MECHANICAL ENGINEERING | RESEARCH ARTICLE

Wear conduct of aluminum matrix composites: A parametric strategy using Taguchi based GRA integrated with weight method

Narinder Kaushik1* and Sandeep Singhal1

Abstract: The present work concentrates on the preparation of AA6063-SiC metal matrix composites and analysis of wear properties using the hybrid Taguchi-GRA-Weight method. AA6063 al-alloy matrix composites were prepared by liquid metal-lurgy stir casting process by varying the weight fraction of SiC particles in steps of 3.5 weight percentage. The SiC particles of average particle size 37 μm were varied in three steps viz, 3.5, 7, and 10.5%. The experiments were performed in accordance with the L27 Taguchi orthogonal array to get the wear data in a controlled manner. Effect of three process parameters, Load (N), Sliding distance (m) and wt. % of SiC on the quality characteristics wear and frictional force in non lubricated dry slippery states was analyzed by using pin-on-disc wear and friction monitor. The optimum level of process parameters was obtained by using GRA for multiple quality characteristics. ANOVA was used to analyze the effect of individual process parameters on wear and frictional force. The experimental outcomes confirmed that the wear behavior of the prepared composites enhanced under optimal trial states. The wear examination results detailed that lower load of 20 N and moderate weight percentage (7 wt. % SiC) and sliding distance (1,046 m) produced minimum wear in the fabricated matrix composites. The optical microscopic analysis of the worn out

ABOUT THE AUTHORS
Narinder Kaushik is pursuing PhD in Mechanical Engineering Department from National Institute of Technology Kurukshetra, India. He received his BTech in Mechanical Engineering from PDM College of Engineering, Bahadurgarh, Haryana and MTech from NIT Kurukshetra. His areas of research include fabrication of composite materials, tribological properties of the composite material, friction stir welding of al-alloys and AMCs, experimental designs, advanced optimization techniques.

PUBLIC INTEREST STATEMENT
AA 6063 is an aluminum alloy, with magnesium and silicon as the major alloying elements. It has generally good mechanical properties and is heat treatable and weldable. This alloy has excellent tensile strength ranging in between 130 and 190 MPa. AA6063 is highly corrosion resistant material and is well suited for many applications. It allows complex shapes to be formed and so is popular for visible architectural applications such as window frames, door frames, roofs, and sign frames. It is widely used in the fabrication of irrigation pipes and railway parts. The incorporation of ceramic material like SiC into the matrix alloy AA6063 enhanced the mechanical and wear properties to a great extent. The pin-on-disc wear examination is useful for the various sectors dealing with improving the tribological performance of mechanical components. The outcome of this investigation is likely to shed some light on various issues related to the wear behavior of aluminum alloy AA6063 reinforced with ceramic agents.
specimens was also carried out to describe the wear mechanism. The validation of the predicted values done through confirmation experiment at optimal variable setting has shown a good agreement with the worn surface morphology.

Subjects: Industrial Engineering & Manufacturing; Mechanical Engineering; Composites; Manufacturing Engineering

Keywords: aluminum matrix composites (AMC’s); AA6063; SiC; wear; GRA; weight method

1. Introduction

Metal matrix composites reinforced with ceramic reinforcements have a wide range of applications in aerospace, automobile, structural components, smartphone sector and defense area. Monolithic aluminum alloys have limitations in achieving good combinations of mechanical properties. Metal matrix composites are produced to overcome these shortcomings and to encounter the world-wide desire for lightweight materials escorted by elevated specific strength, high wear resistance and better stiffness properties (Adamiak, 2006; López, Scoles, & Kennedy, 2003; Tokaji, 2005). The aluminum matrix series like 2xxx, 5xxx, 6xxx, and 7xxx have numerous applications in aerospace, defense instrument, architectural and structural components, automobile, sports goods, and ship building (Adamiak, 2006; Khan, Kutty, & Surappa, 2006; López et al., 2003; Tokaji, 2005). Metallic matrix composites are a combination of two or more chemically and physically distinct phases of metals, intermetallic compounds in which the dispersed phases are embedded within the metallic matrix to impart properties that are not achievable from the discrete phases. For the production of metal matrix composites, several types of fabrication techniques are in use. The well known liquid metallurgy stir casting process is the most recognized and appropriate technique used in the processing of AMCs (Adebisi, Maleque, Ali, & Bello, 2016). The several types of carbides, borides, nitrides and oxides in the form of particles and fibres (continuous or discontinuous) like aluminum oxide, silicon carbide, boron carbide, titanium carbide, titanium dioxide, titanium diboride, magnesium oxide, silicon nitride etc. can be used as reinforcement phase into the matrix phase to form metal-matrix composites (Ipek, 2005; Kerti & Toptan, 2008; Lee, Ahn, & Kwon, 2001). The SiC particles which are very hard and brittle ceramics possess superior and excellent mechanical properties like high strength in tension and compression, good fracture toughness, high hardness number (2500 VPN), great modulus of elasticity, high wear resistant and superior elevated temperature properties which makes it one of the favorable reinforcement agent for many aluminum-alloy based metal-matrix composites (East, 1988). The inclusion of the reinforcement agents into the matrix alloy phase definitely enhanced the mechanical and microstructural properties of the resulting composite materials as compared to the individual monolithic matrix alloy (Singla, Chhibber, Bansal, & Kalra, 2015). For example, the incorporation of particulate TiB₂ in metal matrix AA6063 has shown increased value of tensile strength (increased 1.23 times from 155 MPa to 191 MPa) with a decrease in percentage elongation as compared to the monolithic 6063 Al-matrix (Zhang et al., 2015). At higher vol. percentage of reinforcement agents such as 9 and 12 vol. percentage of SiC a remarkable enhancement in the strength of aluminum alloy 6063 composites was observed without any adverse effect on the ductility of the composites as compared with the monolithic aluminum alloy (Alaneme & Aluko, 2012). It was investigated that the wear performance of silicon nitride sliding against itself in water showing the low coefficient of friction and low wear. The wear of silicon nitride in water occurs mainly due to the tribo-chemical dissolution of material without the release of the solid particle (Xu & Kato, 2000). The pin-on-disc dry sliding wear tests were performed with Si₃N₄ and CoCr disc against Si₃N₄ and Al₂O₃ ball in the presence of phosphate buffered saline (PBS) and bovine serum. Si₃N₄ sliding against Si₃N₄ showed low wear rate in both PBS and bovine serum comparable to other pairs (Olofsson et al., 2012). The wear tests were conducted to analyze the wear performance of AA6061 based composites reinforced with SiC/Red-mud/Al₂O₃. It was detailed that the wear rate starts decreasing with the increase in wt. % of SiC and Al₂O₃ in the fabricated composite, but in the case of red mud as reinforcement, the wear rate of the composite decreases with the incorporation of red mud up to 7.5 weight percent only. Beyond the 7.5 weight percentage red mud composition as reinforcement, the wear rate starts to increase (Singla et al., 2015).
The wear performance of AA6061 + SiC composite when subjected to normal applied load and temperature demonstrated that wear rate lessens with expansion in applied load (Yu, Ishii, Tohgo, Cho, & Diao, 1997). The dry sliding wear examination of Al matrix alloy strengthened with silicon carbide whiskers (from 0 to 16%) detailed that the wear rate of the manufactured composite decreases with the increment in vol. % of SiC whiskers into the matrix compound (Iwai, Yoneda, & Honda, 1995). It was reported that the grating wear rate of AA2124 composites reinforced with SiC particles was increased with increase in applied normal loads. The matrix composites reinforced with SiC particles demonstrated higher wear rate than those reinforced by Al2O3 particles because of the higher hardness of SiC abrasives (İzciler & Muratoglu, 2003). It was observed that AA2104 matrix composites reinforced with Al2O3 particles have shown lower wear rate for all experimental states than the unreinforced AA2104 matrix alloy. The work hardening phenomenon experienced by matrix phase and the dispersion of hard SiC agents was responsible for low wear rate (Modi, 2001). In many experimental cases, we regularly need to manage multi-objective problems, which might be greatly associated with each other. The conventional Taguchi strategy can’t solve multi-response optimization problems. The Taguchi strategy combined with grey relational analysis might be utilized to defeat this issue. Taguchi based multi-objective grey relational analysis (GRA) was successfully implemented to optimize the process parameters like $T_{on}$, $T_{off}$, SV, IP, WF, WT in the WEDM process to analyze their effect on the quality characteristics (Kumar & Singh, 2016).

