom, Bangalore) in unlubricated conditions at temperature of 20 ± 2°C and relative humidity of 55± 5% (Figure 1). The ASTM G99-05 standard is used for testing the samples of 10 mm diameter and 30 mm length under varied experimental conditions according to designed orthogonal array. Steel disc of wear testing have hardness and surface roughness of 60 HRC and 1.6 Ra, respectively. The track diameter was kept constant at 100mm. The flat surface of the cylindrical pin is grounded manually with fine grained abrasive paper of 1200 grit size to achieve average surface roughness (Ra) of 100 nm. The counter weight mechanism has been provided with the tribo-meter to rigidly hold the grounded end of the pin against the steel disc for abrasive action and a digital microbalance with a least count of 1/10000 g was employed to weigh the specimen both before and after the wear test. The percentage weight of Ilmenite, stirring speed and aging time were selected as manufacturing test parameters whereas applied load, sliding distance and velocity were chosen as tribological test parameters based on extensive literature survey for L16 Taguchi array. The selected test parameters influence the sliding wear characteristics of the composite to the great extent and the weight loss due

Figure 1. Pin on disc wear testing machine

to wear was calculated as the difference between initial weight and final weight for each sample after wear test. Coefficient of friction.

(COF) is evaluated as the mean of steady state region from the graphs between coefficient of friction and time generated through WINDCOM software integrated with the tribo-tester (Table 1). An alternative way to find COF is to determine mean tangential force from the software and divide it by normal applied test load. The experiments were conducted with repeatability of two to minimize errors.

3. 2. Morphological Tests The microstructural analysis of the composite specimen was done using FESEM (Maker: Hitachi, Japan, Model: SU 8010 series) with resolution of 1nm at accelerating voltage of 1 kV after following the standard metallographic testing procedure. The specimen was initially polished with emery papers of different grit sizes ranging from 80 to 2000 and then polished on disc machine. After polishing the specimen were cleaned with acetone for clear image in microstructural analysis. The scanning electron micrograph and energy dispersive spectrum of ASTM B-23 Grade 2 Babbitt alloy are shown in Figures 2 and 3 respectively. Figure 4 shows the SEM micrograph of composite corresponding to Experiment No. 13 clearly indicating the presence of Ilmenite in the Babbitt alloy. The energy dispersive spectrum of Babbitt/8% Ilmenite composite shows the presence of peaks of Fe, Ti, Cl, Si, Mn, Mg, Na, Va, Al, Cu and Cr thereby ensuring successful amalgamation of Ilmenite in the metallic matrix (Figure 5). The element and atomic weight percentage for the EDS spectrum of Babbitt alloy and the

TABLE 1. Element and atomic wt% for the EDS spectrum of Babbitt alloy (Figure 3)

Element	wt%	Atomic wt%
Sn	89.9	88.68
Sb	7.39	7.11
Pb	0.62	0.35
Cu	2.09	3.86
Total	100	100

