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Research article

Insitu synthesis of Al– $MgAl_2O_4$ composites and parametric optimization of tribological characteristics

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ABSTRACT

In this research, multiobjective optimization of tribological characteristics of Al–4Mg/in-situ $MgAl_2O_4$ composites fabricated via ultrasonic cavitation treatment assisted stir casting technique was carried out. Al–4Mg alloy dispersed with 0.5, 1 and 2 wt% in-situ $MgAl_2O_4$ was prepared and the microstructural and mechanical characterisation of the same has been carried out. Reinforcement addition, load and sliding velocity at 3 different levels was considered to attain the responses wear rate and friction coefficient. To identify optimised process condition for the developed composites to attain reduced friction coefficient and wear rate condition, grey analysis is tried out. Experimental results analysed via Grey relation and analysis of variance (ANOVA) proved wt.% of $MgAl_2O_4$ particles as significant parameter trailed by load and speed. Based on grey relational grade, minimal wear loss at lowest frictional coefficient can be attained for the composite dispersed with 2 wt% of in-situ $MgAl_2O_4$ at 20 N load and 2 m/s sliding velocity. Mechanisms behind the wear loss was analysed from worn out surface micrographs.

1. Introduction

Aluminum metal matrix composites with its attractive characteristics such as minimal density, excellent corrosion and wear properties, better strength, thermal conductivity etc. makes it an opt material were high strength of weight ratio is mandatory [1–4]. Its application has been widely seen in many industries including aerospace, automobiles, defense, military etc [5–8]. Improvement in the properties such as strength, operating temperature, corrosion resistance etc. of a developed aluminum metal matrix composites mainly depends on characteristics of reinforcements introduced and manufacturing technology. Introduction of reinforcement particles into a matric can be done mainly through external method (ex-situ) or through internal formation (in-situ) method [1,2]. Particle addition through external method is the mostly commonly analysed method where reinforcement particles of different characteristics are added into the materials which led to variations on properties of the developed composites. Fabrication of metal matrix composites through ex-situ method however is having certain setbacks in efficiency when compared with in-situ methods. Dispersion of nanoparticles into matrix is comparatively a difficult task when fabricated via ex-situ methods as the end result composites attained will be having

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adverse characteristics such as minimal wettability between reinforcement particles and matrix metal, non-uniform reinforcement particles distribution, weak interfacial bonding between matrix metal and reinforcement particles etc [4,5]. When it comes to fabrication of metal matrix composites thru in-situ methods, the developed reinforcement particles will be distributed homogenously along the matrix with string interfacial bonding between reinforcement and matrix metal [9–12]. Studies have also stated that the reinforcements formed due to salt reaction between additives and matrix during in-situ reaction swill be thermodynamically stable and free from contaminations.

Fabrication of aluminum metal matrix composites are mainly carried out through stir casting, squeeze casting, powder metallurgy, centrifugal casting, ultrasonic assisted casting etc. in which stir casting technique is the most economical technique which has gained interest with the researchers [13,14]. However when it comes to the fabrication of aluminum composites with minimal particle size, formation of reinforcement clusters happens with nominal wettability thereby reducing the quality and properties of developed composites. So as to overcome the cluster formation of reinforcement particles and attain its homogenous distribution in the synthesized composites, ultrasonic vibrations are incorporated in stir casting equipment. Introduction of ultrasonic vibration into the molten aluminum metal will also help in grain refinement and reducing cavitation along with the homogenous distribution of the reinforcement particles [15–18].

Statistical methods such as Taguchi's method, Response Surface Methodology etc. have been employed by the researchers to analyze, predict and optimize engineering and manufacturing processes. These methods helped the researchers to analyze the effect of each controlling factors on the experimental response. However when it comes to single objective optimization techniques, optimization of the factors for a single response can only be done effectively. In such scenarios multiple responses will be translated into single response so as to evaluate the process via Taguchi method so as to attain the optimal processing conditions. Grey relational analysis has been found to be effective method in optimizing the multiple objectives which makes us to consider this technique in this research work.

Ikubanni et al. [19] employed Taguchi and grey relational analysis technique to categorise process parameters to attain minimal wear index and volume loss for aluminium composites reinforced with hybrid particles employing L16 orthogonal array. Findings proposed speed having major impact on wear consequence rather than load and reinforcement addition. Le and Vu [20] utilized a multi-objective optimization technique to maximize gearbox efficiency and minimize its mass of a two-stage helical gear box by identifying different design factors. Taguchi method and grey relation analysis is used to identify that gear box ratio of first stage has a major influence on minimizing gearbox ratio and maximising the efficiency of gearbox. Devadiga U and Fernandes P [21] studied the role of reinforcements, manufacturing and dry sliding wear conditions on wear loss of aluminium nano composites produced via powder metallurgy. Taguchi method and ANOVA was employed to optimize parameters and studies proved that MWCNT and fly ash had major role in controlling wear loss of developed composites.