The Taguchi strategy was utilized to explore the grating wear conduct of AA2024/Al2O3 matrix composites under various experimental states. The results demonstrated that reinforcement particle size and grating grain size were observed to be the most affecting parameter on grating wear. The wear rate found to be decreased with increase in Al2O3 particle size and sliding distance (Kök, 2011). The dry sliding wear conduct of Al–Si7 Mg composites strengthened with graphite and 10% SiC particles was investigated using CCD approach. Utilizing central composite plan, the impact of % fortification, sliding velocity, sliding distance and normal load, on stir cast AA + graphite, AA + SiC composite, and AA + SiC + Gr hybrid composites were examined. The results demonstrated that hybrid composites displayed better wear qualities (Suresha & Sridhara, 2010). The wear execution of electroless Ni–P coatings was analyzed and optimization of the wear test variables utilizing Taguchi technique combined with grey relation analysis was performed. GRG (grey relational grade) acquired from GRA (Grey relational analysis) has been applied as a performance indicator to examine the conduct of electroless Ni–P coating regarding friction and wear qualities (Sahoo & Pal, 2007).

Taguchi experimental approach is selected for the robust and sophisticated design. As compared to traditional designs Taguchi method gives an easy, systematic and managed approach by minimizing the experimental time and cost of experiments for the optimization of the design factors (Montgomery, 2001). Taguchi experimental plan basically utilizes two important tools (i) S/N (signal to noise) ratio which lessen quality characteristic variation due to unmanageable factors. (ii) Orthogonal array which occupies the design factors for experimentation. The key part is the selection of process parameters in the design of experiment approach. According to Taguchi, optimizing a process is not sufficient: making processes and products more robust to quality issues and environmental noises is crucial. In this strategy, designed experiments clearly play a central role.

In this paper grey relational analysis coupled with the weight of response characteristics was utilized to inspect the wear performance of the prepared composites. The experimental runs have been performed in accordance with the L27 Taguchi orthogonal array. Investigations were carried out for AA6063/3.5% SiC, AA6063/7% SiC and AA6063/10.5% SiC composites. Process factors chosen in this work were load, sliding distance and wt. % SiC. Investigation of the optimum setting of these process variables was the main objective. ANOVA was applied to obtain the contribution of each variable on the quality characteristics. Worn surface morphology examination has been carried out by using optical microscopy to analyze the wear mechanism.
2. Material and experimentation detail

2.1. Fabrication of AA6063/SiC AMC

The modified two-step liquid metallurgy processing technique (stir casting process) has been employed for the fabrication of proposed AA6063-SiC composites. Weighed amount of AA6063 was melted at 810°C in a digital temperature controlled top loading electric resistance furnace using a graphite crucible. After entire melting of al-alloy preheated (in a separate furnace at 900°C) SiC particles in the form of very small packets (enveloped in aluminum foil) were charged into the molten slurry and mechanical stirring at 450 rpm was employed to form a fine vortex (Hashim, Looney, & Hashmi, 1999; Sevik & Kurnaz, 2006). Magnesium metal powder (1% by wt.) was mixed into the melt during vortex stirring to improve the wettability between al-alloy and silicon carbide particles. Mechanical stirring of the molten slurry was employed using an SS impeller comprises four blades covered with alumina powder for 15 min at an average speed of 450 rpm to ensure the complete mixing of the reinforcement SiC particles into the melt. Two-step stirring procedure was employed to ensure a thorough mixing and to overcome problems of agglomeration. The composite slurry at this stage was reheated at temperature 750 ± 30°C, as the temperature lowers down during stirring. At this time mechanical torque was again applied by stirrer and the composite slurry was rotated for 5 min at the same average speed. The Composite samples of different wt. % (3.5%, 7%, 10.5%) were obtained by pouring the mixture slurry into preheated (at 250 deg. Celsius) cast iron mold at a pouring temperature of 720°C and let to cool at room temperature. The OM and SEM images of fabricated AA6063/7% SiC$_p$ matrix composite are shown in Figure 1(a–b). The XRD analysis of this fabricated matrix composite is shown in Figure 2.

2.2. Wear examinations

The composite samples (3.5, 7 & 10.5% weight fraction) have been subjected to sliding wear examinations in non lubricated dry slippery conditions performed on a pin-on-disc wear and friction monitor machine as shown in Figure 3 [DUCOM (TR-20LE)]. The counter-face disc is made of EN-31 steel with a hardness value of 62HRC. The disc has 100 mm diameter and10 mm thickness. The standard test samples of size $32 \times 6 \times 6$ mm as shown in Figure 4 were gripped against the counter-face disc. The test samples prior to the start of wear test have been fine polished with 600-grit size emery paper to make flat face to be pressed against the counter-face disc. The steel disc and test samples were then cleaned thoroughly with acetone to maximize the accuracy of the wear data acquired. The composite specimens were subjected to dry sliding wear tests at room temperature in accordance with Taguchi analysis $L_{27}$ (Kandpal, Kumar, & Singh, 2017) design matrix as appeared in Table 2. The input process factors selected during wear conduct at three levels are mentioned in Table 1. To acquire error-free data the samples were polished after each run. The LVDT arrangement with accuracy of 1 μm during the wear test continuously acquired the wear data in terms of length in micrometer (height loss of the specimens in micrometer). The wear displacement sensor permits for acquiring direct readings of the deflection due to load lever, which is analogous to the wear of the specimen. The wear behavior is usually expressed in terms of wear volume or weight loss [Wear rate
Figure 2. XRD analysis of AA6063/7% SiCp.

Figure 3. View of pin-on-disc wear and friction monitor.

Figure 4. Pin specimens from fabricated composites for wear testing.

