

Evaluation of Tribological Performance for Aluminium Metal Matrix Composites: Entropy- VIKOR MCDM Approach

K. Sri Harsha¹, M. Padmanabham²

¹M. Tech Student, Mechanical Engineering, Sanketika Vidya Parishad Engineering College,
Visakhapatnam, India

²Assistant Professor, Mechanical Engineering, Sanketika Vidya Parishad Engineering College,
Visakhapatnam, India

Abstract

Aluminium Hybrid Metal Matrix Composites (AHMMCs) are increasingly used in aerospace, automotive, and marine applications because of their superior mechanical and tribological properties. This study investigates Al6061-based hybrid composites reinforced with equal proportions of SiC and Al₂O₃, with the total reinforcement content varied from 0-12 wt.%. The composites were fabricated using ultrasonic-assisted stir casting with a bottom-pouring arrangement. Their tribological performance was evaluated using a sliding wear and friction tribometer under varying reinforcement contents, normal loads, sliding velocities, and sliding distances. A Taguchi L27 orthogonal array was employed for experimental design, while volume wear loss (V), wear rate (WR), and coefficient of friction (COF) were simultaneously optimized using Entropy-VIKOR analysis. The results indicated that increasing SiC-Al₂O₃ reinforcement improved the wear resistance of the composites through the formation of protective/self-lubricating tribo-layers. The optimum condition corresponded to 10 wt.% reinforcement, 50 N load, 2.5 m/s sliding velocity, and 750 m sliding distance, yielding the minimum VIKOR index (Q_i). ANOVA confirmed that reinforcement content was the most influential parameter, which influenced the multiple responses. The developed hybrid composites demonstrate promising potential for tribological applications requiring enhanced wear resistance.

Keywords: Metal Matrix Composites (MMCs), Wear Loss, Wear Rate, Coefficient of Friction (COF), VIKOR analysis

1. Introduction

Metal Matrix Composites (MMCs) are advanced materials developed by incorporating ceramic, metallic, or carbon-based reinforcements into a metallic matrix to achieve enhanced mechanical, thermal, and tribological performance. Compared with conventional alloys, MMCs offer a combination of low density, high specific strength, stiffness, hardness, dimensional stability, and wear resistance, making them attractive for lightweight and demanding applications in the automotive, aerospace, marine, defence, and industrial sectors. Among various MMCs, aluminium-based metal matrix composites (AMMCs) have gained considerable attention owing to the low density, good corrosion resistance, castability, and machinability of aluminium alloys, together with the potential for substantial property enhancement

through reinforcement incorporation. The performance of AMMCs is strongly governed by the type, morphology, size, distribution, and concentration of reinforcement. Ceramic particles such as silicon carbide (SiC), aluminium oxide (Al_2O_3), boron carbide (B_4C), titanium carbide (TiC), and titanium diboride (TiB_2) are widely employed to improve hardness, strength, stiffness, and wear resistance. Carbon-based reinforcements, including graphite, graphene, and carbon nanotubes, are additionally used where reduced friction, self-lubrication, or enhanced functional properties are required. However, a single reinforcement may not simultaneously provide the diverse mechanical and tribological characteristics demanded by advanced applications. This limitation has encouraged the development of Hybrid Metal Matrix Composites (HMMCs), in which two or more reinforcement phases are combined within a metallic matrix to exploit their complementary properties. Appropriate hybridization can provide synergistic improvements in strength, hardness, load-bearing capacity, wear resistance, and frictional behaviour. Various combinations, including SiC- Al_2O_3 , SiC- B_4C , SiC- TiB_2 , and Al_2O_3 - TiB_2 , have therefore been investigated for structural and tribological applications. Among these systems, SiC- Al_2O_3 is particularly promising because both reinforcements exhibit high hardness, thermal stability, and resistance to material degradation, enabling improved resistance to deformation and material removal under sliding conditions. Aluminium-based HMMCs reinforced with SiC and Al_2O_3 are consequently promising candidates for wear-critical components such as automotive braking and engine components, aerospace structures, marine components, and other lightweight engineering systems. Their tribological performance, however, depends not only on reinforcement content but also on operating parameters such as normal load, sliding velocity, and sliding distance. Therefore, systematic investigation and multi-response optimization of these parameters are essential for establishing suitable processing and operating conditions for high-performance Aluminium-based HMMCs.

2. Literature Review

MMCs are fabricated through techniques such as stir casting, powder metallurgy, spray deposition, infiltration, squeeze casting, spark plasma sintering (SPS), and friction stir processing (FSP). The selection of fabrication route depends on reinforcement wettability, dispersion, porosity, interfacial bonding, microstructural control, mechanical performance, and production cost. Ramanathan Arunachalama et al. [1] reviewed MMC processing and identified reinforcement dispersion, porosity, wettability, and stirrer wear as major challenges. They recommended bottom-tapping stir casting integrated with electromagnetic/ultrasonic stirring and squeeze casting for improved composite quality. Lokesh Singh et al. [2] reviewed Al- and Mg-based MMCs and emphasized that reinforcement characteristics and processing conditions strongly govern composite performance, highlighting the need for process optimization. S.V. Sujith et al. [3] developed Al7079-TiC composites by in-situ melt reaction and demonstrated that TiC improves hardness, tensile strength, and wear resistance, although excessive reinforcement promotes brittleness. Jaswinder Singh and Amit Chauhan [4] reported that stir-cast aluminium hybrid composites provide improved mechanical and wear properties, offering a cost-effective alternative for automotive applications. Naseem Ahmad et al. [5] investigated Al- Al_2O_3 - TiO_2 composites and found that reinforcement addition improves mechanical performance, with 5% Al_2O_3 + 5% TiO_2 providing the highest tensile strength. Gowrishankar T.P. et al. [6] fabricated Al6061-Graphite-TiC composites and found that TiC enhanced hardness, tensile/yield strength, and wear resistance, while excessive TiC increased brittleness. B. Sadeghi et al. [7] studied nano/micro- Al_2O_3 -reinforced aluminium composites using SPS and FSP and showed that particle size and FSP heat input strongly influence

recrystallization, particle distribution, and hardness. Gebre Fenta Aynalem et al. [8] reviewed AMC fabrication methods and identified stirring time, reaction temperature, wettability, porosity, and reinforcement distribution as critical factors affecting composite quality. Vinod Kumar V. Meti et al. [9] developed AA7075-TiB₂ composites using ultrasound-assisted in-situ processing and reported improved particle distribution, hardness, grain refinement, and wear resistance. Subsequent forging further enhanced performance. V. Sivamaran et al. [10] investigated Al6061-MWCNT/n-SiC composites and found that n-SiC improved CNT dispersion and hardness, with optimum performance at 7.5 wt.% n-SiC; higher contents promoted agglomeration.