SaurabhVashistha et al. [22] analysed the tribological properties of an Al–Co–Cr–Fe–Ni HEA alloy produced via the vacuum induction melting method. They optimised the friction coefficient, wear, and surface roughness using a neural net-based algorithm. From the results, they found that, data-driven modelling methods are most suitable for the progress of advanced materials with better performance and properties. Guotao Liu et al. [23] optimised the grinding parameters for Ti–6Al–4V alloy using orthogonal experiments and grey relational analysis. They were able to obtain the optimal parameter combinations of processing efficiency and surface quality. HilmiPekşen et al. [24] inspected machineability of AISI 430 stainless steel statistically and experimentally by machining at various speeds and feeds. Machining parameters were optimised using ANOVA and Taguchi-based grey relational analysis. From the results, they found that the flank wear and surface roughness multiple performance outputs are optimised using the above analysis.

Considering the in-situ composites, $MgAl_2O_4$ as reinforcement particles has been explored extensively owing to its high hardness

Fig. 1. Fabrication setup for preparing composites.

and chemical inertness along with low density and high temperature strength. $MgAl_2O_4$ an end member of spinel group exhibits good wettability with aluminum and does not forms any undesired reactions during the process. Being a refractory material, $MgAl_2O_4$ exhibits low thermal conductivity and thermal expansion coefficient with excellent thermal shock resistance [25,26]. Numerous studies have been carried out by researchers in developing aluminum in-situ with $MgAl_2O_4$ as reinforcement particles but minimal study has only been carried out in the area of tribological optimization in our knowledge. In this examination in-situ aluminum metal matrix composites of diverse weight fraction of $MgAl_2O_4$ is fabricated via ultrasonic assisted stir casting by adding different proportions of H_3BO_3 powders. The primary purpose of this research involves optimization of tribological parameters based on different factors and identifying the processing conditions for minimal wear loss and friction coefficient values was done.

2. Materials and methods

Al–4Mg alloy (99.7 % pure) with 0.5, 1 and 2 wt% in-situ $MgAl_2O_4$ composites synthesized via the ultrasonic treatment (UT) assisted stir casting process by the adding required quantity of H_3BO_3 powders. H_3BO_3 powder (99.5 % pure, Molecular weight of 61.83) acquired from Sigma-Aldrich with 20 μm average size of is supplemented into the molten Al–Mg alloy and is held for 15 min at a temperature of 750 °C; H_3BO_3 reacts with Al–4Mg alloy and forms $MgAl_2O_4$particles. After 15 min the molten metal with $MgAl_2O_4$- particlesis kept under ultrasonic treatment for 5 min using a SS304 grade made sonotrode magnetostrictive transducer. Setup used for preparing the composites is as provided in Fig. 1. The detailed process of synthesizing in-situ $MgAl_2O_4$ composites was explained in Raghu et al. (2018).

Vickers microhardness of Al–4Mg/in-situ $MgAl_2O_4$ composite composites was evaluated using Mitityo hardness tester at a load of 100 g and a 15-s dwell-time. A tensile test was performed by means of a TINIUS OLSEN H75 KS tensile tester with a strain rate of $0.01s^{-1}$. The mean of three tests was taken as a sample for final hardness and tensile results. To have a detailed analysis of the effect of process parameters on the tribological characteristics of the developed insitu composites, dry sliding wear tests was carried out. Wear tests were carried out employing a pin-on-disc wear tester (Ducom, Bangalore), and wear test samples prepared in accord to ASTM G99 standard. The disc material is EN 35 steel, which has a hardness of about 55 HRC. The wear test was carried out at room temperature, and weight loss of samples was measured using a weighing balance with an accuracy of 0.001 gm. The dry sliding wear tests are carried out mainly based on three processing parameters as shown in Table 1. An Orthogonal array of experimental trials was formed with the aid of Taguchi's method and based the defined trails as shown in Table 2, the output responses wear loss and frictional coefficient values were measured.

In this research, as a part of analysing the consequence of each processing parameters on wear response and coefficient of friction during dry sliding wear test Taguchi's method was adopted. In this method an orthogonal array with different combinations of process parameters to form a design array was created in which three process parameters at three different levels as shown in Table 1 was utilized. Based on the considered process parameters and levels, an orthogonal array if 27 different combinations were considered for this research based on which the dry sliding wear test will be carried out. Response values, say frictional coefficient and wear loss attained from the 27 orthogonal array trails will then be converted into signal to noise ratio (S/N ratio) and in this study both the response factors has to be minimal therefore smaller the better characteristics was considered. The equation used to compute the signal ratio values at smaller the better characteristics is provided as equation (1) wherein 'r', and 'y' represents the total number of trails and response value at 'j' trial number respectively.

$$(S / N)_{SB} = -10\ log_{10}\frac{1}{r}\sum_{j=1}^{r} y_j^2 \tag{1}$$

The best process parameters is attained from the maximum SN ratio value and based on the maximum SN values of each process parameters, the optimum process parameter condition is attained [27–29].