Table 1. The input process factors and their levels

| Sr. No. | Input process factors       | Factors at three level |
|---------|----------------------------|------------------------|
|         |                            | Level 1 | Level 2 | Level 3 |
| 1       | Load (L:N)                 | 20      | 30      | 40      |
| 2       | Sliding distance (SD:m)    | 523     | 1,046   | 1,570   |
| 3       | Wt. % SiC (W: wt %)        | 3.5     | 7       | 10.5    |
\[(\text{mm}^3/\text{m}) = \text{Height loss (mm)} \times \text{Cross-sectional area of the specimen (mm}^2)/\text{Sliding distance (m)}\],

here in this study wear is expressed in terms of height loss in micrometer (μm) of the specimen. The wear values of the specimen in micrometer and frictional force (FF) values in Newton were directly acquired from the LVDT set up.

### 2.3. Taguchi experimental plan

Taguchi experimental approach is selected for the robust and sophisticated design. As compared to traditional designs Taguchi method gives an easy, systematic and managed approach by minimizing the experimental time and cost of experiments for the optimization of the design factors (Montgomery, 2001). A factorial design could be used but the main drawback of a fractionated design is that some interactions may be confounded with other effects. It is important to consider carefully the role of potential confounders and aliases. Failure to take account of such confounding effects can result in erroneous conclusions and misunderstandings. While Taguchi’s designs are usually highly fractionated, this makes them very attractive and the interactions effect can be analysed effectively. When using a Taguchi design, we can guess which interactions are most likely to be significant even before any experiment is performed.

| Exp. No. | L (N) | SD (m) | W (wt. %) | Wear (µm) | FF (N) |
|----------|-------|--------|-----------|-----------|--------|
| 1        | 20    | 523    | 3.5       | 160.25    | 12.01  |
| 2        | 20    | 523    | 7         | 125.37    | 10.82  |
| 3        | 20    | 523    | 10.5      | 97.21     | 8.39   |
| 4        | 20    | 1,046  | 3.5       | 185.43    | 14.53  |
| 5        | 20    | 1,046  | 7         | 130.35    | 3.56   |
| 6        | 20    | 1,046  | 10.5      | 101.34    | 4.32   |
| 7        | 20    | 1,570  | 3.5       | 179.06    | 17.04  |
| 8        | 20    | 1,570  | 7         | 168.01    | 3.59   |
| 9        | 20    | 1,570  | 10.5      | 123.53    | 2.15   |
| 10       | 30    | 523    | 3.5       | 196.24    | 12.31  |
| 11       | 30    | 523    | 7         | 135.27    | 4.15   |
| 12       | 30    | 523    | 10.5      | 107.25    | 8.95   |
| 13       | 30    | 1,046  | 3.5       | 208.71    | 16.0   |
| 14       | 30    | 1,046  | 7         | 141.25    | 2.64   |
| 15       | 30    | 1,046  | 10.5      | 150.94    | 8.17   |
| 16       | 30    | 1,570  | 3.5       | 233.15    | 13.22  |
| 17       | 30    | 1,570  | 7         | 213.1     | 6.95   |
| 18       | 30    | 1,570  | 10.5      | 174.02    | 10.1   |
| 19       | 40    | 523    | 3.5       | 215.52    | 18.73  |
| 20       | 40    | 523    | 7         | 159.85    | 6.89   |
| 21       | 40    | 523    | 10.5      | 145.52    | 17.56  |
| 22       | 40    | 1,046  | 3.5       | 220.25    | 19.05  |
| 23       | 40    | 1,046  | 7         | 155.52    | 7.26   |
| 24       | 40    | 1,046  | 10.5      | 147.25    | 12.95  |
| 25       | 40    | 1,570  | 3.5       | 261.35    | 17.77  |
| 26       | 40    | 1,570  | 7         | 237.03    | 6.61   |
| 27       | 40    | 1,570  | 10.5      | 225.07    | 18.71  |
3. Results and discussion

3.1. Dry sliding pin-on-disc wear analysis

The principal objective of the present study was to minimize the wear performance characteristics, wear (μm) and frictional force (N) for casted composite matrix AA6063/SiCp using the Taguchi-GRA-Weight method. The lower values of wear and frictional force produce better wear performance. The raw data for the two performance characteristics are given in Table 2. This raw data has been utilized to calculate the grey relational coefficients and grey relational grades after processing normalization and deviation sequence. In this study both the quality characteristics are of smaller-is-better type. Equations (1) and (3) have been used to calculate normalized values and deviation sequence respectively as appeared in Table 3. The grey relational grade (GRG) was obtained by introducing the weight value of each performance characteristics. The higher value of grey relational grade showed that the corresponding experimental results were closer to the optimum value.

| Exp. No. | Normalized values | Deviation sequence | Grey relational coefficient |
|----------|-------------------|--------------------|-----------------------------|
| Ref. Seq. | WEAR (µm) | FF (N) | WEAR (µm) | FF (N) | WEAR (µm) | FF (N) |
| 1 | 1.000 | 0.6159 | 0.4166 | 0.3841 | 0.5834 | 0.5656 | 0.4615 |
| 2 | 0.8284 | 0.4870 | 0.1716 | 0.5130 | 0.7445 | 0.4936 |
| 3 | 1.0000 | 0.6308 | 0.0000 | 0.3692 | 1.0000 | 0.5752 |
| 4 | 0.4625 | 0.2675 | 0.5375 | 0.7325 | 0.4819 | 0.4057 |
| 5 | 0.7981 | 0.9166 | 0.2019 | 0.0834 | 0.7124 | 0.8570 |
| 6 | 0.9748 | 0.8716 | 0.0252 | 0.1284 | 0.9521 | 0.7957 |
| 7 | 0.5013 | 0.1189 | 0.4987 | 0.8811 | 0.5007 | 0.3620 |
| 8 | 0.5687 | 0.9148 | 0.4313 | 0.0852 | 0.5369 | 0.8544 |
| 9 | 0.8396 | 1.0000 | 0.1604 | 0.0000 | 0.7572 | 1.0000 |
| 10 | 0.3967 | 0.3988 | 0.6033 | 0.6012 | 0.4532 | 0.4541 |
| 11 | 0.7681 | 0.8817 | 0.2319 | 0.1183 | 0.6832 | 0.8086 |
| 12 | 0.9388 | 0.5976 | 0.0612 | 0.4024 | 0.8910 | 0.5541 |
| 13 | 0.3207 | 0.1805 | 0.6793 | 0.8195 | 0.4240 | 0.3789 |
| 14 | 0.7317 | 0.9710 | 0.2683 | 0.0290 | 0.6508 | 0.9452 |
| 15 | 0.6727 | 0.6438 | 0.3273 | 0.3562 | 0.6043 | 0.5840 |
| 16 | 0.1718 | 0.3450 | 0.8282 | 0.6550 | 0.3765 | 0.4329 |
| 17 | 0.2940 | 0.7160 | 0.7060 | 0.2840 | 0.4166 | 0.6377 |
| 18 | 0.5320 | 0.5296 | 0.4680 | 0.4704 | 0.5166 | 0.5152 |
| 19 | 0.2792 | 0.0189 | 0.7208 | 0.9811 | 0.4096 | 0.3376 |
| 20 | 0.6184 | 0.7195 | 0.3816 | 0.2805 | 0.5671 | 0.6406 |
| 21 | 0.7057 | 0.0882 | 0.2943 | 0.9118 | 0.6295 | 0.3541 |
| 22 | 0.2504 | 0.0000 | 0.7496 | 1.0000 | 0.4001 | 0.3333 |
| 23 | 0.6448 | 0.6976 | 0.3552 | 0.3024 | 0.5846 | 0.6232 |
| 24 | 0.6951 | 0.3609 | 0.3049 | 0.6391 | 0.6212 | 0.4390 |
| 25 | 0.0000 | 0.0757 | 1.0000 | 0.9243 | 0.3333 | 0.3511 |
| 26 | 0.1482 | 0.7361 | 0.8518 | 0.2639 | 0.3699 | 0.6545 |
| 27 | 0.2210 | 0.0201 | 0.7790 | 0.9799 | 0.3909 | 0.3379 |
3.2. Grey relational analysis

