Multi-attribute optimization of EDM process parameters for machining of SiC and B4C particle reinforced Al 6061 metal matrix composite adopting TOPSIS method

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Abstract
The tendencies of using composite materials are increasing rapidly in advanced engineering and technology applications. Ceramic reinforced aluminum composites are difficult to machine by conventional machining processes. In this work, ceramic reinforced aluminum composites are machined by Electric Discharge Machine (EDM). The goal of this study is to focus on the influence of EDM settings on Al6061 Metal Matrix Composite (MMC) reinforced with Silicon Carbide (SiC) and Boron Carbide (B4C) particles. The MMC is prepared by stirring casting route, then the workpiece is mounted on the electric discharge machine to perform the machining. Because MMC contains high abrasive ceramic (SiC and B4C) particles that are difficult to machine using traditional machining methods, an electrical discharge machine is used for machining. The experiments were conducted with four process parameters like Pulse current (I), Pulse off Time (P-Off), Pulse on Time (P-On), and Tool Lift (TL) with three levels in each parameter to examine the response measures such as Material Removal Rate (MRR), Surface Roughness (SR), Tool Wear Rate (TWR) and Surface Crack Density (SCD). The experimental results reveal that the surface crack density, MRR, SR, and TWR increases with an increase in current and pulse in time. The optimal combinations of process parameters were identified. Obtained optimal machining conditions are I input level at 9 Amps, P-On input level at 20 µs, P-Off input level at 50 µs, and Tool Lift input level at 4.5 µs with results of 0.103g/min MRR, 0.022 g/min TWR, 4.108µm SR and 0.0048 µm SCD.

Keywords
Composite material, MRR, SR, Optimization, TOPSIS, Unconventional machining, EDM.

1. Introduction
A composite material is defined as a material that is made up of at least two or more constituent materials. These constituent materials have remarkably different physical and chemical properties, and when combined, they form a material with characteristics not found in the individual constituents [1]. Composite materials are typically made up of two phases: matrix and reinforcement. If the matrix phase is considered with metal or alloy and in the reinforcement phase two or more materials are used, then it is known as Hybrid Metal Matrix Composite (HMMC). The tendencies of using HMMC materials are increasing rapidly in modern engineering applications such as space, aircraft, automotive industries, defense, and nuclear fields.

The addition of ceramic reinforcements in the metal matrix results in a composite material with high specific strength and hardness [2]. HMMC materials are challenging to machine using traditional methods due to their high reinforced strength, so the machining of these HMMC’s is usually done by non-traditional machines. Electric Discharge Machine (EDM) is an unconventional machine used for machining materials possessing high hardness and specific strength like superalloys, Metal Matrix Composite (MMC) and HMMC [3]. The background of the EDM process began with Joseph Priestly's findings in 1770. In his investigations, it is observed that electrical discharges had eroded material from the electrodes. Lazarenko, the Soviet researcher, invented a machining technology that became the cornerstone for contemporary EDM in 1940. The basic principle of EDM is simple. A gap is maintained between an electrode and a workpiece, and an electrical spark is formed in this gap. The movement of electricity is...
The main objectives of this article are as under:
1. Selection of work sample which has superior properties for modern engineering applications.
2. Selection of a non-conventional machine, EDM for machining components. Selection of machining parameters of the EDM through Design of Experiments (DOE).
3. Performing experiments and analyzing the data
4. Finding the optimal machining conditions by a proper optimization technique.
5. Prediction and validation of data.

2. Literature review
In a hybrid metal matrix composite, Al 6061 was used as the matrix material, and two ceramic reinforcements, Silicon Carbide (SiC) and Boron Carbide (B4C), were used in appropriate proportions. Based on mechanical properties, an appropriate composition (90 weight percent of Al-6061, 7 weight % of B4C, and 3 weight % of SiC) was recommended after examining various combinations of B4C, SiC, and Al6061. Because of the presence of B4C (the third hardest material) and SiC ceramic reinforcements, MMC materials are hard [5].

Aluminum alloys reinforced with nano B4C have a higher dislocation density than monolithic alloys, as seen in TEM images. The addition of nano B4C to an aluminum alloy matrix increases its tensile strength and hardness while maintaining its impact resistance and ductility [6].