Tribological performance of MMCs is governed by reinforcement type/content, applied load, sliding speed, sliding distance, and fabrication conditions. Pin-on-disc testing and statistical/MCDM techniques are widely employed to characterize and optimize wear rate and coefficient of friction. A. Prasad Reddy et al. [11] investigated ultrasonically cast Al6061-SiC-Graphite composites and found that graphite initially reduced wear rate and friction, whereas excessive graphite caused clustering and property deterioration. Pagidi Madhukar et al. [12] studied Al7150-hBN nanocomposites using Taguchi and ANOVA and identified applied load as the dominant wear parameter. Up to 1.5 wt.% hBN improved hardness and wear resistance. Sandeep Kumar et al. [13] examined erosive wear of Al-Al₃Ti composites and found that impingement angle and stand-off distance strongly affect material loss, while increased reinforcement reduces erosion. Sudipta Chand et al. [14] investigated Al6061/B₄C/BN composites and identified impact velocity as the most influential erosion parameter. B₄C addition enhanced hardness, compressive strength, and erosion resistance, with ALO providing optimum conditions. Ali Alizadeh et al. [15] compared stir and squeeze casting of Al5083-SiC composites and demonstrated that combined processing reduces porosity and wear while improving hardness, compressive strength, and particle distribution. M. Lakshmanana et al. [16] developed AA7075/h-BN/NiTi composites using ultrasonic-assisted squeeze casting and reported improved wettability, grain refinement, load-bearing capacity, and wear resistance, with h-BN providing solid-lubrication effects. K. Suganeswaran et al. [17] investigated FSP of AA7075-Al₂O₃-SiC composites and found that combined tribofilm formation and load-bearing action improved wear resistance. The optimum composition contained 3.7 wt.% Al₂O₃ and 3.0 wt.% SiC. S. Sakthivelu et al. [18] studied dry sliding wear of AA8011-Al₂O₃ composites and identified load as the dominant parameter (58.97%). Taguchi-GRA yielded optimized wear conditions. Shuaihang Pan et al. [19] investigated AA7075-TiB₂ nanocomposites and demonstrated that COF is influenced by substrate hardness and counter-surface characteristics, providing new insights into friction mechanisms. Gowrishankar T.P. et al. [20] reported that Al6061-Graphite-TiC composites exhibit improved wear resistance and reduced friction, with optimum mechanical properties at approximately 4 wt.% TiC. E. Jayakumar et al. [21] investigated A319/SiC functionally graded composites and found that SiC-rich outer regions provide superior wear resistance, with abrasive wear as the dominant mechanism. J. David Raja Selvam et al. [22] showed that in-situ TiC reinforcement in AA6061 promotes grain refinement, load-bearing capacity, and wear resistance, while wear mechanisms change from ploughing/adhesion to delamination with increasing load. Siva Sankara Raju et al. [23] applied hybrid Grey-Fuzzy optimization to Al-coconut shell ash composites and identified load as the most influential parameter, followed by sliding distance and reinforcement content.

Radhika N. and R. Raghu [24] reported that AlN reinforcement improves the hardness, tensile strength, and wear resistance of LM13, while load remains the dominant wear parameter. R. Ambigai and S. Prabhu [25] demonstrated that Al-Graphite-Si₃N₄ hybrid composites provide synergistic strengthening and solid-

lubrication effects, reducing wear and friction compared with nano-reinforced composites. Pardeep Sharma et al. [26] investigated AA6101-Graphite composites and found that graphite reduces wear rate and friction, with 4 wt.% providing optimum tribological performance. Shalok Bharti et al. [27] studied FSP of AA2014- Al_2O_3 and reported substantial grain refinement, hardness improvement, and wear reduction, with 1400 rpm providing optimum performance. Mukesh Kumar [28] investigated AA356- $\text{Al}_2\text{O}_3/\text{SiC}/\text{Graphite}$ composites using Taguchi-GRA and identified the equal $\text{Al}_2\text{O}_3/\text{SiC}$ composition as the best-performing combination, while sliding distance was the dominant parameter. Mukesh Kumar et al. [29] evaluated SiO_2/SiC -reinforced AA2024 composites and showed that balanced ceramic reinforcement improves strength, hardness, and wear resistance; PSI effectively ranked the alternatives. Ashiwani Kumar et al. [30] studied AA7075- $\text{SiC}/\text{marble dust}/\text{Graphite}$ hybrids using Entropy-VIKOR and identified 6 wt.% SiC + 2 wt.% marble dust + 3 wt.% graphite as the best overall composition. M. Kumar et al. [31] reported that equal Al_2O_3 - SiC reinforcement in AA2024 provides superior mechanical and wear performance, with PSI effectively supporting material selection.

R. Ambigai and S. Prabhu [32] confirmed that Al-Graphite- Si_3N_4 hybrids exhibit lower wear and friction due to the combined strengthening and solid-lubrication effects; sliding distance and load were the major factors. J. Udaya Prakash et al. [33] optimized 356/ B_4C composites using Taguchi analysis and identified load as the most influential parameter (35.35%), followed by sliding distance and speed. Naseem Ahamad et al. [34] investigated Al- Al_2O_3 - TiO_2 hybrids and found that reinforcement improves hardness and wear resistance, while ANOVA identified load and reinforcement as significant factors. TOPSIS ranked the optimum composite. P. Venkateshwar Reddy et al. [35] investigated Al6063- TiC composites and reported that increasing TiC improves hardness, strength, and wear resistance. RSM identified reinforcement content and sliding speed as major factors and predicted wear behaviour with high accuracy. Overall, the literature confirms that hard reinforcements such as SiC , Al_2O_3 , TiC , TiB_2 , and B_4C enhance hardness and load-bearing capacity, whereas graphite and hBN contribute solid-lubrication effects. Hybrid reinforcement systems can therefore provide simultaneous mechanical and tribological improvements. However, the optimum reinforcement level and dominant wear parameters vary with the matrix, reinforcement combination, fabrication route, and operating conditions. Limited research has systematically investigated Al6061 reinforced with equal proportions of SiC and Al_2O_3 over varying reinforcement levels while simultaneously optimizing volume wear loss, wear rate, and coefficient of friction. Therefore, an Entropy-VIKOR-based multi-response optimization approach can provide a useful framework for identifying the most favourable combination of material composition and tribological parameters.