GRA was created by Deng in (1982). GRA works like a discovery idea where known and obscure components are assembled to get the optimum level of the responses. GRA utilizes normalization of values to compute GRC (grey relational coefficients) and GRG (grey relational grade). It computes the optimal process level and ANOVA is connected to forecast the optimal level of grey relational grades.

\[
X_1^*(k) = \frac{\max X_i^O(k) - X_i^P(k)}{\max X_i^O(k) - \min X_i^O(k)} \quad \text{(smaller is better)}
\]

(1)

\[
X_1^*(k) = \frac{X_i^O(k) - \min X_i^O(k)}{\max X_i^O(k) - \min X_i^O(k)} \quad \text{(larger is better)}
\]

(2)

The steps used in normalization calculation (using Table 2) in case of experiment No. 1 are given below:

\[
X_{i\text{WEAR}}^*(1) = \frac{\max X_i^O(k) - X_i^P(k)}{\max X_i^O(k) - \min X_i^O(k)} = \frac{261.35 - 160.25}{261.35 - 97.25} = 0.6159
\]

\[
X_{i\text{RF}}^*(1) = \frac{\max X_i^O(k) - X_i^P(k)}{\max X_i^O(k) - \min X_i^O(k)} = \frac{19.05 - 12.01}{19.05 - 2.15} = 0.4166
\]

In the above equations (4, 5) \( i \) = 1 to \( m \) and \( k \) = 1 to \( n \); \( m \) is the number of experimental runs and \( n \) is the number of process factors. The term \( X_i^O(k) \) represents the original or reference sequence; \( \min X_i^O(k) \) and \( \max X_i^O(k) \) represents the minimum and maximum values in the original sequence; \( X_i^P(k) \) represents the sequence produced after data processing.

The grey relational coefficients after data processing were calculated with the particular deviation calculations as given in Equations (3) and (4) (Çaydaş & Hasçalık, 2008; Deng, 1982).

\[
\Delta_o(k) = \left| X_i^O(k) - X_i^P(k) \right|
\]

(3)

\[
\xi_j(k) = \frac{\Delta_{\text{min}} + \psi \Delta_{\text{max}}}{\Delta_o(k) + \psi \Delta_{\text{max}}}
\]

(3)

The deviation sequence (using equation 3) for exp. No. 1 is calculated as given below:

\[
\Delta_{i\text{WEAR}}(1) = \left| X_{i\text{WEAR}}^O(k) - X_{i\text{WEAR}}^P(k) \right| = |1 - 0.6159| = 0.3841
\]

\[
\Delta_{i\text{RF}}(1) = \left| X_{i\text{RF}}^O(k) - X_{i\text{RF}}^P(k) \right| = |1 - 0.4166| = 0.5834
\]

Where \( \Delta_o(k) \) is deviation sequence of original reference sequence of \( X_i^O(k) \) and compatibility sequence \( X_i^O(k); \xi_j(k) \) denotes the grey relational coefficient (GRC) and \( \psi \) is distinguishing coefficient and is usually taken 0.5 when equal weightage is given to the process parameters. The Grey relational coefficients (GRC) for all experimental runs of the L_{18} orthogonal array as appeared in Table 3 have been computed using Equation (4). The example calculation for GRCs (using Equation 4) for experiment No. 1 is given below:

\[
\xi_{i\text{WEAR}}(1) = \frac{\Delta_{\text{min}} + \psi \Delta_{\text{max}}}{\Delta_o(k) + \psi \Delta_{\text{max}}} = \frac{0 + 0.5 \times 1}{0.3841 + 0.5 \times 1} = 0.5656
\]
3.3. GRG computation

In the final step of computation, the grey relational grade has been calculated using equation (5). After calculating the grey relational coefficients, the grey relational grade was computed by introducing weight method. The weight values have been assigned in three ways. (i) Here, like if the performance characteristics Wear and Frictional Force are assigned equal weight, then GRC of Wear and Frictional Force (FF) are multiplied by 0.5. (ii) If Wear is assigned more weight than Frictional Force (FF), then GRC of Wear is multiplied by 0.7 and Frictional Force (FF) is multiplied by 0.3. (iii) If Wear is assigned less weight than Frictional Force, then Wear is multiplied by 0.3 and Frictional Force (FF) is multiplied by 0.7. The sample calculation for GRG for experiment No. 1 is given below:

\[
\xi_{FF}(1) = \frac{\Delta_{\min} + \psi \cdot \Delta_{\max}}{\Delta_{o_i}(k) + \psi \cdot \Delta_{\max}} = \frac{0 + 0.5 \cdot 1}{0.5834 + 0.5 \cdot 1} = 0.4615
\]

\[
\gamma_i(\text{GRG}) = W_1 \xi_{\text{WEAR}}(1) + W_2 \xi_{\text{FF}}(1)
\]

\[
\gamma_i(\text{GRG}) = 0.5 \cdot 0.5656 + 0.5 \cdot 0.4615 = 0.5135
\]

In equation (8) \( \gamma_i \) denotes GRG of ith experiment and \( W_1, W_2 \) denotes weight assigned. The higher value of grey relational grade showed that the corresponding experimental results were closer to the optimum value or normalized value. GRG of each experimental run using L27 orthogonal array are presented in Table 4. The highest GRG value indicated that the corresponding test result was closer to the ideally normalized value. In case of equal weight (i.e. \( W_1 = W_2 = 0.5 \)) and when Wear was assigned a minimum weight (i.e. 0.3), Frictional Force (FF) was assigned a maximum weight (i.e. 0.7), then the ninth experimental run produced the highest grey relational grade (GRG) value. The sixth experimental run produced the highest GRG value when Wear was assigned a maximum weight (i.e. 0.7) and Frictional Force (FF) was assigned a minimum weight (i.e. 0.3). The highest grey relational grade values are shown by bold and highlighted text in Table 4.