A stir casting course was chosen for the preparation of ZrO2- Al MMCs. They included distinct weight rates of ZrO2 in the range of 0 to 10 wt. percent in the Al6061 matrix. They discovered that as weight levels increased, mechanical property estimations improved while elongation decreased [7].

A Non-Conventional EDM was considered for machining the prepared MMC. The EDM process is a novel machining technique in which the material is eroded as a result of the Transformation of electrical to thermal energy by a series of several electrical discharges that occur between the work sample and tool electrode, both of which are immersed in a dielectric medium and separated by a small gap [8].

The mechanical properties of Al-MMC is influenced by the weight percent of adding reinforcements, followed by stirrer speed, time, and temperature of the stir casting process [9].

In performance measures such as Material Removal Rate (MRR), Surface Roughness (SR), Tool Wear Rate (TWR) and Surface Crack Density (SCD), EDM machining of tungsten carbide with a cooper tool result in less surface cracks and TWR [10].

In the EDM process, a servo system maintains a small gap between the workpiece and the tool, ranging from 0.025 to 0.03 mm. TWR and MRR were improved by increasing the pulse on time and pulse current during EDM machining of Al-SiC composite [11].

In ceramic reinforced composites, SiC particles protect and conceal the MMC workpiece from electric discharges in EDM and reduce MRR, SR, and TWR [12].

Taguchi DOE and analysis exhibits optimum combination parameters for a single response in a set of input independent machining parameters [13].

The Data Envelopment Analysis Ranking (DEAR) approach was found to be an effective method of multi-objective optimization in two case study problems [14].

When using Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) to perform multi-objective optimization of Ti alloy, the Taguchi method was used, and it was discovered that increasing process parameters like pulse on time and pulse current improved performance measures [15].

MMC materials are challenging to machine using traditional methods due to their high reinforced strength, so the machining of these MMC’s is usually done by non-traditional machines [16].

Liquid and solid phase techniques can be used to create composite materials. In HMMC, Al 6061 was used as the matrix material and two ceramic reinforcements, SiC and B4C, were used in
appropriate proportions to obtain superior properties to monolithic Al alloy [17, 18].

A typical stir casting procedure was used to create an aluminum-based MMC with an AA6061 alloy configuration and reinforcement of 1.5 wt percent SiC and B4C [19].

The Al reinforced with SiC and B4C particle reinforced exhibited improved mechanical properties such as impact, tensile strength, hardness, and flexural strength when compared to monolithic Al alloy. [20, 21].

Al-SiC MMC is commonly used in dies, parts, and products in the aerospace, electronics, military, automotive, and medical industries. V, IP, Duty Factor, and Ton were the control parameters used during the machining MMC on EDM. The material removal rate is optimal and the surface roughness is excellent when the current is high and the voltage is low [22].

The Taguchi method and DEAR were used to optimize the process input parameters on TiB2 reinforced Al7075 MMC in the AWJM process [23].

TOPSIS and Grey Relational Analysis (GRA) with Taguchi were investigated for ED machining of H-11 Die steel with electrolytic copper and the effectiveness of multi-attribute optimization was evaluated [24].

DEAR with the Taguchi method was revealed that the optimal set of input parameters in an efficient way [25].

To improve performance measures like MRR, SR, TWR, surface integrity factors, and Kerfs width, machining parameters such as pulse off time, servo voltage, wire tension, pulse current, wire-speed, and pulse on time can be used. The Taguchi, GRA Response Surface Methodology (RSM), and Analysis of Variance (ANOVA) are used for analysis of various materials such as steel alloys, nickel superalloys, and MMCs [26].

Scientists and practitioners have given Multi-objective Decision-Making techniques a lot of thought in terms of identifying, analyzing, and placing options via various technologies. TOPSIS continues to perform admirably in a variety of application areas [27].

Tribological properties were vital for Al 6061-based HMMC s reinforced with B4C and SiC ceramics. The presence of ceramic reinforcements increased the coefficient of friction at higher sliding speeds. Oxidation, adhesion, and abrasion were identified as the main wear mechanisms, and these were confirmed using Field Emission Scanning Electron Microscope (FESEN) and Energy-dispersive Spectroscopy (EDS) on worn-out specimens [28].