3. Methodology

3.1 Taguchi Method

The Taguchi method is a robust design-of-experiments (DOE) approach widely employed for process optimization and quality improvement under experimental variability. It uses orthogonal arrays (OA) to systematically evaluate the effects of multiple control factors and their levels with a reduced number of experimental trials. The balanced structure of OA enables efficient estimation of the influence of individual process parameters while minimizing experimental effort. The method further incorporates the signal-to-noise (S/N) ratio to evaluate response robustness by considering both the desired performance and experimental variation. Depending on the optimization objective, S/N characteristics such as larger-the-better, smaller-the-better, and nominal-the-best can be adopted. Consequently, the Taguchi approach

provides a statistically efficient and economical framework for identifying optimal process conditions and improving the consistency and performance of engineering systems.

Common SNR Categories:

- **Smaller-the-Better:** Used when the objective is to minimize the response (e.g., defects or errors).

$$SNR = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right)$$

where y_i is the observed value.

- **Larger-the-Better:** Used when the objective is to maximize the response (e.g., strength or efficiency).

$$SNR = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right)$$

- **Nominal-the-Best:** Used when the objective is to maintain the response close to a specific target value.

$$SNR = 10 \log_{10} \left(\frac{\mu^2}{\sigma^2} \right)$$

where μ is the mean and σ^2 is the variance.

3.2 Multi-Criteria Decision-Making and VIKOR Analysis

Multi-Criteria Decision-Making (MCDM) or Multi-Attribute Decision-Making (MADM) methods are effective tools for evaluating alternatives under multiple, often conflicting, performance criteria. These approaches enable the simultaneous consideration of different responses and facilitate the identification of the most preferable alternative based on defined decision criteria. In engineering applications, MCDM techniques are increasingly employed for process optimization, material selection, performance evaluation, and parameter ranking, particularly when multiple responses must be optimized simultaneously.

3.2.1 VIKOR Analysis

VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) is an MCDM technique developed to determine a compromise solution from a set of alternatives evaluated against conflicting criteria. The method identifies the alternative that provides the closest overall compromise to the ideal solution. The sequential procedure adopted for VIKOR analysis is presented in Figure 1.

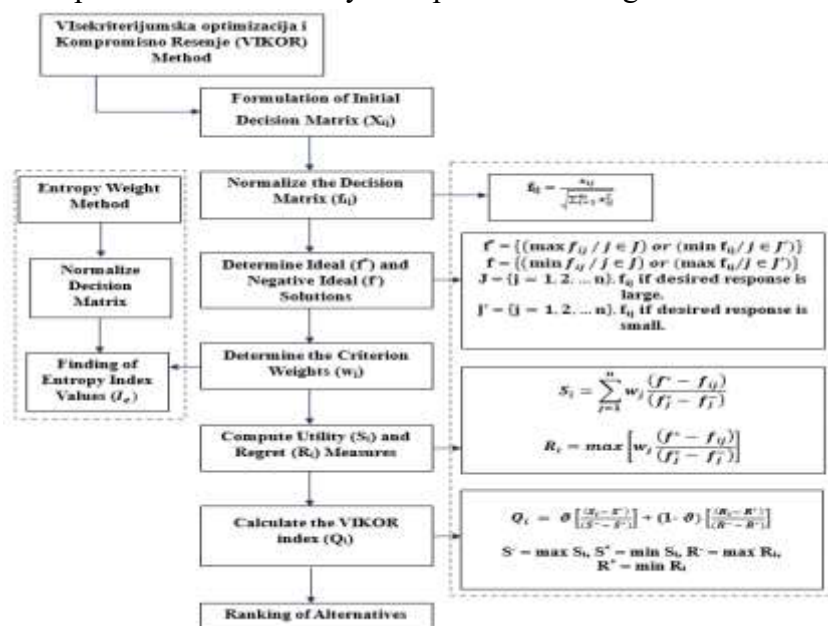


Figure 1. Flow Chart for Entropy-VIKOR

Initially, the alternatives and evaluation criteria are defined, and a decision matrix is constructed, with alternatives represented by rows and criteria by columns. The criteria are classified as benefit or cost attributes, depending on whether higher or lower values are preferred. The best and worst values for each criterion are then determined to establish the positive ideal solution (f_i^*) and negative ideal solution (f_i^-), respectively. The decision matrix is subsequently normalized, and the utility measure (S_i) and regret measure (R_i) are calculated. The S_i measure represents the overall deviation of an alternative from the ideal solution, whereas R_i denotes its maximum individual regret for any criterion. These measures are integrated through the VIKOR index (Q_i) to determine the overall compromise ranking. Alternatives are ranked according to their Q_i values, with the lowest Q_i indicating the most preferable compromise solution.

4. Experimentation Details

4.1 Dry Sliding Wear and Friction Test

The wear resistance of the Al6061/SiC/Al₂O₃ hybrid composites was evaluated using a pin-on-disc tribometer (MMT, Micromatic Technologies, Bengaluru, India), as shown in Figure 2. Before testing, the specimen surfaces were polished using 100-grit SiC emery paper to obtain a clean and uniform contact surface. Dry sliding wear tests were conducted at room temperature in accordance with ASTM G99, using an EN31 steel counter disc with a hardness of 62 HRC and dimensions of 150 mm diameter x 8 mm thickness, having an initial surface roughness of 0.6 μm R_a. The principal specifications of the pin-on-disc tribometer are provided in Table 1.