3.4. Evaluation of optimal combination of input process factors and ANOVA implementation

To estimate the optimum level and percentage contribution (PC) of each process parameter, the Taguchi analysis was performed using the GRG values. The analysis of variance (ANOVA) has been applied to compute the most significant factor to the process parameter-level response (Rajeswari, Amirthagadeswaran, & Anbarasu, 2015). The main effects Table, ANOVA Table and main effects plot (when equal weight 0.5 was assigned to both responses) as appeared in Table 5, Table 6 and Figure 5 respectively depicts the optimal level (in bold underlined text Table 5 and Figure 5) and percentage contribution (PC) of each process parameter (Table 6). The optimal parameter set is described as L1SD2W2, which means Load at 1st level (20 N), Sliding Distance at 2nd level (1,046 m) and Wt. % SiC at 2nd level (7wt. %). The main effects plot which clearly justifies the optimal parameter setting is shown in Figure 5. The ANOVA Table 6 clearly indicates that Wt. % SiC is the most influencing parameter (PC = 43.88) followed by Load (PC = 24.43) and Sliding distance (PC = 3.84) in enhancing the wear performance of the prepared composites. The effect of the significant parameters has been considered to predict the optimal value of every response characteristic. The residual plots were also considered to assess statistic for the issues like non normality, non-random variation, non constant variance, higher-order relationships, and outliers. From Figure 6 it can be analyzed that the residuals follow an approximately straight line in normal probability plot, and an approximate symmetric nature of histogram indicates that the residuals are normally distributed. Residuals possess constant variance as they are scattered randomly around zero in residuals vs. the fitted values. Residuals exhibit no clear pattern in residual versus order plot, thus there is no error due to time or data collection order.

3.5. Confirmation experiment

The results obtained at optimum process parameter setting have been validated through confirmation experimental runs. To get the average values three confirmation experiments were performed.
for every quality characteristics (Wear and Frictional Force). The predicted mean value of GRG at optimum level of parameter setting was computed by using equation (6). The estimated values for multi-response optimization at optimum level of parameter setting were confirmed through confirmation experimental results as presented in Table 7. The average values of the response variables must lie within the 95% confidence interval, obtained from confirmation experiments $C_{ICE}$ and $C_{pop}$.

**Table 4. Grey Relational Grade (GRG)**

| Exp. No. | W$^1_1 = W^2_2 = 0.5$ |  | W$^1_1 = 0.7, W^2_2 = 0.3$ |  | W$^1_1 = 0.3, W^2_2 = 0.7$ |  |
|----------|------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
|          | WEAR (µm) 0.5          | FF (N) 0.5              | GRG                     | WEAR (µm) 0.7          | FF (N) 0.3              | GRG                     | WEAR (µm) 0.3          | FF (N) 0.7              | GRG                     |
| 1        | 0.2828                 | 0.2307                  | 0.5135                  | 0.3959                 | 0.1384                  | 0.5343                  | 0.1697                 | 0.3230                  | 0.4927                  |
| 2        | 0.3723                 | 0.2468                  | 0.6191                  | 0.5212                 | 0.1481                  | 0.6992                  | 0.2324                 | 0.3455                  | 0.5689                  |
| 3        | 0.5000                 | 0.2876                  | 0.7876                  | 0.7000                 | 0.1726                  | 0.8726                  | 0.3000                 | 0.4027                  | 0.7027                  |
| 4        | 0.2410                 | 0.2028                  | 0.4438                  | 0.3374                 | 0.1217                  | 0.4591                  | 0.1464                 | 0.2840                  | 0.4285                  |
| 5        | 0.3562                 | 0.4285                  | 0.7847                  | 0.4986                 | 0.2571                  | 0.7557                  | 0.2137                 | 0.5999                  | 0.8136                  |
| 6        | 0.4760                 | 0.3978                  | 0.8739                  | 0.6665                 | 0.2387                  | 0.9052                  | 0.2856                 | 0.5570                  | 0.8426                  |
| 7        | 0.2503                 | 0.1810                  | 0.4314                  | 0.3505                 | 0.1086                  | 0.4591                  | 0.1502                 | 0.2534                  | 0.4036                  |
| 8        | 0.2684                 | 0.4272                  | 0.6956                  | 0.3758                 | 0.2563                  | 0.6321                  | 0.1611                 | 0.5981                  | 0.7591                  |
| 9        | 0.3786                 | 0.5000                  | 0.8786                  | 0.5300                 | 0.3000                  | 0.8300                  | 0.2272                 | 0.7000                  | 0.9272                  |
| 10       | 0.2266                 | 0.2270                  | 0.4536                  | 0.3172                 | 0.1362                  | 0.4534                  | 0.1360                 | 0.3178                  | 0.4538                  |
| 11       | 0.3416                 | 0.4043                  | 0.7459                  | 0.4782                 | 0.2426                  | 0.7208                  | 0.2050                 | 0.5660                  | 0.7710                  |
| 12       | 0.4455                 | 0.2770                  | 0.7225                  | 0.6237                 | 0.1662                  | 0.7899                  | 0.2673                 | 0.3879                  | 0.6552                  |
| 13       | 0.2120                 | 0.1895                  | 0.4015                  | 0.2968                 | 0.1137                  | 0.4105                  | 0.1272                 | 0.2652                  | 0.3924                  |
| 14       | 0.3254                 | 0.4726                  | 0.7980                  | 0.4555                 | 0.2836                  | 0.7391                  | 0.1952                 | 0.6616                  | 0.8569                  |
| 15       | 0.3022                 | 0.2920                  | 0.5942                  | 0.4230                 | 0.1752                  | 0.5982                  | 0.1813                 | 0.4088                  | 0.5901                  |
| 16       | 0.1882                 | 0.2164                  | 0.4047                  | 0.2635                 | 0.1299                  | 0.3934                  | 0.1129                 | 0.3030                  | 0.4160                  |
| 17       | 0.2073                 | 0.3189                  | 0.5262                  | 0.2902                 | 0.1913                  | 0.4815                  | 0.1244                 | 0.4464                  | 0.5708                  |
| 18       | 0.2583                 | 0.2576                  | 0.5159                  | 0.3616                 | 0.1546                  | 0.5162                  | 0.1550                 | 0.3607                  | 0.5156                  |
| 19       | 0.2048                 | 0.1688                  | 0.3736                  | 0.2867                 | 0.1013                  | 0.3880                  | 0.1229                 | 0.2363                  | 0.3592                  |
| 20       | 0.2836                 | 0.3203                  | 0.6039                  | 0.3970                 | 0.1922                  | 0.5892                  | 0.1701                 | 0.4484                  | 0.6186                  |
| 21       | 0.3147                 | 0.1771                  | 0.4918                  | 0.4406                 | 0.1062                  | 0.5469                  | 0.1888                 | 0.2479                  | 0.4367                  |
| 22       | 0.2001                 | 0.1667                  | 0.3667                  | 0.2801                 | 0.1000                  | 0.3801                  | 0.1200                 | 0.2333                  | 0.3534                  |
| 23       | 0.2923                 | 0.3116                  | 0.6039                  | 0.4092                 | 0.1869                  | 0.5962                  | 0.1754                 | 0.4362                  | 0.6116                  |
| 24       | 0.3106                 | 0.2195                  | 0.5301                  | 0.4349                 | 0.1317                  | 0.5665                  | 0.1864                 | 0.3073                  | 0.4936                  |
| 25       | 0.1667                 | 0.1755                  | 0.3422                  | 0.2333                 | 0.1053                  | 0.3387                  | 0.1000                 | 0.2457                  | 0.3457                  |
| 26       | 0.1849                 | 0.3273                  | 0.5122                  | 0.2589                 | 0.1964                  | 0.4553                  | 0.1110                 | 0.4582                  | 0.5691                  |
| 27       | 0.1955                 | 0.1689                  | 0.3644                  | 0.2737                 | 0.1014                  | 0.3750                  | 0.1173                 | 0.2365                  | 0.3538                  |