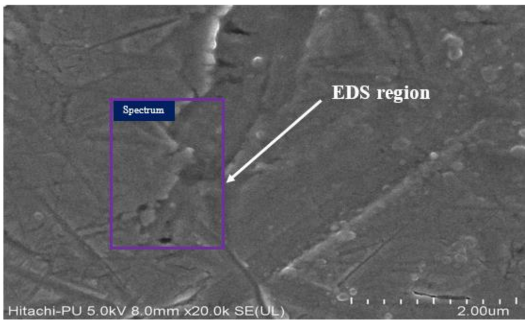


Figure 2. SEM image of Babbitt alloy at 20,000X magnification

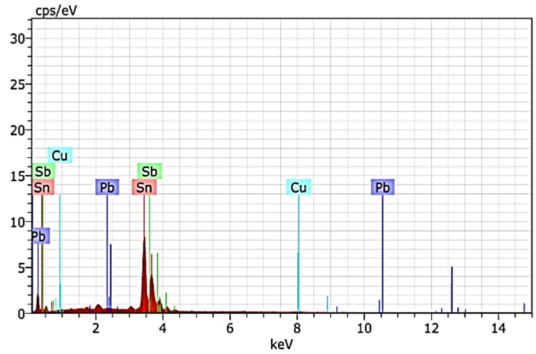


Figure 3. EDS spectrum of Babbitt alloy

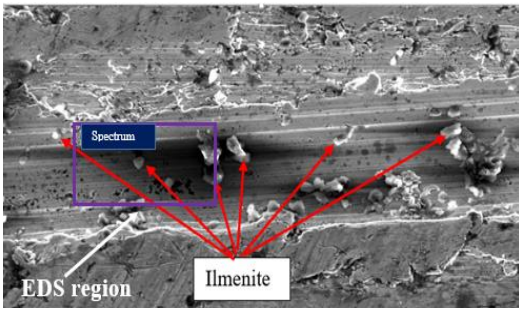


Figure 4. SEM image of composite sample (reinforcement 8wt%, stirring speed 250 rpm, aging time 48h) at 20,000X magnification

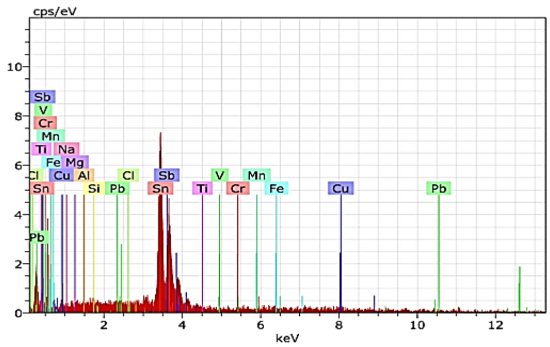


Figure 5. EDS spectrum of composite sample (reinforcement 8wt%, stirring speed 250 rpm, aging time 48h)

fabricated composite (reinforcement 8wt%, stirring speed 250 rpm, aging time 48h) are shown in Tables 1 and 2, respectively. The correct temperature and vortex conditions maintained throughout fabrication of composite resulted in homogeneous dispersion of Ilmenite particles in the Babbitt alloy thereby minimizing clustering for defect free castings.

The composite samples were fabricated at different levels of controllable parameters which include weight percentage of reinforcement, stirring speed and aging time according to L16 orthogonal array (Table 3). The SEM micrographs of the fabricated composites corresponding to set of controllable parameters are shown in Figures 6, 7 and 8 which confirmed the uniform distribution of Ilmenite in Babbitt matrix.

3. 2. 1. Wear Mechanism under Mild and Severe Conditions The composite's worn surface morphology was investigated for mild and severe wear conditions in order to establish a correlation between wear mechanism and test conditions. The transition of wear mechanism was observed with variation in applied load (10N - 40N) and sliding distance (2000m – 4000m). Under mild conditions (10N load and 2000m sliding distance) the wear is mostly abrasive with presence of wear scars due to micro ploughing by the hard counter-surface. Although some debris were formed due to micro-cutting and delamination but mild wear conditions were characterized with little material loss. With increase in load (40N) and sliding distance (4000m) the morphology of wear specimen shows deep long grooves that covers most of the area. Under severe conditions the cracks nucleate at highly strained sites and propagate to

TABLE 2. Element and atomic wt% for the EDS spectrum of the composite (reinforcement 8wt%, stirring speed 250 rpm, aging time 48h) (Extracted from Figure 5)

Element	wt%	Atomic wt%
Sn	83.51	76.75
Al	0.40	1.64
Mg	0.34	1.53
Mn	0.04	0.10
V	0.01	0.01
Pb	0.71	0.37
Si	0.38	1.47
Ti	0.75	1.73
Fe	0.02	0.02
Cu	4.30	7.45
Sb	9.31	8.30
Na	0.04	0.04
Cl	0.16	0.56
Cr	0.03	0.03
Total	100	100