Analyzing the role of parameters on response factors and identifying optimised process conditions for attaining the best individual response value can be done through Taguchi's method; however, when it comes to establishing an interrelationship between output responses multi response optimization techniques comes to handy. In this research a multi-objective optimization technique named Grey Relational Analysis (GRA) techniques is used in computing optimal process parameter to attain the minimal wear loss and frictional coefficient [30–32]. In GRA technique, the output responses wear loss and friction coefficient values are converted into a single objective based on which the optimal process parameters for attaining minimal wear loss and frictional coefficient values is obtained. In GRA technique, the attained wear loss and frictional coefficient values are normalized between 0 and 1 as the initial stage. Normalization is carried out so as to reduce the variability of a response and the below equation (2) is used for carrying out the same.

Table 1
Process parameters and levels.

Process parameters	Levels		
	1	2	3
Wt.% of $MgAl_2O_4$	0.5	1	2
Load (N)	20	40	60
Velocity (m/s)	2	4	6

Table 2
Mechanical properties of specimens.

Materials	Vickers Hardness (HV)	0.2 % YS (MPa)	UTS (MPa)	Elongation (%)
Al–4Mg	62	70	170	7.4
Al–4Mg/0.5 wt% $MgAl_2O_4$	70	78	194	7
Al–4Mg/1 wt% $MgAl_2O_4$	78	88	208	6.2
Al–4Mg/2 wt% $MgAl_2O_4$	86	97	230	5.2

$$x_i^*(k) = \frac{a_i(k) - \min a_i(k)}{\max a_i(k) - \min a_i(k)} \quad (2)$$

in equation (2), $x^*_i(k)$ and $a_i(k)$stands for normalized value and output response wherein i and k is experimental number and comparability sequence. After normalizing, deviation sequence is calculated from a reference sequence which is taken as 1. Equation (3) is used for computing the same in which $\Delta_{oi}(k)$ and $x^*_o(k)$ represents deviation and reference sequence respectively.

$$\Delta_{oi}(k) = |x_o^*(k) - x_i^*(k)| \quad (3)$$

Based on the deviation sequence the Grey Relation Coefficient ($\xi_i(k)$) is attained as shown in equation (4) in which an identification coefficient (ζ) considered as 0.5 is employed.

$$\xi_i(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{oi}(k) + \zeta\Delta_{max}} \quad (4)$$

The grey relation coefficient value for each output response is then averaged to attain grey relational grade (γ_i) value which aids in converting the multiple objectives int a single objective. Equation (5) is used for the computation in which I stands for trial and n for the number of trials.