The morphology of the surface layer was examined using Scanning Electron Microscope (SEM), and the chemical composition was investigated using Energy-Dispersive X-ray Spectroscopy (EDX). The ideal machining settings for the best-machined surface quality and the narrowest kerf width were determined for precision machining [29].

The machining parameters for surface roughness optimization have been attempted. Confirmation tests were conducted to test the model, and the predicted results were found to be very close to the experimental data. The surface morphology of machined surfaces has also been studied using SEM. Several surface flaws and their causes have been discovered [30].

For LM6-Alumina stir casted MMC, the EDM Machining parameters are optimised to achieve the best MRR, reduced SR, and TWR. Multiple performance characteristics are designed and optimised using grey relation analysis. The discharged current, according to the findings, is the most important factor influencing surface finish and material removal rate [31].

Al MMC is made using a stir casting method with three different weight percentages of B4C and Gr reinforcements. The prepared sample is then machined on an EDM for optimal response optimization of EDM process parameters. The Wear Ratio (WR) decreases initially with Ton and increases with an increase in reinforcement percentages. The formation of a ceramic layer between the tool and the workpiece causes a decrease in WR in a nonlinear style [32].

EDM is used to machine MMCs to find the best process parameters. The most influencing parameter for MMC machining is current, polarity, and followed by T-on and gap voltage due to the availability of high temperature generated by series of sparks by EDM [33].

An in-depth examination was conducted to determine the impact of process parameters on response parameters. It has been reported that MRR and TWR
are mostly influenced by current, polarity and followed by T-on due to high temperature [34].

The machining of Al-B4C MMC was performed on vibration-assisted EDM to increase the performance of process parameters on responses. Current and tool vibration was the most influential parameter for MRR, SR, and flushing pressure for TWR [35].

The machining of Al/Cu/Ni on EDM was employed and it is analyzed that the current is the most significant parameter followed by T On, Toff, and Current Peak (CP) on the surface quality of the machined sample [36].

The effectiveness of optimum input parameters of EDM on die steel was evaluated. The TOPSIS multi-objective optimization was employed to recognize the optimum process parameters to achieve excellent surface quality and MRR with a low-frequency vibration tool [37].

EDCM was used to machine the Al6063-SiC MMC. The results show that when high Ton is used for longer than 3 ms, the generation of heat decreases and the MRR decreases. The intermittent gas film collapses, causing electrical discharges to be hampered [38].

Al-SiC-Gr MMC was prepared by stir casting method and machining was performed on MMC by EDM. The most impacting parameter on MRR responses of Al-SiC-Gr workpiece on EDM has been reported as current and T On. T Off has less significance on MRR [39].

The machining of high hardened materials, including MMC by EDM is easy and efficient. The attempt was made to machine SiC-Al MMC in which more than 50% of SiC was reinforced. Due to the high ceramic quantity in MMC while machining it forms a shielding layer in the spark gap. Particle Swarm Optimization (PSO) and Support Vector Regression (SVR) hybrid optimization was employed to find the optimal process parameters of EDM. It has been recorded that as current and T On increases MRR and surface roughness increases due to the availability of high thermal energy [40].

Based on a literature review, the background and motivation for this work are to prepare and machine a novel HMMC with superior properties that can serve modern engineering applications. This article focuses on finding the optimum machining parameters to develop the quality and lifetime of the component made by HMMC. This novel HMMC was made with Al 6061 as matrix material and reinforcement materials 3% SiC and 7% B4C was considered for fabrication of workpiece. This novel HMMC is difficult to machine by conventional methods as they possess high hard and abrasive ceramic particles like SiC and B4C. Hence a non-conventional machine, EDM was considered for machining of this HMMC. According to the literature review, the majority of the work is done on MMC using wire EDM; however, it is understood that few researchers attempted machining of Hybrid MMC using Die-Sink EDM, and no work has been reported on multi-attribute optimization with TOPSIS method for machining of a novel based Al6061 reinforced SiC and B4C Hybrid MMC on EDM. Here TOPSIS aided with the Taguchi method has been used to find the optimal input machining parameters for better process parameters.