TABLE 3. L16 orthogonal array with predicted and experimental responses

							Weight loss(g)		COF	
Exp. No.	W	S	A	L	SS	SD	Predicted	Observed	Predicted	Observed
1	2	250	2	1	0.5	2000	0.0586	0.0583	0.308	0.319
2	2	300	8	2	0.5	4000	0.0618	0.0621	0.347	0.336
3	2	350	24	3	1	2000	0.0427	0.0426	0.379	0.368
4	2	400	48	4	1	4000	0.0815	0.0812	0.384	0.395
5	4	250	8	3	1	4000	0.0565	0.0562	0.338	0.349
6	4	300	2	4	1	2000	0.0479	0.0482	0.453	0.442
7	4	350	48	1	0.5	4000	0.0361	0.0364	0.304	0.293
8	4	400	24	2	0.5	2000	0.0081	0.0078	0.285	0.296
9	6	250	24	4	0.5	4000	0.0754	0.0757	0.323	0.312
10	6	300	48	3	0.5	2000	0.0226	0.0223	0.341	0.353
11	6	350	2	2	1	4000	0.0348	0.0345	0.249	0.260
12	6	400	8	1	1	2000	0.0045	0.0048	0.193	0.182
13	8	250	48	2	1	2000	0.0033	0.0036	0.214	0.203
14	8	300	24	1	1	4000	0.0055	0.0052	0.187	0.198
15	8	350	8	4	0.5	2000	0.0228	0.0225	0.359	0.370
16	8	400	2	3	0.5	4000	0.0191	0.0194	0.235	0.224

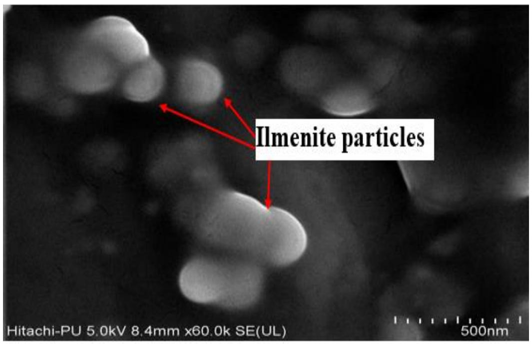


Figure 6. SEM image of composite sample (reinforcement 2wt%, stirring speed 250rpm, aging time 2h) at 60000X magnification

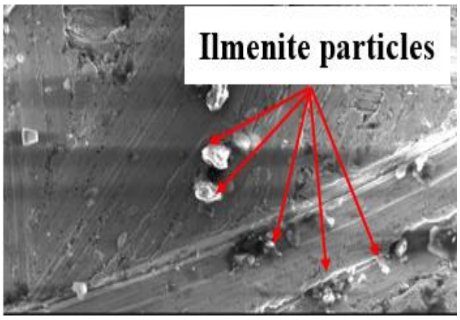


Figure 7. SEM image of composite sample (reinforcement 4wt%, stirring speed 350rpm, aging time 48) at 10000X magnification

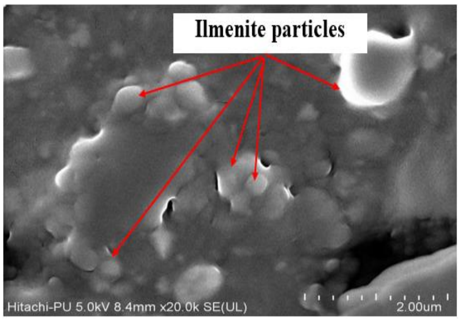
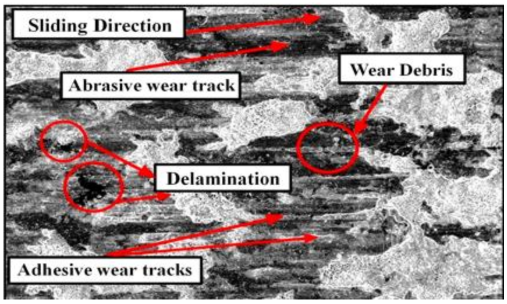
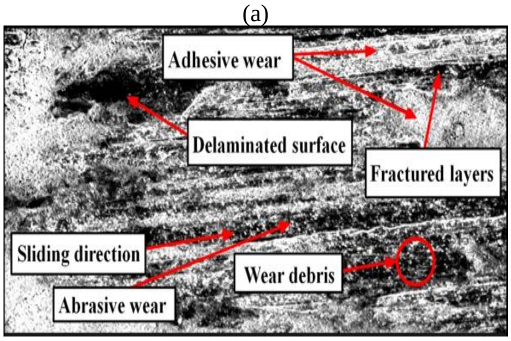