Figure 2. PIN-ON-DISC Test Machine

Table 1. Specifications of PIN-ON-DISC Test Machine

Make	MMT
Normal Load	10-200N Dead Weights
Sliding Speed	0.26-10 m/s
Disc Speed	50-2000 RPM

Disc Material	EN31 of 62 HRC
Wear Disc Diameter	165 x 8 mm thick
Wear Track Diameter	10-140 mm
Specimen Pin Diameter	3-12 mm
Pin Length	25-30 mm
Ball Diameter	6-12 mm (bearing Steel)
Specimen Standards	ASTM G99 & DIN 50324

The composite compositions considered for the experimental investigation are presented in Table 2. Following the dry sliding tests, the wear loss of the pin specimens and coefficient of friction (COF) were evaluated using the weight-loss method.

Table 2. Details of Wear Test Composite Samples

Sample	Al (wt.%)	SiC (wt.%)	Al ₂ O ₃ (wt.%)
A	98	1	1
B	94	3	3
C	90	5	5

4.2 Design of Experiments (DOE)

The Box-Behnken Design (BBD) under the Response Surface Methodology (RSM) framework was employed to design the experimental trials. Using MINITAB 18, four input parameters reinforcement content (wt.%), normal load, sliding velocity, and sliding distance were considered at three levels, while the track radius was maintained constant at 35 mm. The selected factor levels are presented in Table 3, and the resulting L27 BBD experimental matrix is provided in Table 4.

Table 3. Input Parameters and Respected Levels

Input Variable	Units	Levels		
		-1	0	+1
Reinforcement Content	wt.%	2	6	10
Load (N)	N	10	30	50
Sliding Velocity (v)	m/s	1	1.75	2.5
Sliding Distance (D)	m	300	525	750

Table 4. L27 Experimental Runs

Exp.	Reinforcement wt.%	N	v	D
1	2	10	1	300
2	2	10	1.75	525
3	2	10	2.5	750
4	2	30	1	525
5	2	30	1.75	750
6	2	30	2.5	300
7	2	50	1	750
8	2	50	1.75	300

9	2	50	2.5	525
10	6	10	1	525
11	6	10	1.75	750
12	6	10	2.5	300
13	6	30	1	750
14	6	30	1.75	300
15	6	30	2.5	525
16	6	50	1	300
17	6	50	1.75	525
18	6	50	2.5	750
19	10	10	1	750
20	10	10	1.75	300
21	10	10	2.5	525
22	10	30	1	300
23	10	30	1.75	525
24	10	30	2.5	750
25	10	50	1	525
26	10	50	1.75	750
27	10	50	2.5	300

5. Results and Discussions

The wear and friction behavior of Al-6061/SiC/Al₂O₃ hybrid composites was investigated under varying dry sliding conditions to determine the optimal tribological parameters. The Entropy-VIKOR approach, a multi-criteria decision-making (MCDM) technique, was employed to simultaneously evaluate the multiple tribological responses and identify the most favorable parametric combination. By integrating objective criteria weighting through the Entropy method with compromise ranking using VIKOR, the approach provides a systematic framework for determining the optimal operating conditions and enhancing the overall tribological performance of the hybrid composites.

5.1 Measurement of Responses and Optimization

In tribometer testing, volumetric wear loss (V), wear rate (WR), and coefficient of friction (COF) are key responses for evaluating material performance under dry sliding conditions. These responses are influenced by parameters such as reinforcement content (wt.%), applied load (N), sliding velocity (v), and sliding distance (SD). Volumetric wear loss is determined from the measured weight loss and material density, while wear rate is obtained by normalizing the wear loss with respect to sliding distance. The coefficient of friction is defined as the ratio of frictional force to the applied load. The experimentally obtained wear responses are presented in Table 5, and the corresponding calculations are given by equations 1 to 3.

$$\text{Volumetric Wear Loss (V)} = \frac{\Delta m}{\rho} \times 1000; \text{mm}^3 \quad \text{Eq. (1)}$$

$$\text{Wear Rate (WR)} = \frac{\text{Volumetric wear Loss (V)}}{\text{Sliding Distance (D)}} = \frac{\Delta m}{\rho \times D}; \text{mm}^3/\text{m} \quad \text{Eq. (2)}$$

$$\text{Coefficient of Friction (COF)} = \frac{\text{Frictional force (F)}}{\text{Applied load (N)}} \quad \text{Eq. (3)}$$

5.2 Entropy-Vikor Analysis Optimization

The Entropy-VIKOR procedure described in the methodology was applied to determine the criteria weights and VIKOR index values for the considered alternatives. The corresponding normalized decision matrix and entropy-based indices for the selected responses are presented in Table 6.

Table 5. Empirical Findings of Responses

S.No.	V, mm ³	WR, mm ³ /m	COF
1	9.435	0.023	0.458
2	7.992	0.015	0.525
3	6.512	0.009	0.592
4	6.845	0.013	0.498
5	5.365	0.007	0.521
6	5.661	0.019	0.499
7	4.255	0.006	0.506
8	4.514	0.015	0.494
9	3.071	0.006	0.507
10	6.329	0.012	0.317
11	4.894	0.007	0.388
12	5.188	0.017	0.320
13	3.753	0.005	0.451
14	4.048	0.014	0.431
15	2.576	0.005	0.452
16	2.907	0.008	0.452
17	1.472	0.003	0.465
18	0.077	0.001	0.479
19	3.279	0.004	0.176
20	3.571	0.012	0.112
21	2.114	0.004	0.179
22	2.443	0.008	0.361
23	0.984	0.002	0.383
24	0.438	0.006	0.405
25	0.146	0.003	0.424
26	1.567	0.002	0.437
27	1.276	0.004	0.424

From the entropy indices, the entropy (e_j) values for the criteria are calculated to be 0.9309 for Volumetric-Loss (V), 0.9045 for Wear-Rate (WR), and 0.9871 for Coefficient-of-Friction (COF). The degree of diversification (d_j) represents the contrast or variability associated with each criterion, where a higher d_j value indicates greater discriminatory capability and, consequently, a higher criterion weight. The obtained d_j values for V, WR, and COF are 0.0691, 0.0954, and 0.0128, respectively. Normalization of these values yielded the corresponding weights of $w_V = 0.3893$, $w_{WR} = 0.5380$, and $w_{COF} = 0.0726$. These criterion weights were subsequently used to determine the utility measure (S_i) and regret measure (R_i) for each

alternative. Finally, the VIKOR index (Q_i) was calculated by assigning $v = 0.5$, providing an equal balance between the utility and regret measures. The calculated S_i , R_i , and Q_i values are presented in Table 7.