3. Methods and materials

The purpose of this paper is to discuss the preparation and machining of novel HMMC. EDM machining of HMMC to reduce manufacturing time, SR roughness, and SCD level, thereby increasing component service life in key applications. To prepare the HMMC Work sample, the stir casting method is used. The experimental run and test flowchart is depicted in Figure 1.

![Flow chart](image)

**Figure 1 Flow chart**
3.1 Development of work sample
The stir casting method was used to prepare the Hybrid MMC. Based on mechanical and physical properties, a pilot experiment was conducted to determine the appropriate reinforcement percentage. Table 1 shows the Al-6061 Chemical composition. The matrix phase was chosen to be Al 6061 alloy, with particulate phase reinforcement consisting of 7% B4C and 3% SiC by weight. Table 2 lists the mechanical and thermal properties of SiC and B4C. Initially, the chemical composition of Al 6061 billet was confirmed by spectroscopic examination, and the results were tabulated.

Table 1 Al-6061 Chemical composition

| Elements         | Composition (wt. %) |
|------------------|---------------------|
| Magnesium        | 0.8-1.2             |
| Iron             | Max. 0.7            |
| Silicon          | 0.4 – 0.8           |
| Zinc             | Max. 0.25           |
| Copper           | 0.15-0.40           |
| Manganese        | Max. 0.15           |
| Titanium         | Max. 0.15           |
| Chromium         | 0.04-0.35           |
| Others           | 0.05                |
| Aluminum         | Balance             |

Table 2 Properties of SiC and B4C

| Mechanical & Thermal Properties | SiC          | B4C          |
|---------------------------------|--------------|--------------|
| Density                         | 3.21 gm/cc   | 2.51 gm/cc   |
| Melting Point Temperature       | 2760 °C      | 2450 °C      |
| Elastic Modulus                 | 410 GPa      | 362 GPa      |
| Hardness (Vickers)              | 2800 Kg/mm2  | 3810 Kg/mm2  |
| Tensile strength                | 210-370 MPa  | 261 MPa      |
| Fracture Toughness KIC          | 3.2 MPa/m1/2 | 3 MPa/m1/2   |
| Thermal Conductivity            | 115 W/m°K    | 17 W/m°K     |
| Coefficient of Thermal Expansion| 4.0 x10^-6/°C| 4.6 x10^-6/°C|

Al6061 alloy billet is made into small rectangular shaped parts to achieve a larger surface area for absorbing the heat and thus melts quickly. Then after it is inserted in a crucible and heated to melt in a stir casting furnace. To achieve proper melting the billet is heated up to 800oC and maintained for 30 minutes. Dry argon gas is passed into the furnace for the degasification of molten metal. Now the preheated ceramics 3 wt % of SiC particles of size 45 microns and 7 wt % of B4C particles of size 63 microns at 400°C were inserted through the provision of a stir casting furnace. The stirring action was done for 25 minutes for achieving uniform distribution of reinforcements in the matrix phase. The molten material is now poured into cylindrical molds. Molds were allowed to solidify at room temperature for 5 hours. The uniform distribution of reinforcements in the matrix phase is identified by SEM analysis and the SEM image is shown in Figure 2.

Figure 2 SEM image showing Uniform distribution of reinforcements in Al matrix
3.2 EDM and its mechanism

EDM consists of two electrodes, one electrode is connected to the tool and the other electrode is connected to the work sample. These two electrodes are separated with a small gap and always this gap is kept constant by the servo controller with the help of a feedback mechanism. The two electrodes are submerged in a dielectric fluid and they are connected to a programmable circuit power supply, this is known as the ignition phase which is shown in Figure 3. A closed circuit is formed when the voltage exceeds the breakdown voltage and sparks are produced in the dielectric fluid. This is known as the generation of plasma phase, which is shown in Figure 3. In this phase, high pressure and temperature are generated and this plasma is maintained for some time known as a pulse on time. After this phase suddenly plasma breaks down, which makes the molten materials at both tool and work surface boil violently and small droplets of liquid metal are ejected from the molten metal pool. This phase is known as melting and evaporation and is shown in Figure 3. The material eroded (debris) from two electrodes tool and work surface are flushed away by the dielectric fluid. The mechanism of the EDM process is shown in Figure 3.