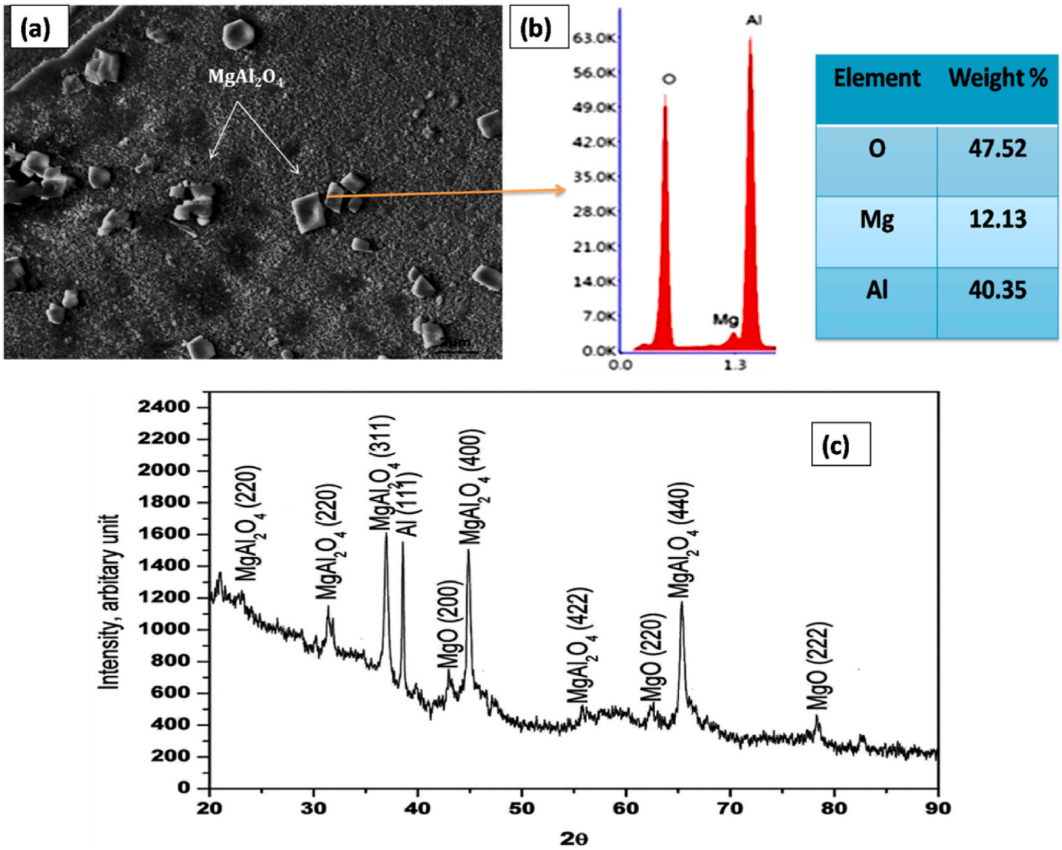

Fig. 2. (a) Al–$MgAl_2O_4$ composite SEM micrograph, (b)EDS spectra of $MgAl_2O_4$ particles and (c) XRD pattern of Al–$MgAl_2O_4$ composite.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{5}$$

3. Results and discussion

3.1. Microstructure and mechanical behaviour

The microstructure of Al–4Mg/in-situ $MgAl_2O_4$ composites was explained in a previous study by Raghu et al. [3]. A sample micrograph of the Al–4Mg/in-situ $MgAl_2O_4$ composites is shown in Fig. 2. The in-situ $MgAl_2O_4$ particles having a size of about 2 μm, were uniformly distributed and had excellent bonding with the matrix. EDS results of $MgAl_2O_4$ particles reinforced composites and XRD pattern of extracted $MgAl_2O_4$ particles from the composite are as demonstrated in Fig. 2 (b) and (c) respectively. Ultrasonic treatment and presence of in-situ $MgAl_2O_4$ particles significantly refined the grain structure of the Al–4Mg alloy. Ultrasonic treated Al–4Mg alloy has about 250 μm grain size, whereas composite samples added with 2 wt % in-situ $MgAl_2O_4$ have about 50 μm. Presence of hard reinforcement and grain refinement will significantly improve the mechanical properties.

Uniform distribution of the in-situ formed $MgAl_2O_4$ particles has been achieved with nil defects or cavities which is evident from the SEM micrograph. This uniformity in particle dispersion with minimal defects can be attributed to the high intensity ultrasonic waves inputted during the fabrication processes which generate cavitation leading to the formation of a nil defect composite material.

The Vickers microhardness of the Al–4Mg alloy is about 62 HV, whereas the Al–4Mg/2 wt% in-situ $MgAl_2O_4$ composite has the highest hardness of about 86 HV, as shown in Table 2. This increase in hardness with respect to rise in in-situ $MgAl_2O_4$ distribution can be accredited to the effective scattering of formed $MgAl_2O_4$ particles which strengthens Al–4Mg alloy's soft characteristics which resists the plastic deformation while applying load. $MgAl_2O_4$ phase formed during the fabrication is a ceramic particle of high hardness having the capability to bear and transfer the applied load into the Al–4Mg alloy matrix. Henceforth, increase in $MgAl_2O_4$ particles formation in Al–Mg alloy and its uniform dispersion will lead to increase in hardness value of the developed composites.

Tensile strength evaluation of developed composites reveals yield and tensile strength with reverence to the dispersion of wt% $MgAl_2O_4$. The Al–4Mg alloy has a yield and tensile strength of 76 and 170 MPa, whereas the Al–4Mg/2 wt% in-situ $MgAl_2O_4$ composite has the highest yield and tensile strength of 97 and 230 MPa with a 32.28 % increase in strength. Significant improvement in hardness and tensile properties has been observed due to good interfacial bonding among Al–4Mg matrix and in-situ $MgAl_2O_4$ particles, which effectively transfer stress to the matrix. Along with this, variation in thermal expansion coefficient value between Al–4Mg alloy and $MgAl_2O_4$ leads to the formation of tri-axial strains during the solidification process. This will lead to the restriction of dislocation movement during tensile testing and henceforth more loads will be required for the dislocation movement through grain boundaries. This will lead to enhancement in tensile characteristics of developed composites. However, decrease in ductility is observed with respect to particle increment which may be mainly due to the brittle characteristics of formed ceramic phase.