Table 6. Normalization and Entropy Indices Values of Responses

S.No.	Normalization (f_{ij})			Entropy Indices		
	V	WR	COF	V	WR	COF
1	0.4103	0.5506	0.2045	-0.22184	-0.27162	-0.13037
2	0.3476	0.2665	0.2343	-0.20108	-0.17935	-0.14302
3	0.2832	0.1525	0.2641	-0.17709	-0.12372	-0.1549
4	0.2977	0.2279	0.2224	-0.18275	-0.16221	-0.13806
5	0.2333	0.1262	0.2323	-0.15622	-0.1083	-0.14219
6	0.2462	0.3314	0.2229	-0.16182	-0.20513	-0.13827
7	0.1850	0.0999	0.2260	-0.13369	-0.09152	-0.13956
8	0.1963	0.2630	0.2203	-0.13918	-0.17785	-0.13717
9	0.1336	0.1017	0.2262	-0.10643	-0.09269	-0.13967
10	0.2752	0.2122	0.1414	-0.1739	-0.15475	-0.10054
11	0.2128	0.1140	0.1712	-0.14697	-0.10066	-0.11521
12	0.2256	0.3033	0.1429	-0.1528	-0.19441	-0.10129
13	0.1632	0.0877	0.2014	-0.1226	-0.08312	-0.12899
14	0.1760	0.2367	0.1919	-0.12918	-0.16624	-0.12477
15	0.1120	0.0859	0.2018	-0.09377	-0.08189	-0.12919
16	0.1264	0.1701	0.2017	-0.10233	-0.13336	-0.12915
17	0.0640	0.0491	0.2077	-0.06176	-0.0536	-0.13175
18	0.0032	0.0018	0.2136	-0.00528	-0.00336	-0.13434
19	0.1426	0.0772	0.0784	-0.11152	-0.07559	-0.06492
20	0.1553	0.2087	0.0500	-0.11841	-0.15305	-0.04588
21	0.0919	0.0701	0.0798	-0.08109	-0.07037	-0.06582
22	0.1062	0.1420	0.1609	-0.09017	-0.1177	-0.11028
23	0.0428	0.0333	0.1709	-0.04522	-0.03957	-0.11506
24	0.0190	0.0105	0.1808	-0.02362	-0.0155	-0.1197
25	0.0063	0.0053	0.1891	-0.00947	-0.00865	-0.1235
26	0.0681	0.0368	0.1950	-0.06477	-0.04282	-0.12618
27	0.0555	0.0754	0.1894	-0.05533	-0.0743	-0.12362

Table 7. Utility (S_i), Regret (R_i) Measures, and VIKOR Index Values of Alternatives

S.No.	Utility Measure (S_i)	Regret Measure (R_i)	VIKOR Index (Q_i)
1	0.9797	0.5380	1.0000
2	0.6513	0.3293	0.6127
3	0.4881	0.2678	0.4628
4	0.5618	0.2816	0.5164
5	0.4039	0.2201	0.3693
6	0.6141	0.3231	0.5864

7	0.3298	0.1739	0.2828
8	0.4985	0.2561	0.4566
9	0.2823	0.1247	0.2077
10	0.4974	0.2602	0.4601
11	0.3515	0.2005	0.3213
12	0.5398	0.2956	0.5186
13	0.2885	0.1530	0.2395
14	0.4437	0.2303	0.4010
15	0.2380	0.1041	0.1630
16	0.3343	0.1650	0.2763
17	0.1580	0.0582	0.0737
18	0.0554	0.0555	0.0156
19	0.2168	0.1333	0.1810
20	0.3482	0.2028	0.3218
21	0.1619	0.0848	0.1025
22	0.2736	0.1375	0.2158
23	0.1097	0.0410	0.0303
24	0.0680	0.0444	0.0112
25	0.0536	0.0472	0.0062
26	0.1456	0.0621	0.0709
27	0.1694	0.0721	0.0938

5.3. Response-Surface-Methodology (RSM)

Response Surface Methodology (RSM) is a statistical and mathematical approach used to model and optimize processes influenced by multiple input variables. It enables the evaluation of relationships between process parameters and responses, prediction of optimal operating conditions, and reduction of experimental effort through design of experiments (DOE). RSM is widely applied in materials science and manufacturing for process optimization and performance improvement. In the present study, a multiple linear regression model was developed to correlate the selected input parameters with the VIKOR index (Q_i), as expressed in Equation 4.

$$Q_i = 2.1296 - 0.13271 RFwt. \% - 0.01994 N - 0.1309 v - 0.002573 SD + 0.002049 RFwt. \% * RFwt. \% + 0.000055 N * N + 0.0024 v * v + 0.000002 SD * SD + 0.000749 RFwt. \% * N + 0.00718 RFwt. \% * v + 0.000048 RFwt. \% * SD + 0.001002 N * v + 0.000007 N * SD - 0.000049 v * SD$$

Eq.(4)

Table 8. ANOVA Findings of VIKOR Index (Q_i)

Source	DF	Adj SS	Adj MS	F	P
Model	14	1.41262	0.100902	214.67	0.000
Linear	4	1.27336	0.318339	677.26	0.000
RF wt. %	1	0.66550	0.665495	1415.84	0.000
N	1	0.34650	0.346502	737.18	0.000

V	1	0.05740	0.057396	122.11	0.000
SD	1	0.20396	0.203962	433.93	0.000
Square	4	0.04992	0.012480	26.55	0.000
RF wt.%* RF wt.%	1	0.00645	0.006446	13.71	0.003
N*N	1	0.00294	0.002938	6.25	0.028
v*v	1	0.00001	0.000011	0.02	0.881
SD*SD	1	0.04053	0.040526	86.22	0.000
2 way Interaction	6	0.08935	0.014891	31.68	0.000
RF wt.%*N	1	0.04039	0.040390	85.93	0.000
RF wt.%*v	1	0.00522	0.005220	11.11	0.006
RF wt.%*SD	1	0.02069	0.020695	44.03	0.000
N*v	1	0.00254	0.002538	5.40	0.039
N*SD	1	0.00976	0.009759	20.76	0.001
V*SD	1	0.00079	0.000785	1.67	0.221
Error	12	0.00564	0.000470		
Total	26	1.41826			