Figure 8. SEM image of composite sample (reinforcement 6wt%, stirring speed 400rpm, aging time 8h) at 20000X magnification

surface causing surface layer fracture. The fragmented wear debris formed at the surface due to tribo- chemical reaction at high load and sliding distance conditions in wear test fill the grooves leading to predominant adhesive wear. An increase in load and sliding distance generates local heating and a rise in temperature, resulting in the formation of a mechanically mixed layer that affects the wear mechanism which is in agreement with [13, 14]. Severe wear conditions were characterized with heavy material loss due to excessive delamination fracturing at the wear surface (Figure 9(a) and (b)).



(a)



(b)

Figure 9. SEM micrographs of Babbitt/2 % Ilmenite under: (a) mild wear and (b) severe wear

4. MULTI-PERFORMANCE OPTIMIZATION

Entropy based grey relation analysis (EGRA) was used for multi objective optimization of the tribological characteristics of the composite. Objective weights of the responses were determined using entropy method [29, 30]. The procedure for calculating weights of the responses for multi criteria optimization is as:

1) Normalization of the performance characteristics:

$$p_{ij}=\frac{y_{ij}}{\sum_1^m y_{ij}} \tag{5}$$

where, p_{ij} is the project outcome of i^{th} experiment, y_{ij} is the experimental response of i^{th} experiment and m are the total number of trials.

2) Estimation of entropy measure of project outcome using the equation:

$$E_j = -c \sum_1^m p_{ij} \ln p_{ij} \tag{6}$$

where, c = 1/ln(m), m=16

3) Determining the objective weight based on entropy concept from the equation:

$$W_j = \frac{1-E_j}{\sum_{j=1}^m (1-E_j)} \tag{7}$$

The higher the value of Grey relational grade, the better are the multi-performance characteristics of the composite. Experiment No.13 has the highest grey relation grade with parameters setting of $A_4B_1C_4D_2E_2F_1$ corresponding to 8wt% Ilmenite, 250 rpm stirring speed, 48 hours of aging, 2kg$_f$ applied load, 1m/s sliding velocity and 2000 m sliding distance. The most influencing parameter towards multi criteria optimization from delta analysis was found to be percentage weight of reinforcement followed by applied load, stirring speed, sliding distance, aging time and sliding speed (Table 6).

TABLE 4. Determination of objective weights of the responses

Wear loss		COF	
p_{ij}	**p_{ij} ln p_{ij}**	**p_{ij}**	**p_{ij} ln p_{ij}**
0.100379	-0.23075	0.065102	-0.177846
0.106921	-0.23904	0.068571	-0.183763
0.073347	-0.19162	0.075102	-0.194432
0.139807	-0.27507	0.080612	-0.20299
0.096763	-0.22599	0.071224	-0.188169
0.082989	-0.20656	0.090204	-0.217002
0.062672	-0.17359	0.059796	-0.168434
0.01343	-0.05789	0.060408	-0.169543
0.130337	-0.26558	0.063673	-0.175356
0.038395	-0.12516	0.072041	-0.189505
0.059401	-0.16772	0.053061	-0.155804
0.008264	-0.03963	0.037143	-0.122311
0.006198	-0.03151	0.041429	-0.1319
0.008953	-0.04222	0.040408	-0.129659
0.03874	-0.12594	0.07551	-0.19508
0.033402	-0.11354	0.045714	-0.141044
	∑ pij ln pij = -2.5118		∑ pij ln pij = -2.7428
W_j= 0.897		W_j= 0.103	