Table 3
Process parameters and response values.

Exp. No.	Wt.% of $MgAl_2O_4$	Load (N)	Velocity (m/s)	Wear Loss (WL) $\times 10^{-2}$ (g)	Friction Coefficient (FC)
1	0.5	20	2	14.49	0.577
2	0.5	20	4	15.82	0.537
3	0.5	20	6	17.94	0.451
4	0.5	40	2	16.88	0.508
5	0.5	40	4	18.82	0.462
6	0.5	40	6	21.04	0.389
7	0.5	60	2	17.64	0.452
8	0.5	60	4	19.68	0.422
9	0.5	60	6	27.74	0.412
10	1	20	2	13.69	0.505
11	1	20	4	14.82	0.482
12	1	20	6	17.14	0.471
13	1	40	2	15.8	0.455
14	1	40	4	16.85	0.436
15	1	40	6	18.68	0.402
16	1	60	2	16.28	0.391
17	1	60	4	17.8	0.378
18	1	60	6	19.58	0.342
19	2	20	2	11.04	0.429
20	2	20	4	12.82	0.402
21	2	20	6	14.44	0.386
22	2	40	2	13.64	0.379
23	2	40	4	14.82	0.342
24	2	40	6	16.44	0.339
25	2	60	2	15.28	0.342
26	2	60	4	16.82	0.312
27	2	60	6	17.54	0.278

3.2. Outcome of process parameter on response values

Wear test on developed composites has been done based on the L27 orthogonal array and the response values (Wear Loss and friction coefficient) was attained as depicted in Table 3.

A detailed view on process parameters (reinforcement percentage, load and velocity) on Wear Loss (WL) and Friction Coefficient (FC) is provided in Fig. 3.

Detailed scrutiny on role of process parameters on wear loss can be conceded from the Taguchi analysis results as shown in Figs. 4 and 3. Figs. 3 and 4 clearly demonstrates that with introduction of $MgAl_2O_4$, wear loss decrease. This wear loss reduction can be ascribed to high hardness of samples and grain refinement. Occurrence of hard $MgAl_2O_4$ acts as a barrier between pin and disc, reducing the direct contact of matrix material with the rotating disc. However, it is observed that with surge in load and sliding velocity, wear loss tends to decrease as the load and velocity leads to thermal softening of matrix metal. This thermal softening in turn increases the chances of ploughing away of matrix metal.

Influence of wt% of $MgAl_2O_4$ particles, load, and sliding velocity over friction coefficient is represented in Fig. 5. It is noticed that with higher wt% of $MgAl_2O_4$ particles, load, and sliding velocity, the friction coefficient gets declined. At higher speeds, the pin surface gets polished, which reduces the friction coefficient. With an increase in load, the temperature of pin increases, it becomes soft, and thereby declining friction coefficient. With higher wt. % of $MgAl_2O_4$ particles and uniform dispersion by UT, reduced direct contact between disc and pin surface decreased friction coefficient. The results are in line with Thakur and Dhindaw [33].

3.3. Grey relational analysis: multi-objective optimization

To attain a set of process parameters at which a minimal wear loss happens along with minimum friction al coefficient value, grey relational analysis was carried out. The normalized values of wear loss and friction coefficient value along with Grey Relational Coefficient value is provided in Table 4. Averaging grey relational coefficient values of wear loss and friction coefficient values gives grey relational grade is attained as provided in Table 4. Based on the maximum grade attained for the experimental trails ranking was carried out in descending order from 1 to 27. Rank 1 was provided for the set of input parameters were the minimal wear loss happened at minimal friction coefficient value and the same occurred for Al–4Mg/2 wt% $MgAl_2O_4$ composite at 20 N load when the pin was rotating at 2 m/s sliding velocity. Henceforth the experimental number 19 was considered as the optimal parameter for attaining a combined effect of least loss through wear and friction coefficient satisfying the objective of this concerned research.

Table 4 depicts the response for means of GRG values in which the optimal parameter levels are bolded for the easy identification. It is evident from the response table that minimum wear loss with minimal friction coefficient values occurs for the composite specimen reinforced with two percentages of $MgAl_2O_4$ when a load of 20 N is applied by the specimen on a rotating disc with sliding velocity 2 m/s. The optimal parameters portrayed by the response table are similar to that of the rank 1 graded experimental set from Table 4.