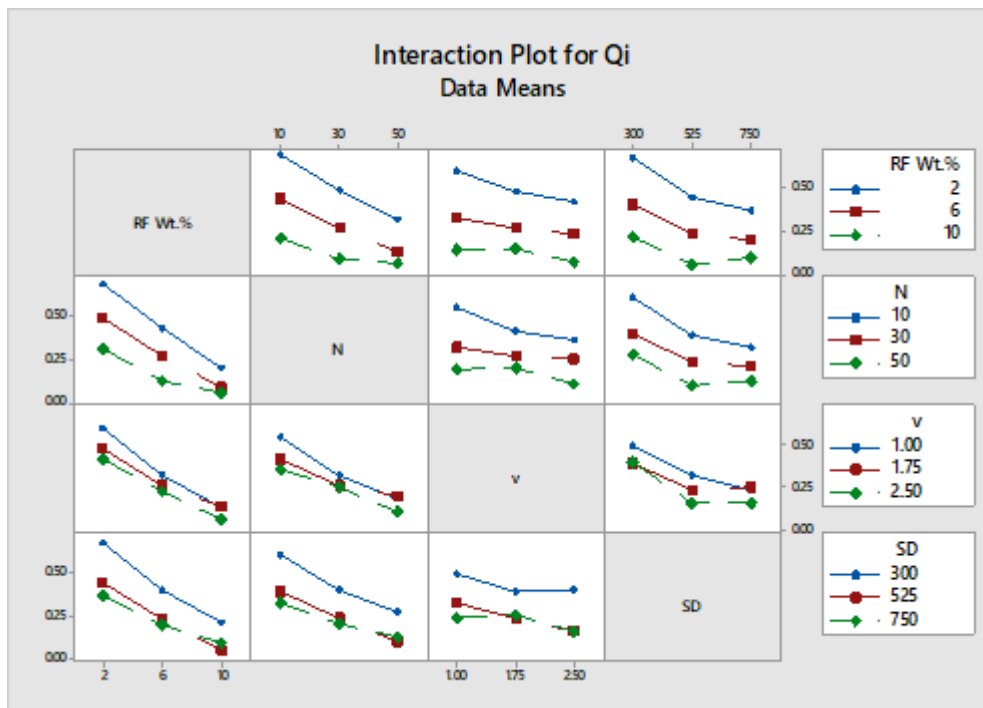


Figure 3. Interaction Effects Plot for VIKOR Index (Q_i)

Table 8 presents the ANOVA results for the VIKOR index (Q_i). The results indicate that all considered process parameters are statistically significant, with p-values < 0.05 at the 95% confidence level. The interaction effects among the tribometer parameters are also significant, as evidenced by the Q_i interaction plots presented in Figure 3. The ANOVA results indicate that reinforcement content (wt.%) is the most influential parameter in achieving a lower VIKOR index (Q_i), with an F-value of 1415.84. The adequacy

and reliability of the developed model were further verified using the residual plots for Q_i , presented in Figure 4. The plots confirm that the residuals satisfy the assumptions of normality and constant variance, indicating that the model is statistically adequate and suitable for predicting multi-response performance. The model demonstrates an excellent fit, with a standard deviation (S) of 0.0216803, an R^2 value of 99.60%, and an adjusted R^2 value of 99.14%.

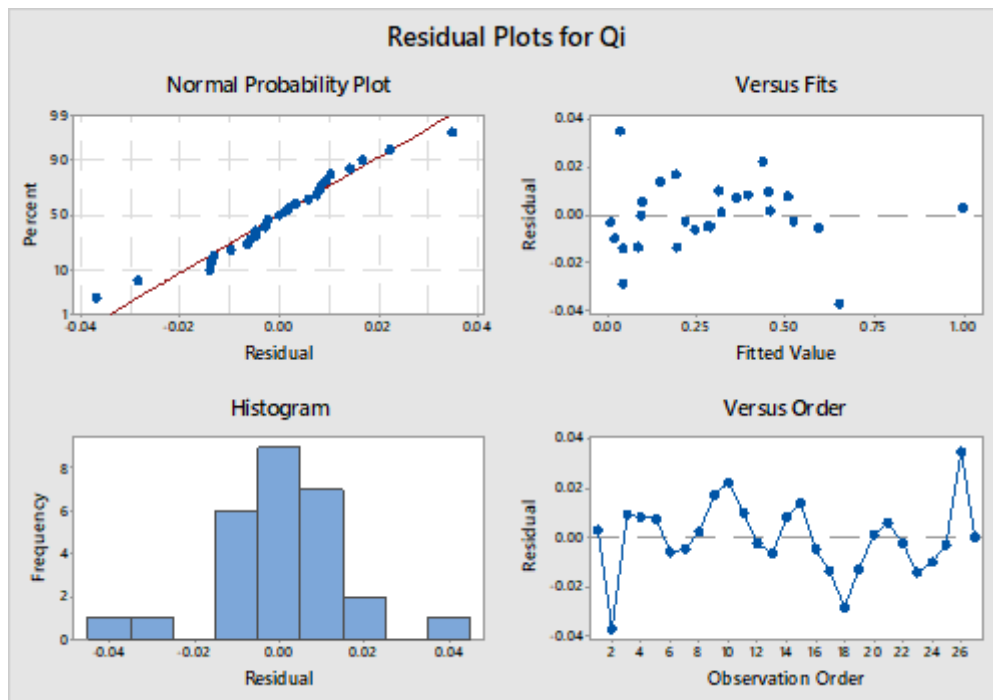


Figure 4. Residual Plots for VIKOR Index (Q_i)

6. Conclusions

Based on the experimental investigations and optimization results obtained using the Entropy-VIKOR approach, the following conclusions can be drawn:

- The Entropy-VIKOR analysis identified the optimum process parameters for achieving a minimum VIKOR index (Q_i) as 10 wt.% reinforcement content, 50 N applied load, 2.5 m/s sliding velocity, and 750 m sliding distance.
- ANOVA confirmed that reinforcement content (wt.%) is the most influential parameter affecting the VIKOR index, with an F-value of 1415.84.
- The developed regression model for the VIKOR index (Q_i) exhibited excellent predictive capability, with a standard deviation (S) of 0.0216, R^2 of 99.60%, and adjusted R^2 of 99.14%.
- The developed Al6061-based hybrid composites demonstrate potential for wear-resistant engineering applications, including aerospace fittings and brackets, turbine components, pistons, cylinder liners, cutting tools, bearings, and gears subjected to demanding sliding and wear conditions.