**Table 5. Taguchi analysis: Main effects table for GRG ($W_1 = W_2 = 0.5$)**

| Level | L  | SD | W  |
|-------|----|----|----|
| 1     | 0.6698 | 0.5902 | 0.4145 |
| 2     | 0.5736 | 0.5996 | 0.6544 |
| 3     | 0.4654 | 0.5190 | 0.6399 |
| Delta | 0.2044 | 0.0806 | 0.2398 |
| Rank  | 2   | 3   | 1   |

*Optimum level of the factors = $L_1, S_0, W_r$. 
The 95% confidence intervals of confirmation experiments ($CI_{CE}$) and of the population ($CI_{pop}$) are computed by using the Equations (7) and (8). The comparison between actual GRG and predicted GRG values is shown in Figure 7.

\[ \hat{\gamma} = \gamma_m + \sum_{i=1}^{v} (\gamma_i - \gamma_m) \]  
(6)

\[ \hat{\gamma} = 0.5696 + (0.6698 - 0.5696) + (0.5996 - 0.5696) + (0.6544 - 0.5696) = 0.7846 \]  
(Using Table 5 and Table 6; when $W_1 = W_2 = 0.5$)

Where $\hat{\gamma}$ predicted mean GRG value, $\gamma_m$ total mean of GRG, $\gamma_i$ mean GRG at optimum level, $v$ No. of process parameters.

\[ CI_{CE} = \sqrt{F_{\alpha}(1, f_e)} V_e \left( \frac{1}{n_{eff}} + \frac{1}{R} \right) \]  
(7)

**Table 6. ANOVA results for GRG**

| Source | DF | Adj SS  | Adj MS  | $F$-Value | $P$-Value | PC  |
|--------|----|---------|---------|-----------|-----------|-----|
| L      | 2  | 0.18817 | 0.094084| 11.97     | 0.000     | 24.43|
| SD     | 2  | 0.03496 | 0.017479| 2.22      | 0.134     | 3.84 |
| W      | 2  | 0.32551 | 0.162755| 20.71     | 0.000     | 43.88|
| Error  | 20 | 0.15721 | 0.007860|           |           | 27.85|
| Total  | 26 | 0.70584 |         |           |           | 100.00|

Figure 5. Graph showing main effects plot of grey relational grade (GRG).
Figure 6. Graph showing Residual plot for mean in terms of GRG.

Table 7. Predicted optimal values, confidence intervals and results of confirmation test

| Sr. No. | W₁ = W₂ = 0.5 | Predicted optimal value (GRG) | Predicted confidence intervals at 95% confidence level | Actual value (Avg. of 3 confirmation test) |
|---------|---------------|------------------------------|--------------------------------------------------------|------------------------------------------|
| 1.      | Optimal parameter setting | Predicted optimal value (GRG) | Predicted confidence intervals at 95% confidence level | Actual value (Avg. of 3 confirmation test) |
|         | L₁SD₂W₂     | 0.7846                       | CIₐ₃̂: 0.6649 < γ < 0.9043 CI₃ₐ: 0.7302 < γ < 0.8389 | 0.7929                                    |
| 2.      | W₁ = 0.7, W₂ = 0.3 | Predicted optimal value (GRG) | Predicted confidence intervals at 95% confidence level | Actual value (Avg. of 3 confirmation test) |
|         | L₁SD₂W₁     | 0.8197                       | CIₐ₃̂: 0.7131 < γ < 0.9262 CI₃ₐ: 0.8054 < γ < 0.8339 | 0.8319                                    |
| 3.      | W₁ = 0.3, W₂ = 0.7 | Predicted optimal value (GRG) | Predicted confidence intervals at 95% confidence level | Actual value (Avg. of 3 confirmation test) |
|         | L₁SD₂W₂     | 0.8066                       | CIₐ₃̂: 0.6667 < γ < 0.9464 CI₃ₐ: 0.7879 < γ < 0.8252 | 0.8238                                    |

Figure 7. Graph showing a comparison between actual GRG and predicted GRG values.
Calculation for $CI_{ce}$ and $CI_{pop}$ using Equations (7) and (8) is as follows:

$N = \text{Total number of results} = 27 \times 3 = 81$

$R = \text{Sample size for confirmation experiments} = 3$

$V_e = \text{Error variance} = 0.007860$ (Table 6)

$fe = \text{Error DOF} = 20$ (Table 6)

$F_{0.05} (1, 20) = 4.35$ (Tabulated $F$-value)

DOF associated in the estimate of mean response $= 6$ (Table 6)

\[ n_{eff} = \frac{N}{1 + \text{DOF associated in the estimate of mean response}} = \frac{81}{7} = 11.57 \]

\[ CI_{ce} = \sqrt{(4.35 \times 0.007860 \times 0.4197)} = \sqrt{0.01431} = \pm 0.1196 \]

\[ CI_{pop} = \sqrt{\frac{4.35 \times 0.007860}{11.57}} = \sqrt{0.0029} = \pm 0.05435 \]

where, $F_{\alpha} (1, fe)$ is the $F$ ratio at confidence level of $(1-\alpha)$ against DOF 1 and error degree of freedom $fe$, $R$ is the No. of confirmation runs ($R = 3$), $N$ is total No. of results ($N = 27 \times 3 = 81$), $V_e$ is error variance and $n_{eff}$, $N/1 + \text{DOF associated in the estimate of mean response}$. Therefore, the predicted confidence interval $CI_{ce}$ and the 95% confirmation interval $CI_{pop}$ of the predicted mean for confirmation experiments is:

Mean $\hat{\gamma}_{wear,FF} - CI_{ce} < \hat{\gamma}_{wear,FF} < \text{Mean } \hat{\gamma}_{wear,FF} + CI_{ce}$

$0.7846 - 0.1196 < 0.7846 < 0.7846 + 0.1196$

$0.6649 < 0.7846 < 0.9043$

Mean $\hat{\gamma}_{wear,FF} - CI_{pop} < \hat{\gamma}_{wear,FF} < \text{Mean } \hat{\gamma}_{wear,FF} + CI_{pop}$

$0.7846 - 0.05435 < 0.7846 < 0.7846 + 0.05435$

$0.7302 < 0.7846 < 0.8389$

3.6. Worn surface morphology

The optical microscopic examination of the worn surfaces of AA6063 matrix composite wear test samples at different conditions has been shown in Figure 8(a–c). During the wear testing as the matrix composite surface makes contact with the rotating disc wear progresses by the grooving action. A lot of scratches and cracks were seen on the worn surfaces due to primary abrasive wear mechanism. In the optimized conditions, the formation of fine grooves and fine layers (Figure 8(a)) has been observed. The optimal parameter set is described as load at 1st level (20 N), sliding distance at 2nd level (1046 m) and weight percentage at 2nd level (7wt. % SiC). For the optimal parameter set less material removal rate was observed. At lower load (20 N), it was observed that the contact
Pressure on the pin surface was low (Ambigai & Prabhu, 2017). As a result of it, less amount of heat has been generated in between the pin surface and counterface disc. The shearing effect was also minimized at lower load. The combined effect of low heat generation and less shearing resulted in less material removal rate from the pin surface.