TABLE 5. Generation of entropy based Grey relation Grade

	Normalization		Grey relation Coefficient		GRG
Experiment No.	**Wear**	**COF**	**Wear**	**COF**	
1	0.2951031	0.473077	0.414973	0.486891	0.422346
2	0.246134	0.407692	0.398767	0.457746	0.404813
3	0.4974227	0.284615	0.498715	0.411392	0.489763
4	0	0.180769	0.333333	0.379009	0.338016
5	0.3221649	0.357692	0.424508	0.43771	0.425861
6	0.4252577	0	0.465228	0.333333	0.451707
7	0.5773196	0.573077	0.541899	0.539419	0.541645
8	0.9458763	0.561538	0.902326	0.532787	0.864442
9	0.0708763	0.5	0.349865	0.5	0.365256
10	0.7590206	0.342308	0.674783	0.431894	0.649883
11	0.6018041	0.7	0.556671	0.625	0.563676
12	0.9845361	1	0.97	1	0.973075
13	1	0.919231	1	0.860927	0.985743
14	0.9793814	0.938462	0.960396	0.890411	0.953221
15	0.7564433	0.276923	0.672444	0.408805	0.645417
16	0.7963918	0.838462	0.710623	0.755814	0.715256

Complete experimental design is expensive and time-consuming. A factorial design reduces number of experiments and trial cost however it may not contain the best design point. Taguchi's design philosophy addresses this issue [31] using an orthogonal array to design low-cost, high-quality trials. ANOVA test applied on Grey relational grade as lone distinguishing response [24-27] confirmed percentage weight of Ilmenite, applied load, sliding distance and stirring speed to be the significant test parameters with regard to multi criteria optimization with contribution of 44.46 %, 23.82 %, 11.33% and 5.66%, respectively (Table 7). ANOVA statistical technique predicted the load, sliding distance and speed conditions to be significant which influence the sliding wear characteristics of the composite to great extent. The ANOVA results of the predicted model is in agreement with previous research [10-12]. Optimum level of controllable parameters from hybrid Taguchi Grey relation analysis (TGRA) was found to be $A_4B_4C_3D_1E_2F_1$ (Figure 10). The confirmation experiments validated hybrid Taguchi grey relation model with deviations of 2.4% and 2.7% for wear loss and COF respectively (Table 8). Based on ANOVA analysis Equation (8) is proposed for estimating multi-attribute performance of the composite (GRG):

$$\text{GRG} = 0.303 + 0.0650\,\text{W} + 0.000928\,\text{S} + 0.00159\,\text{A} - 0.0952\,\text{L} + 0.1430\,\text{SS} - 0.000073\,\text{SD} \tag{8}$$

The adequacy of the linear fit for GRG was verified from normal probability plot which clearly indicate that the points are close to the fitted line suggesting very good fit. Residual Vs fit plot shows randomly distributed residuals required for desirable constant variance (Figure 11(a) and (b)). There is an overall improvement in wear and COF at multi criteria optimized conditions by 38.6% and 44.2 %, respectively (Table 9). The results were similar to the

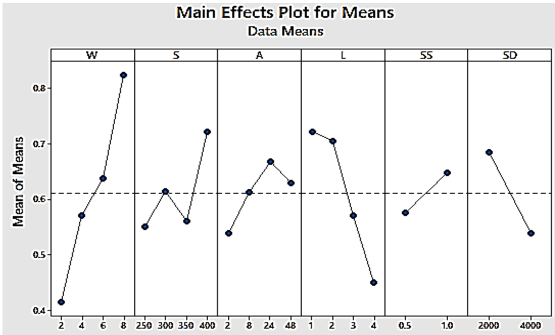


Figure 10. Means of GRG Vs test parameters

TABLE 6. Delta analysis for Grey relation grade

Level	W	S	A	L	SS	SD
1	0.4137	0.5498	0.5382	0.7226*	0.5761	0.6853*
2	0.5709	0.6149	0.6123	0.7047	0.6476*	0.5385
3	0.6380	0.5601	0.6682*	0.5702	-	-
4	0.8249*	0.7227*	0.6288	0.4501	-	-
Delta	0.4112	0.1729	0.1299	0.2725	0.0715	0.1468
Rank	1	3	5	2	6	4
Average Grey relational grade = 0.6118						

TABLE 7. ANOVA test for multi-performance optimization

Source	DOF	Sum of squares	Mean Squares	F-statistic	p -statistic	% contribution
Regression	6	0.69072	0.11511	14.77	0.000	90.78%
% wt.	1	0.33830	0.33830	43.42	0.000	44.46%
Stirring speed	1	0.04304	0.04304	5.52	0.043	5.66%
Aging time	1	0.02147	0.02147	2.75	0.131	2.82%
Load	1	0.18122	0.18122	23.26	0.001	23.82%
Sliding speed	1	0.02045	0.02045	2.62	0.140	2.69%
Sliding distance	1	0.08624	0.08624	11.07	0.009	11.33%
Error	9	0.07013	0.0078			9.22%
Total	15	0.76084				100%