Future Scope

Future investigations may be extended to the following aspects:

- The effects of alternative solid lubricants, such as graphite (Gr), MoS_2 , hBN, and WS_2 , can be investigated as potential substitutes for magnesium (Mg) to further enhance the tribological performance.

nce of the hybrid composites.

- Friction and wear experiments can be conducted using a pin-on-disc (POD) apparatus under a wider range of applied loads and temperatures to evaluate the tribological stability and performance of the composites under diverse operating conditions.

References

1. Singh, L., Singh, B., & Saxena, K. K. (2020). Manufacturing techniques for metal matrix composites (MMC): an overview. *Advances in Materials and Processing Technologies*, 6(2), 441-457. <https://doi.org/10.1080/2374068X.2020.1729603>
2. Sharma, A., Sharma, V. M., Mewar, S., Pal, S. K., & Paul, J. (2018). Friction stir processing of Al6061-SiC-graphite hybrid surface composites. *Materials and Manufacturing Processes*, 33(7), 795-804. <https://doi.org/10.1080/10426914.2017.1401726>
3. Sujith, S. V., Mahapatra, M. M., & Mulik, R. S. (2020). Microstructural characterization and experimental investigations into two body abrasive wear behavior of Al-7079/TiC in-situ metal matrix composites. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 234(4), 588-607. <https://doi.org/10.1177/1350650119883559>
4. Singh, J., & Chauhan, A. (2019). A review of microstructure, mechanical properties and wear behavior of hybrid aluminium matrix composites fabricated via stir casting route. *Sādhanā*, 44, 1-18. <https://doi.org/10.1007/s12046-018-1025-5>
5. Ahamad, N., Mohammad, A., Sadasivuni, K. K., & Gupta, P. (2020). Structural and mechanical characterization of stir cast Al-Al₂O₃-TiO₂ hybrid metal matrix composites. *Journal of Composite Materials*, 54(21), 2985-2997. <https://doi.org/10.1177/0021998320906207>
6. Gowrishankar, T. P., Manjunatha, L. H., & Sangmesh, B. (2020). Mechanical and Wear behaviour of Al6061 reinforced with Graphite and TiC Hybrid MMC's. *Materials Research Innovations*. <https://doi.org/10.1080/14328917.2019.1628497>
7. Sadeghi, B., Shamanian, M., Ashrafizadeh, F., Cavaliere, P., & Rizzo, A. (2018). Friction stir processing of spark plasma sintered aluminum matrix composites with bimodal micro-and nano-sized reinforcing Al₂O₃ particles. *Journal of Manufacturing Processes*, 32, 412-424. <https://doi.org/10.1016/j.jmapro.2018.03.013>
8. Aynalem, G. F. (2020). Processing methods and mechanical properties of aluminium matrix composites. *Advances in Materials Science and Engineering*, 2020(1), 3765791. <https://doi.org/10.1155/2020/3765791>
9. Meti, V. K. V., Konaraddi, R., & Siddhalingeswar, I. G. (2018). Mechanical and tribological properties of AA7075 based MMC processed through ultrasound assisted casting technique. *Materials Today: Proceedings*, 5(11), 25677-25687. <https://doi.org/10.1016/j.matpr.2018.11.009>
10. Sivamaran, V., Balasubramanian, V., Gopalakrishnan, M., Viswabaskaran, V., Rao, A. G., & Sivakumar, G. (2020). Mechanical and tribological properties of Self-Lubricating Al 6061 hybrid nano metal matrix composites reinforced by nSiC and MWCNTs. *Surfaces and Interfaces*, 21, 100781. <https://doi.org/10.1016/j.surfin.2020.100781>
11. Bellamkonda, P. N., & SUDABATHULA, S. (2019). Wear and electrochemical corrosion behaviour of nano ZrO₂ reinforced AA7075 metal matrix composites. *International Journal of Mechanical and Production Engineering Research and Development*, 9(3), 793-802