In serious wear conditions, the matrix composite observed heavy scratches and scars. The deep grooves and ploughing action have been seen (Figure 8(b) and (c)). These grooves have been produced due to the plastic flow of matrix material prompted either because of the cutting or ploughing effect of the presence of hard and stiff SiC reinforcement agents (Figure 8(b) and (c)). Figure 8(c) depicts that at higher normal applied load of 40 N intense plastic deformation has been appeared on the ductile matrix surface and therefore the material removed from wear surface due to ploughing and shearing effect. The hard SiC particles at higher load sheared the material from the wear surface. In this situation, large flakes have been produced and kept along the wear path for a long time. Because of heat generation, these flakes have been exposed to intense plastic deformation and expend over the wear surface. High material removal rate was observed at 40 N normal applied load, 1,570 m sliding distance and 3.5 wt. % SiC. This was due to the more dislodgement or removal of SiC particles at higher load and large sliding distance. The removal or dislodgement of SiC particles has been observed as shown in Figure 8(c). These dislodged particles act as an abrasive material and increased the material removal rate from the pin surface.

3.7. Effect of process parameters on wear behavior
The effect of different process parameters on the output response characteristics in terms of grey relational grade (GRG) has been shown in Figure 5 and Table 5. The GRG reflects the impact of Load, Sliding distance (SD) and Wt. % SiC on the output response characteristics. The effect of each process factor of wear behavior on the grey relational grade at different levels can be separated out and the optimal level is described. The larger GRG value corresponds to the high-quality performance.
From the main effects table and main effects plot for GRG (Table 5 and Figure 5), the optimal set of the process parameter is described as L1SD2W2. This optimal set of the process parameter is explained as Load at 1st level (20 N), Sliding distance at 2nd level (1,046 m) and Wt. % SiC at 2nd level (7%). The ANOVA table (Table 6) clearly indicates that wt. % SiC is the most influencing parameter followed by load and sliding distance towards the process optimization.

The effect of individual parameters on dry sliding wear performance has been presented in Figure 5. It is observed from Figure 5 that with an increase in normal load a decrease in GRG value is listed. When the load was increased from 20 to 40 N the GRG value decreased which resulted in poor wear performance. Due to increase in load, the contact pressure on the sliding surface increased which resulted into more wear at increased load. At higher loads, the amount of heat generation increased and plastic deformation takes place at the pin surface which resulted into more material removal rate and adversely affected the wear performance. The formation of lots of pits, dislodgement of SiC particles and non uniform tribolayer was observed at higher load (40 N) which resulted in higher wear as shown in Figure 8(c). While at lower load due to low contact pressure the contact area was less and few points of the pin surface would be in contact with the disc, which resulted in less material removal rate (Ambigai & Prabhu, 2017). The formation of some fine grooves and fine layers have been seen on the worn surface at lower load (20 N) as shown in Figure 8(a). The wear performance of the composites has been found to be satisfactory at lower load (20 N).

The sliding distance has been observed the least influencing parameter having 3.84 percentage contribution towards the process during dry sliding wear behavior. The Figure 5 revealed that the GRG value increased with increase in sliding distance. As the sliding distance increased from 523 to 1,046 m the sliding time also increased. As a result of it, the self-lubrication phenomenon (Ambigai & Prabhu, 2017) (formation of the tribolayer) and clogging of wear debris between pin and counterface disc arises. The formation of tribolayer was gradually increased up to 1,046 m sliding distance and then it stabilized. The combined effect of wear debris and thin tribolayer leads to the formation of mechanically mixed layer which reduced the material removal rate from the specimen surface and enhanced the wear performance of the composite.

The weight percentage of SiC reinforcement particles has been observed the most significant parameter having 43.88% contribution towards the process during dry sliding wear behavior. The wear performance of the cast composites enhanced with the increase in wt. % of SiC reinforcement particles up to 7% weight percentage of SiC particles as shown in Figure 5. It was observed that the GRG value increased up to 7 wt. % SiC and then decreased. This is attributed to the homogeneous distribution of SiC particles in case of AA6063/7% SiC fabricated matrix composite. The inhomogeneous distribution and segregation of SiC particles beyond 7wt. % reinforcement resulted in a decrease in hardness of the composite matrix. The existence of these hard SiC particles increased the wear resistance characteristic of the composite (Ambigai & Prabhu, 2017). The increase in weight percentage of SiC particles up to 7wt. % SiC reinforcement in the matrix alloy increased the hardness of the alloy which reduced the material removal rate in the composite matrix. This property of the reinforcement agent improves the wear performance of the cast composites.

4. Conclusions
The integrated Taguchi-GRA-Weight method for the optimization of wear performance of AA6063/SiCp matrix composites has been carried out successfully. The optimal level of the process parameters is obtained and confirmation experiments are performed to justify the results. The outcomes of this work can be summarized as:

(1) The optimal parameter setting (L1SD2W2), when Load at 1st level (20 N), Sliding Distance at 2nd level (1,046 m) and Wt. % SiC at 2nd level (7wt. %) produced the best results during simultaneous optimization of Wear and Frictional Force (when \( W_1 = W_2 = 0.5 \)). The predicted value of GRG at optimal parameter setting was found within the 95% confidence interval level. An improvement of .0083 in GRG value was observed.
(2) The wt. % SiCₚ (PC = 43.88) has been observed the most significant parameter followed by load (PC = 24.43) and sliding distance.

(3) The wear mechanism has been explained for the best and worst conditions. The phenomenon of grooving such as fine grooves and deep grooves, ploughing, delamination, cutting along with scratches, cracks and dislodgement of SiC particles during the wear mechanism of the composite surfaces has been reported using OM examination. The phenomenon of shearing and dislodgement was observed at higher applied load. At a load of 40 N, sliding distance 1,570 m and 3.5 wt. % SiCₚ, serious wear has been observed.

References

Adamiak, M. (2006). Selected properties of the aluminum alloy base composites reinforced with intermetallic particles. Journal of Achievements in Materials and Manufacturing Engineering, 14(1–2), 43–47.

Adebisi, A. A., Maleque, M. A., Ali, M. Y., & Bello, K. A. (2016). Effect of variable particle size reinforcement on mechanical and wear properties of 6061Al–SiCp composite. Composite Interfaces, 23(6), 533–547. https://doi.org/10.1080/09276440.2016.1167614

Alaneme, K. K., & Aluko, A. O. (2012). Fracture toughness (KIC) and tensile properties of as-cast and age-hardened aluminum (6063)–silicon carbide particulate composites. Scientia Iranica, 19(4), 992–996. https://doi.org/10.1016/j.scient.2012.06.001

Ambigaik, R., & Prabhu, S. (2017). Optimization of friction and wear behavior 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

Çaydas, Ü., & Hasçalı, A. (2008). Use of the grey relational analysis to determine optimum laser cutting parameters with multi-performance characteristics. Optics & Laser Technology, 40(7), 987–994.