From Table 5 it is also evident that the particle addition has major impact on governing response factor trailed by the load applied

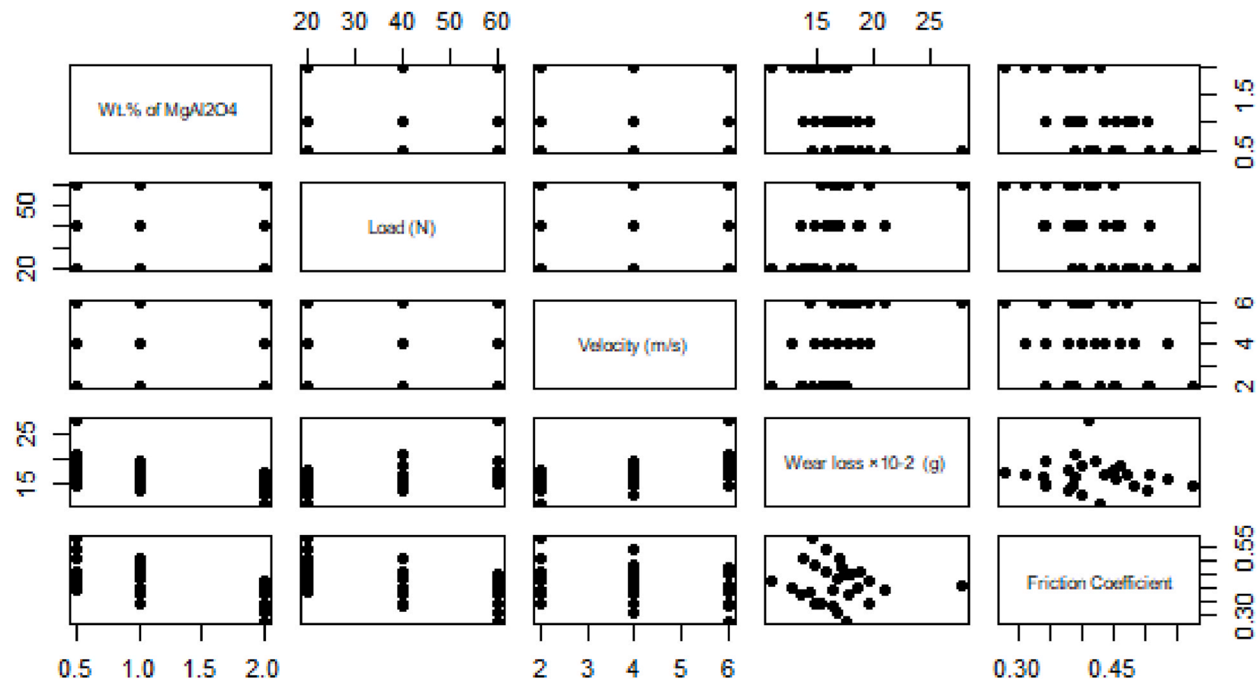

Fig. 3. Process parameters vs. Response values.

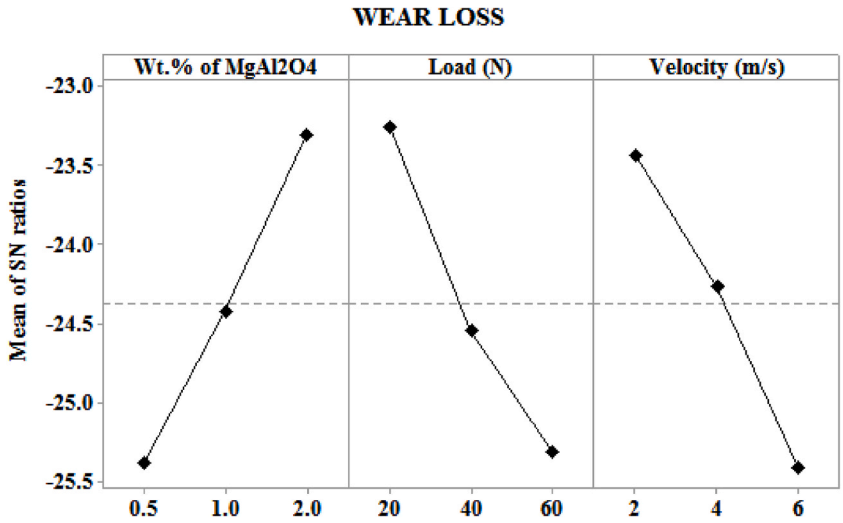

Fig. 4. Outcome of process parameters on Wear Loss.