A Nonconventional V3525 Askar Microns Die-Sink EDM was considering for machining of Al-Hybrid MMC. The selected die sink EDM is shown in Figure 4. The specification of EDM is shown in Table 3. Electrolytic copper was considered a tool with a 10 mm diameter. The EDM 30 oil was used as a dielectric medium during machining. It is also used for flushing debris or eroded material from tool and work surfaces.

![Figure 3 Mechanism of EDM process](image)

| Table 3 Specifications of EDM | Melting & evaporation |
|-----------------------------|-----------------------|
| EDM Mechanism               | Spontaneous condensation and evaporation |
| Spark gap                   | 0.010-0.500 mm        |
| Peak voltage                | 30-250 V              |
| Spark frequency             | 200-500 kHz           |
| Workspace Dimensions        | 600x390x275 mm³       |
| Table Dimension             | 350x250 mm²           |
| Table loading               | 200 Kg                |
| Dielectric medium           | EDM 30-grade oil      |
3.3 Selection of process parameters

Initially, a series of experiments were done on a work sample on EDM with copper toll to recognize the influence of input factors and their levels. The parameters and their levels are tabulated in Table 4.

| Input Parameters (Units) | Levels |
|--------------------------|--------|
| **I** (Pulse Current) (A) | 9      | 12    | 15    |
| **P-On** (Pulse on time) (µs) | 20    | 50    | 100   |
| **P-Off** (Pulse off time) (µs) | 50    | 100   | 200   |
| **TL** (Tool Lift) (µs)     | 1.5    | 3     | 4.5   |

Figure 4 Electric discharge machine

3.4 Experimentation and data collection

The hybrid MMC samples were mounted on EDM for machining with various input parameters and levels. Before machining the surfaces of the work sample and the tool were grounded by emery papers to obtain a good surface finish of 1 µm. Experiments were executed based on Taguchi DOE L29 orthogonal array. TWR, SR, MRR and SCD were treated as response characteristics and input machining parameters as I, P-On, P-Off, and TL and all the parametric values are presented in Table 5. MRR and TWR are evaluated by *Equations 1 and 2* respectively. SR values are obtained by The Mitutoyo SJ-210-Series Portable Surface Roughness Tester shown in Figure 5. SCD was calculated by ZESIS SEM image analyzer software. *Figure 6* and *Figure 7* shows the SCD for experimental run 3 and 14.

\[
MRR = \frac{(W1 - W2)\text{mg}}{T \text{ min}} \tag{1}
\]

\[
TWR = \frac{(T1 - T2)\text{mg}}{T \text{ min}} \tag{2}
\]

W1, W2, T1, and T2 are the weights of the work sample and tool former and later machining with a digital balance in milligrams respectively and T is the time taken for machining in minutes.
Figure 5 Mitutoyo SJ-210 series surface roughness tester