Model Summary: R-sq=89.65%; R-sq(adj)= 82.76%;R-sq(Pred)=70%

TABLE 8. Confirmation Test for hybrid Taguchi grey relation analysis

Optimum Conditions	Response	
$A_4B_4C_3D_1E_2F_1$	Wear loss	COF
Predicted	0.0207	0.149
Experimental	0.0212	0.145

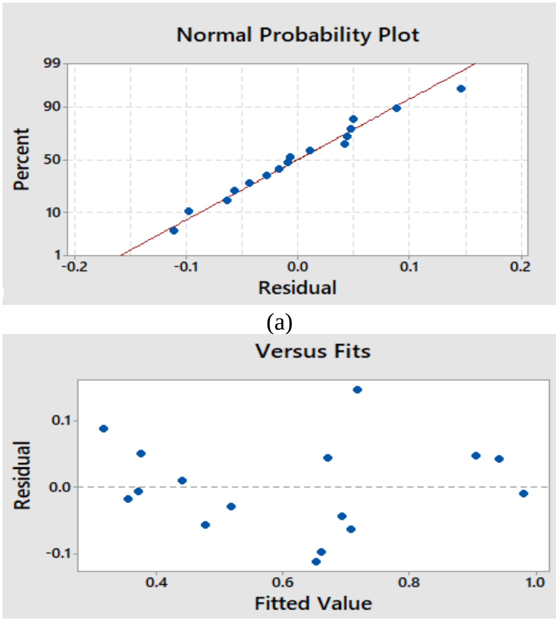


Figure 11 (a, b). Normal distribution and residual vs fit plot for GRG

TABLE 9. Improvement in multi-performance tribological aspects of composite

Condition	Wear loss	COF
Initial ($A_3B_3C_1D_2E_2F_2$)	0.0345	0.260
Optimal TGRA ($A_4B_4C_3D_1E_2F_1$)	0.0212	0.145
Improvement	38.6 %	44.2 %

*Initial condition is taken near the mean value of GRG

wear study conducted by Singhal and Pandey [32] on Ilmenite reinforced aluminum metal matrix composite which reported improvement in wear resistance and coefficient of friction by 57% and 47%, respectively at the optimum conditions. A similar study conducted by Priyadarshani et al. [33] observed improvement in wear resistance and coefficient of friction of AA 6061/Ilmenite composite which is in agreement with the current investigation. Ilmenite-reinforced composites showed similar tribological improvements [34, 35] in line with current study.

5. RESULTS AND DISCUSSION

There is an improvement in tribological aspects of the composite with increase in percentage weight of Ilmenite because of reduction in contact area of mating parts. The fluctuating trend of the tribological behavior of the composite with stirring speed was observed due to variation in dispersion of the reinforcement in the matrix. There is an improvement in the tribological behavior of the composite with increase in aging time up to certain optimum limit as a result of its strengthening due to dislocation pile up on grain boundaries. Over aging of the composites causes precipitates to coalesce and form big particles thereby weakening the dislocation barrier and promoting dislocation movement resulting in diminishing of the tribological characteristics of the composite. With increase in load from 10 N to 40 N, there is increase in counter surface penetration which causes increased abrasion of the composite resulting in the increase of wear loss and higher values of coefficient of friction. Increase in sliding velocity decreases area of contact and rubbing time of mating surfaces thereby improving tribological aspects of the composite. The increased temperature caused due to high sliding velocity leads to the formation of mechanically mixed layer. Wear loss increases as the sliding distance is increased from 2000 m to 4000 m due to weakening of the unstable tribo-layer. At greater sliding distances, the ilmenite particles are significantly fractured which interfere with the mechanically mixed layer on the composite surface and deteriorate the tribological properties of the composite.