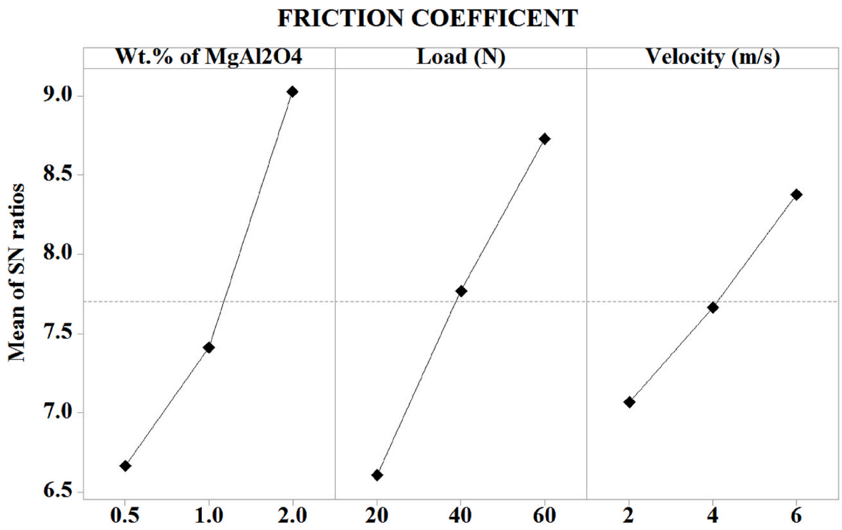

Fig. 5. Outcome of process parameters on Wear Loss.

during the dry sliding wear test. Sliding velocity has more or less similar impact on defining the response factors while analyzing the wear results.

To have a detailed brief on role of reinforcement in matrix metal while carrying out wear tests, a detailed analysis on the worn out surface via scanning electron microscope has been carried out and the attained results are as shown in Fig. 6(a–d). To have a comparison on how the reinforcement act while carrying put pin on disc testing, all three specimens along with a substrate metal is allowed to run along a hardened disc rotating at 2 m/s velocity and 40 N load acting on the specimen. Worn out surface of substrate metal investigated under the provided conditions are provided as Fig. 6(a). It illustrates deep grooves and delamination along the sliding direction. Wear tested samples of Al–4Mg alloy show delamination wear caused by the generation of cracks and their propagation at right angles to sliding direction, leading to loss of pin materials in the form of laminates. Fig. 6(b–d) depicts worn out surfaces of developed aluminum composites with 0.5 %, 1 % and 2 % of $MgAl_2O_4$ particles respectively. Worn out surfaces portrayed a shallow abrasive grooves with minimum wear loss with respective to increase in in-situ $MgAl_2O_4$ particles formation. This reduction in wear loss is due to the formation of hard in-situ $MgAl_2O_4$ particles that carry away the load and at the same time forms a thin oxide layer which further reduces the wear loss. The presence of in-situ $MgAl_2O_4$ particles has excellent bonding with the matrix, where the load will effectively transfer to the particles and improve the wear properties.

Table 4
Grey relation response.

Exp.No.	NormalizedWL	Normalized FC	GRC WL	GRC FC	GRG	Rank
1	0.7934	0	0.7076	0.3333	0.5205	12
2	0.7138	0.0693	0.6359	0.3495	0.4927	17
3	0.5868	0.2184	0.5475	0.3901	0.4688	23
4	0.6503	0.1196	0.5884	0.3622	0.4753	20
5	0.5341	0.1993	0.5177	0.3844	0.451	24
6	0.4012	0.3258	0.455	0.4258	0.4404	26
7	0.6048	0.2166	0.5585	0.3896	0.4741	21
8	0.4826	0.2686	0.4915	0.4061	0.4488	25
9	0	0.286	0.3333	0.4118	0.3726	27
10	0.8413	0.1248	0.7591	0.3636	0.5613	6
11	0.7737	0.1646	0.6884	0.3744	0.5314	11
12	0.6347	0.1837	0.5779	0.3799	0.4789	18
13	0.715	0.2114	0.6369	0.388	0.5125	14
14	0.6521	0.2444	0.5897	0.3982	0.4939	15
15	0.5425	0.3033	0.5222	0.4178	0.47	22
16	0.6862	0.3224	0.6144	0.4246	0.5195	13
17	0.5952	0.3449	0.5526	0.4329	0.4927	16
18	0.4886	0.4073	0.4944	0.4576	0.476	19
19	1	0.2565	1	0.4021	0.701	1
20	0.8934	0.3033	0.8243	0.4178	0.621	2
21	0.7964	0.331	0.7106	0.4277	0.5692	5
22	0.8443	0.3432	0.7626	0.4322	0.5974	3
23	0.7737	0.4073	0.6884	0.4576	0.573	4
24	0.6766	0.4125	0.6073	0.4598	0.5335	10
25	0.7461	0.4073	0.6632	0.4576	0.5604	7
26	0.6539	0.4593	0.5909	0.4804	0.5357	9
27	0.6108	0.5182	0.5623	0.5093	0.5358	8

Table 5
Response table for Means.