12. Prasad Reddy, A., Vamsi Krishna, P., & Rao, R. N. (2019). Tribological behaviour of Al6061–2SiC-xGr hybrid metal matrix nanocomposites fabricated through ultrasonically assisted stir casting technique. *Silicon*, 11(6), 2853-2871. <https://doi.org/10.1007/s12633-019-0072-9>
13. Madhukar, P., Selvaraj, N., Rao, C. S. P., & Kumar, G. V. (2019). Tribological behavior of ultrasonic assisted double stir casted novel nano-composite material (AA7150-hBN) using Taguchi technique. *Composites Part B: Engineering*, 175, 107136. <https://doi.org/10.1016/j.compositesb.2019.107136>
14. Kumar, S., Manani, S., Nikunj, P., & Pradhan, A. K. (2020). Synthesis and air jet erosion wear behavior of aluminum–Al3Ti In-Situ composite. *Materials Today: Proceedings*, 28, 2572-2578. <https://doi.org/10.1016/j.matpr.2020.05.701>
15. Chand, S., & Chandrasekhar, P. (2020). Influence of B4C/BN on solid particle erosion of Al6061 metal matrix hybrid composites fabricated through powder metallurgy technique. *Ceramics International*, 46(11), 17621-17630. <https://doi.org/10.1016/j.ceramint.2020.04.064>
16. Alizadeh, A., Khayami, A., Karamouz, M., & Hajizamani, M. (2022). Mechanical properties and wear behavior of Al5083 matrix composites reinforced with high amounts of SiC particles fabricated by combined stir casting and squeeze casting; A comparative study. *Ceramics International*, 48(1), 179-189. <https://doi.org/10.1016/j.ceramint.2021.09.093>
17. Lakshmanan, M., Rajadurai, J. S., Chakkravarthy, V., & Rajakarunakaran, S. J. M. L. (2021). Tribological investigations on h-BN/NiTi inoculated Al7075 composite developed via ultrasonic aided squeeze casting. *Materials Letters*, 285, 129113. <https://doi.org/10.1016/j.matlet.2020.129113>
18. Suganeswaran, K., Parameshwaran, R., Mohanraj, T., & Radhika, N. (2021). Influence of secondary phase particles Al2O3/SiC on the microstructure and tribological characteristics of AA7075-based surface hybrid composites tailored using friction stir processing. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 235(1), 161-178. <https://doi.org/10.1177/0954406220932939>
19. Sakthivelu, S., Sethusundaram, P. P., Ravichandran, M., & Meignanammoorthy, M. (2021). Experimental investigation and analysis of properties and dry sliding wear behavior of Al-Fe-Si alloy matrix composites. *Silicon*, 13(4), 1285-1294. <https://doi.org/10.1007/s12633-020-00662-4>
20. Pan, S., Saso, T., Yu, N., Sokoluk, M., Yao, G., Umehara, N., & Li, X. (2020). New study on tribological performance of AA7075-TiB₂ nanocomposites. *Tribology International*, 152, 106565. <https://doi.org/10.1016/j.triboint.2020.106565>
21. Gowrishankar, T. P., Manjunatha, L. H., & Sangmesh, B. (2020). Mechanical and Wear behaviour of Al6061 reinforced with Graphite and TiC Hybrid MMC's. *Materials Research Innovations*. <https://doi.org/10.1080/14328917.2019.1628497>
22. Jayakumar, E., Praveen, A. P., Rajan, T. P. D., & Pai, B. C. (2018). Studies on tribological characteristics of centrifugally cast SiCp-reinforced functionally graded A319 aluminium matrix composites. *Transactions of the Indian Institute of Metals*, 71, 2741-2748. <https://doi.org/10.1007/s12666-018-1442-5>
23. David Raja Selvam, J., Dinaharan, I., Rai, R. S., & Mashinini, P. M. (2019). Dry sliding wear behaviour of in-situ fabricated TiC particulate reinforced AA6061 aluminium alloy. *Tribology-Materials, Surfaces & Interfaces*, 13(1), 1-11. <https://doi.org/10.1080/17515831.2018.1550971>

24. Raju, S. S., Rao, G. S., & Samantra, C. (2019). Wear behavioral assessment of Al-CSAp-MMCs using grey-fuzzy approach. *Measurement*, 140, 254-268. <https://doi.org/10.1016/j.measurement.2019.04.004>
25. Radhika, N., & Raghu, R. (2017). Investigation on mechanical properties and analysis of dry sliding Wear behavior of Al LM13/AlN metal matrix composite based on Taguchi's technique. *Journal of Tribology*, 139(4), 041602. <https://doi.org/10.1115/1.4035155>
26. Ambigai, R., & Prabhu, S. (2019). Fuzzy logic algorithm-based optimisation of the tribological behavior of Al-Gr-Si₃N₄ hybrid composite. *Measurement*, 146, 736-748. <https://doi.org/10.1016/j.measurement.2019.07.025>
27. Sharma, P., Paliwal, K., Garg, R. K., Sharma, S., & Khanduja, D. (2017). A study on wear behaviour of Al/6101/graphite composites. *Journal of Asian ceramic societies*, 5(1), 42-48. <https://doi.org/10.1016/j.jascer.2016.12.007>
28. Bharti, S., Ghetiya, N. D., & Patel, K. M. (2020). Micro-hardness and wear behavior of AA2014/Al₂O₃ surface composite produced by friction stir processing. *SN Applied Sciences*, 2(11), 1760. <https://doi.org/10.1007/s42452-020-03585-2>
29. Kumar, M. (2021). Mechanical and sliding wear performance of AA356-Al₂O₃/SiC/graphite alloy composite materials: parametric and ranking optimization using Taguchi DOE and hybrid AHP-GRA method. *Silicon*, 13, 2461-2477. <https://doi.org/10.1007/s12633-020-00544-9>
30. Kumar, M., & Kumar, A. (2020). Application of preference selection index method in performance based ranking of ceramic particulate (SiO₂/SiC) reinforced AA2024 composite materials. *Materials Today: Proceedings*, 27, 2667-2672. <https://doi.org/10.1016/j.matpr.2019.11.244>
31. Kumar, A., Kumar, M., & Pandey, B. (2022). Investigations on mechanical and sliding wear performance of AA7075- SiC/marble dust/graphite hybrid alloy composites using hybrid ENTROPY-VIKOR method. *Silicon*, 14(5), 2051-2065. <https://doi.org/10.1007/s12633-021-00996-7>
32. Kumar, M., Bhaskar, S., Kumar Shakyawal, N., & Kumar, A. (2020). Application of preference selection index method in performance (mechanical properties and sliding wear) based ranking of AA2024-Al₂O₃/SiC alloy composites. *Materialwissenschaft und Werkstofftechnik*, 51(12), 1662-1685. <https://doi.org/10.1002/mawe.201900138>
33. Ambigai, R., & Prabhu, S. (2017). Optimization of friction and wear behaviour of Al-Si₃N₄ nano composite and Al-Gr-Si₃N₄ hybrid composite under dry sliding conditions. *Transactions of Nonferrous Metals Society of China*, 27(5), 986-997. [https://doi.org/10.1016/S1003-6326\(17\)60116-X](https://doi.org/10.1016/S1003-6326(17)60116-X)
34. Udaya Prakash, J., Jebarose Juliyana, S., Saleem, M., & Moorthy, T. V. (2021). Optimisation of dry sliding wear parameters of aluminium matrix composites (356/B4C) using Taguchi technique. *International Journal of Ambient Energy*, 42(2), 140-142. <https://doi.org/10.1080/01430750.2018.1525590>
35. Ahamad, N., Mohammad, A., Sadasivuni, K. K., & Gupta, P. (2021). Wear, optimization and surface analysis of Al-Al₂O₃-TiO₂ hybrid metal matrix composites. *Proceedings of the institution of mechanical engineers, Part J: Journal of Engineering Tribology*, 235(1), 93-102. <https://doi.org/10.1177/1350650120970432>