6. CONCLUSIONS

In the current investigation Babbitt-Ilmenite composite developed via stir casting process was tested for wear loss and coefficient of friction with pin on disc tribometer. The effect of controllable parameters which include percentage weight of Ilmenite, stirring speed and aging time with varying applied load, sliding velocity and sliding distance on the tribological properties of the composite was studied. Morphological tests were conducted to ascertain the uniform distribution of Ilmenite in Tin-Babbitt and the type of wear mechanism. Weighted Grey relational analysis was performed for multi-objective optimization of the tribological attributes of the composite. The weights of the responses were determined objectively using entropy method. Hybrid Taguchi grey relation analysis determined the significant test parameters and their contribution for multi-performance optimization of tribological aspects of the composite. The following pertinent observations were made in the present study:

1. A morphological analysis conducted on the Babbitt-Ilmenite composite confirmed the uniform dispersal of Ilmenite in the Tin-Babbitt metal matrix.
2. The investigation of worn surface morphology under mild and severe conditions indicated predominant abrasive wear under mild condition characterized with scars on wear surface due to micro-ploughing and debris formed due to micro-cutting with little material loss. Under severe conditions the debris formed due to surface fracture are further fragmented as a result of tribo- chemical reactions and the wear is predominantly adhesive in nature with heavy material loss due to excessive delamination fracturing at wear surface.
3. The weights of the responses (wear and COF) were evaluated objectively using entropy method and grey relation analysis was applied to determine optimal parameter setting for multi-attribute optimization of the tribological aspects of composite. Experiment No.13 has the highest grey relation grade with parameters setting of $A_4B_1C_4D_2E_2F_1$ corresponding to 8% weight Ilmenite, 250 rpm stirring speed, 48 hours of aging, 2 kg_f applied load, 1m/s sliding velocity and 2000 m sliding distance.
4. The linear regression equation was proposed for estimating GRG and the confirmation tests validated the hybrid Taguchi grey relation model with deviations of 2.4% and 2.7% for wear loss and COF, respectively.
5. Optimum level of controllable parameters for hybrid Taguchi Grey relation analysis (TGRA) were found to be $A_4B_4C_3D_1E_2F_1$. The percentage weight of Ilmenite was the most influential test parameter with contribution of 44.46% followed by applied load, sliding distance and stirring speed with contribution of 23.82 %, 11.33% and 5.66%, respectively.
6. There is an overall improvement in wear and COF at optimal TGRA conditions by 38.6 % and 44.2 %, respectively.

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Persian Abstract

چکیده

کامپوزیت بابیت–ایلمنیت تهیه‌شده به روش ریخته‌گری هم‌زن با پارامترهای قابل کنترل که شامل درصد وزن ایلمنیت، سرعت همزدن و زمان پیری می‌شود، از نظر ویژگی‌های سایش لغزشی و ضریب اصطکاک (COF) با بار اعمالی متغیر، سرعت لغزش و فاصله لغزش مورد بررسی قرار گرفت. آزمایش‌های مورفولوژیکی برای شناسایی کامپوزیت و تعیین مکانیسم سایش در شرایط خفیف و شدید انجام شد. برای بهینه‌سازی چند هدفه ویژگی‌های تریبولوژیکی کامپوزیت، از فلسفه تاگوچی با تکنیک آماری آنالیز واریانس (ANOVA) استفاده شد. تجزیه و تحلیل رابطه خاکستری مبتنی بر آنتروپی (EGRA) که برای بهینه‌سازی وزنی چند عملکردی جنبه‌های تریبولوژیکی روش رابطه خاکستری ترکیبی و ترکیبی تاگوچی (TGRA) انجام شد، تأیید کرد که درصد وزن ایلمنیت، بار اعمال شده، فاصله لغزش و سرعت هم‌زدن معنی‌دار هستند. پارامترهای مربوط به بهینه سازی چند معیاره به ترتیب با سهم ٤٤.٤٦، ٢٣.٨٢، ١١.٣٣ و ٥.٦٦ درصد است. بهبود کلی در مقاومت به سایش و COF در شرایط بهینه TGRA وجود دارد. کامپوزیت Babbitt-Ilmenite را می توان در بوش های بلبرینگ فولادی برای برق، خودرو و هوافضا استفاده کرد.