Level	Wt.% of $MgAl_2O_4$	Load (N)	Velocity (m/s)
1	0.4605	**0.5494**	**0.5469**
2	0.504	0.5052	0.5156
3	**0.5808**	0.4906	0.4828
Delta	0.1203	0.0588	0.0641
Rank	1	2	3

4. Conclusions

In the present study, Al–4Mg/in-situ $MgAl_2O_4$ composite was subjected to mechanical and tribological characteristics and the wear behavior was analysed via a multi-objective optimization technique so as to scrutinize process parameters to attain a minimal wear loss and friction coefficient. Based on this research it was concluded that.

1. Al–4Mg/in-situ $MgAl_2O_4$ composites were successfully produced using ultrasonic treatment. $MgAl_2O_4$ particles are uniformly distributed in the matrix.
2. Compared to Al–4Mg alloy properties, the hardness, yield, and tensile of the 2 wt% in-situ $MgAl_2O_4$ composites are increased by 38 %, 37 %, and 35 %, respectively.
3. ANOVA and Grey results revealed that wt.% $MgAl_2O_4$ particles are the influencing factor, trailed by load and sliding velocity.
4. Based on Grey relational grade analysis, the lowest friction coefficient and wear loss was achieved for following optimal process parameters: 2 wt% in-situ $MgAl_2O_4$, at a load of 20 N and sliding velocity of 2 m/s.
5. From the investigation, it was found that Taguchi coupled with Grey relational analysis can be used for optimization of process parameter multi-responsive systems.

Data availability

Data will be available on request.

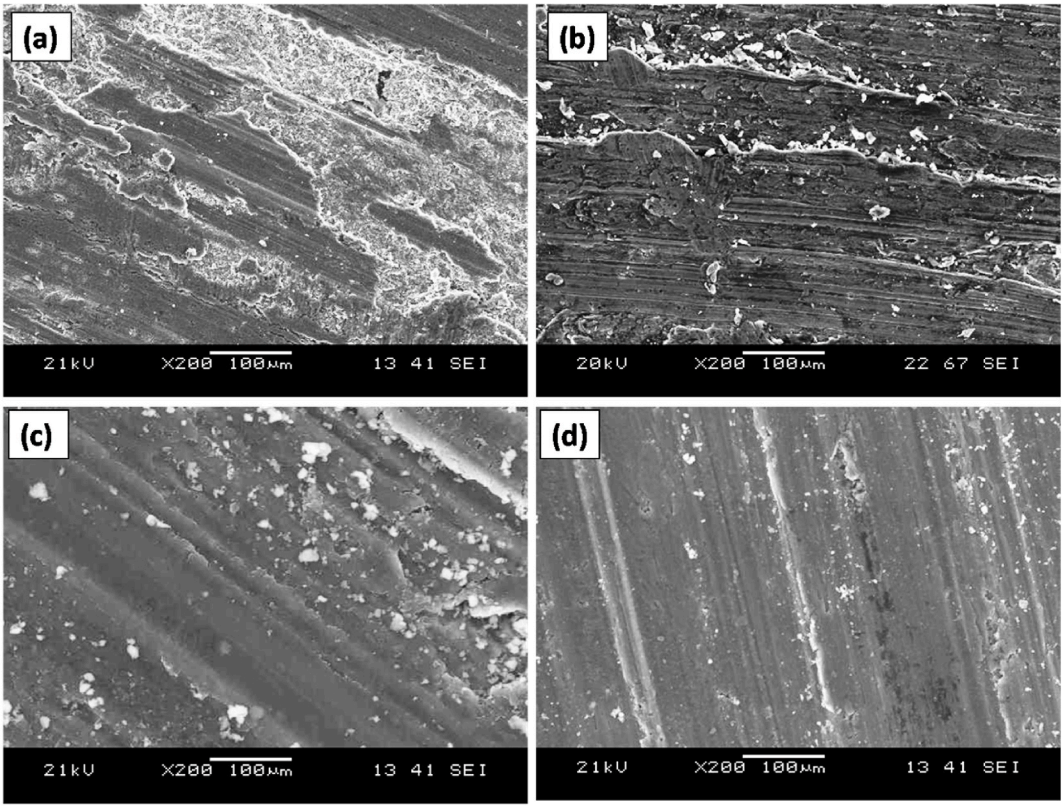

Fig. 6. Worn out surfaces of (a)Al–4Mg (b) Al–4Mg/0.5 wt%$MgAl_2O_4$(c) Al–4Mg/1 wt% $MgAl_2O_4$ and (d) Al–4Mg/2 wt% $MgAl_2O_4$.

CRediT authorship contribution statement

Satish Kumar Thandalam: Writing – review & editing. **Titus Thankachan:** Writing – review & editing, Visualization, Validation, Supervision, Data curation, Conceptualization. **Emad Makki:** Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jayant Giri:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sathish Thanikodi:** Validation, Supervision, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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