Deng, J. L. (1982). Control problems of grey systems. Sys. & Contr. Lett., 1(5), 288–294.

East, W. F. (1988). Metal-matrix composites take-off. Materials Engineering, 1988, 33–36.

Hashim, J., Loaney, L., & Hashmi, M. S. J. (1999). Metal matrix composites: Production by the stir casting method. Journal of Materials Processing Technology, 92, 1–7. https://doi.org/10.1016/S0924-0136(99)00118-1

Ipek, R. (2005). Adhesive wear behaviour of 4 C and SiC reinforced 4147 Al matrix composites (Al/4 C-AV/6C). Journal of Materials Processing Technology, 162, 71–75. https://doi.org/10.1016/j.jmatprotec.2005.02.207

Iwai, Y., Yoneba, H., & Honda, T. (1995). Sliding wear behavior of SiC whisker-reinforced aluminum composite. Wear, 181, 594–602. https://doi.org/10.1016/0043-1648(95)90175-2

Izcler, M., & Muratoglu, M. (2003). Wear behavior of SiC reinforced 2124 Al alloy composite in RWAT system. Journal of Materials Processing Technology, 132(1–3), 67–72. https://doi.org/10.1016/S0924-0136(02)00263-7

Kondpal, B. C., Kumar, J., & Singh, H. (2017). Optimization and characterization of EDM of AA 6061/10% Al2O3 AMMC using Taguchi’s approach and utility concept. Production & Manufacturing Research, 5(1), 351–370. https://doi.org/10.1080/21693277.2017.1389315

Kerti, I., & Toptan, F. (2008). Microstructural variations in cast B 4 C-reinforced aluminium matrix composites (AMCs). Materials Letters, 62(8), 1215–1218. https://doi.org/10.1016/j.matlet.2007.08.015

Khan, K. B., Katty, T. R. G., & Surappa, M. K. (2006). Hot hardness and indentation creep study on Al-5% Mg alloy matrix-B4C particle reinforced composites. Materials Science and Engineering: A, 427(1–2), 76–82. https://doi.org/10.1016/j.msea.2006.04.015

Kök, M. (2011). Computational investigation of testing parameter effects on abrasive wear behavior of AL 2 O 3 particle-reinforced MMCs using statistical analysis. The International Journal of Advanced Manufacturing Technology, 52(1–4), 207–215.

Kumar, M., & Singh, H. (2016). Multi-response optimization in wire electrical discharge machining of Inconel X-750 using Taguchi’s technique and grey relational analysis. Cogent Engineering, 3(1), 1266123.

Lee, K. B., Ahn, J. P., & Kwon, H. (2001). Characteristics of AA6061/BN composite fabricated by pressureless infiltration technique. Metallurgical and Materials Transactions A, 32(6), 1007–1018. https://doi.org/10.1007/s11661-001-0358-5

López, V. H., Scales, A., & Kennedy, A. R. (2003). The thermal stability of TiC particles in an Al7wt.% Si alloy. Materials Science and Engineering A, 356(1–2), 316–325. https://doi.org/10.1016/S0921-5093(03)00143-6

Modi, O. P. (2001). Two-body abrasion of a cast Al-Cu (2014 Al) alloy–Al2O3 particle composite: Influence of heat treatment and abrasion test parameters. Wear, 248(1–2), 100–113. https://doi.org/10.1016/S0043-1648(00)00534-2

Montgomery, D. C. (2001). Design and analysis of experiments (pp. 64–65). New York: John Wiley & Sons.

Olofsson, J., Grekh, T. M., Berlind, T., Persson, C., Jacobson, S., & Engqvist, H. (2012). Evaluation of silicon nitride as a wear resistant and resorbable alternative for total joint replacement. Biomatter, 2(2), 1–9.

Rajeswaran, B., Amirthagadeswaran, K. S., & Anbarasu, K. G. (2015). Investigation on mechanical properties of aluminum 7075-silicon carbide-alumina hybrid composite using Taguchi method. Australian Journal of Mechanical Engineering, 13(2), 127–135. https://doi.org/10.7158/M13-051.2015.13.2

Sahoo, P., & Pol, S. K. (2007). Tribological performance optimization of electroless Ni-P coatings using the Taguchi method and grey relational analysis. Tribology...
Letters, 28(2), 191–201. https://doi.org/10.1007/s11249-007-9264-3
Sevik, H., & Kurnaz, S. C. (2006). Properties of alumina particulate reinforced aluminum alloy produced by pressure die casting. Materials & Design, 27(8), 676–683. https://doi.org/10.1016/j.matdes.2005.01.006
Singla, Y. K., Chhibber, R., Bansal, H., & Kalra, A. (2015). Wear behavior of aluminum alloy 6061-based composites reinforced with SiC, Al2O3, and Red Mud: A comparative study. JOM Journal of the Minerals Metals and Materials Society, 67(10), 2160–2169. https://doi.org/10.1007/s11837-015-1365-0
Suresha, S., & Sridhara, B. K. (2010). Wear characteristics of hybrid aluminum matrix composites reinforced with graphite and silicon carbide particulates. Composites Science and Technology, 70(11), 1652–1659. https://doi.org/10.1016/j.compscitech.2010.06.013
Tokaji, K. (2005). Effect of stress ratio on fatigue behavior in SiC particulate-reinforced aluminum alloy composite. Fatigue & Fracture of Engineering Materials & Structures, 28(6), 539–545. https://doi.org/10.1111/ffe.2005.28.issue-6
Xu, J., & Kato, K. (2000). Formation of a tribochemical layer of ceramics sliding in water and its role for low friction. Wear, 245, 61–75. https://doi.org/10.1016/S0043-1648(00)00466-X
Yu, S. Y., Ishii, H., Tohgo, K., Cho, Y. T., & Diao, D. (1997). Temperature dependence of sliding wear behavior in SiC whisker or SiC particulate reinforced 6061 aluminum alloy composite. Wear, 213(1–2), 21–28. https://doi.org/10.1016/S0043-1648(97)00207-X
Zhang, S. L., Yang, J., Zhang, B. R., Zhao, Y. T., Chen, G., Shi, X. X., & Liang, Z. P. (2015). A novel fabrication technology of in situ TiB2/6063Al composites: High energy ball milling and melt in situ reaction. Journal of Alloys and Compounds, 639, 215–223. https://doi.org/10.1016/j.jallcom.2015.03.156

© 2018 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.
You are free to:
Share — copy and redistribute the material in any medium or format
Adapt — remix, transform, and build upon the material for any purpose, even commercially.
The licensor cannot revoke these freedoms as long as you follow the license terms.
Under the following terms:
Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made.
You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.
No additional restrictions
You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.

Cogent Engineering (ISSN: 2331-1916) is published by Cogent OA, part of Taylor & Francis Group.
Publishing with Cogent OA ensures:
• Immediate, universal access to your article on publication
• High visibility and discoverability via the Cogent OA website as well as Taylor & Francis Online
• Download and citation statistics for your article
• Rapid online publication
• Input from, and dialog with, expert editors and editorial boards
• Retention of full copyright of your article
• Guaranteed legacy preservation of your article
• Discounts and waivers for authors in developing regions
Submit your manuscript to a Cogent OA journal at www.CogentOA.com