Table 5 Taguchi orthogonal array L27

| EXP No | I (A) | P-On (µs) | P-Off (µs) | T L (µs) | MRR  | TWR  | SR   | SCD  |
|--------|-------|-----------|------------|----------|------|------|------|------|
| 1      | 1     | 1         | 1          | 1        | 0.106| 0.023| 4.25009| 0.006042|
| 2      | 1     | 1         | 2          | 2        | 0.103| 0.030| 4.28688| 0.005677|
| 3      | 1     | 1         | 3          | 3        | 0.092| 0.023| 4.09385| 0.004245|
| 4      | 1     | 2         | 1          | 2        | 0.108| 0.034| 4.44577| 0.006331|
| 5      | 1     | 2         | 2          | 3        | 0.094| 0.032| 4.13882| 0.004806|
| 6      | 1     | 2         | 3          | 1        | 0.098| 0.034| 4.36129| 0.005968|
| 7      | 1     | 3         | 1          | 3        | 0.093| 0.020| 4.45018| 0.00801|
| 8      | 1     | 3         | 2          | 1        | 0.078| 0.030| 4.67013| 0.008936|
| 9      | 1     | 3         | 3          | 2        | 0.096| 0.031| 4.56787| 0.007951|
| 10     | 2     | 1         | 1          | 2        | 0.121| 0.030| 4.56780| 0.007843|
| 11     | 2     | 1         | 2          | 3        | 0.112| 0.030| 4.28645| 0.005579|
| 12     | 2     | 1         | 3          | 1        | 0.12  | 0.030| 4.48244| 0.007161|
| 13     | 2     | 2         | 1          | 3        | 0.126| 0.030| 4.47944| 0.007082|
| 14     | 2     | 2         | 2          | 1        | 0.120| 0.04 | 4.61859| 0.008186|
| 15     | 2     | 2         | 3          | 2        | 0.125| 0.042| 4.53496| 0.007306|
| 16     | 2     | 3         | 1          | 1        | 0.108| 0.03 | 4.99459| 0.011512|
| 7      | 2     | 3         | 2          | 2        | 0.098| 0.028| 4.83230| 0.01019|
| 18     | 2     | 3         | 3          | 3        | 0.108| 0.03 | 4.68857| 0.009085|
| 19     | 3     | 1         | 1          | 3        | 0.148| 0.042| 4.57082| 0.008148|
| 20     | 3     | 1         | 2          | 1        | 0.140| 0.042| 4.74232| 0.009177|
| 21     | 3     | 1         | 3          | 2        | 0.154| 0.05 | 4.72720| 0.00901|
| 22     | 3     | 2         | 1          | 1        | 0.160| 0.051| 4.84045| 0.010659|
| 23     | 3     | 2         | 2          | 2        | 0.157| 0.052| 4.79246| 0.009215|
| 24     | 3     | 2         | 3          | 3        | 0.156| 0.05 | 4.54360| 0.007634|
| 25     | 3     | 3         | 1          | 2        | 0.14  | 0.038| 5.22730| 0.013004|
| 26     | 3     | 3         | 2          | 3        | 0.128| 0.04 | 5.01186| 0.011422|
| 27     | 3     | 3         | 3          | 1        | 0.132| 0.04 | 5.18301| 0.012274|
4. Results and data analysis

The main goals of this work are to maximize performance characteristic MRR and minimize the other three performance characteristics TWR, SR & SCD.

4.1 Influence of process parameters on MRR

Minitab16 software was used to plot the response (MRR) versus process parameters (P-On and I).

*Figure 8* shows that MRR increases as pulse current increases due to an increase in discharge energy. MRR initially increases to a certain range in the case of P-On time, then decreases due to irregular discharges caused by the formation of a layer of ceramic SiC particles that acts as a shielding effect between the tool and the workpiece.

*Figure 6* SEM image of machined surface of experimental run 3

*Figure 7* SEM image of machined surface of experimental run 14

*Figure 8* Surface plot of MRR Vs. I and P-On
4.2 Influence of process parameters on TWR
Minitab16 software was employed to plot the TWR response with a P-On and Current(I) process parameters. From the surface plot, Figure 9, it can be understood that TWR increases with an increase in pulse current due to an increase in the discharge energy, and also that leads to an increase in TWR. Whereas for a Pulse On - time, TWR initially increases to a certain range than after it decreases. The discharges are irregular due to the formation of a layer of ceramic SiC particles and acts as a shielding effect between the tool and workpiece.

![Surface Plot of TWR vs P On and I](image)

**Figure 9** Surface plot for TWR Vs P-On and I

4.3 Influence of process parameters on SR and SCD
Minitab16 software was employed to plot the SR and SCD responses with P-On and Current(I) process parameters. From the surface plots in Figure 10 and Figure 11, it can be understood that SR and SCD both increase with an increase in pulse current and P-On due to an increase in the intensity of discharge energy and also increase in availability time of discharge energy.

![Surface Plot of SR vs P On and I](image)

**Figure 10** Surface plot of SR Vs. P-On and I

![Surface Plot of SCD vs P On and I](image)

**Figure 11** Surface plot for SCD Vs. P-On and I
4.4 Multi-response optimization

Multi-attribute optimization is executed by the TOPSIS method. The procedure is depicted by the following sequence of steps.

Step I: Develop a decision matrix that consists of ‘n’ number of responses and m number of alternatives and it is defined by the following matrix.

\[
D_{i,j} = \begin{bmatrix}
    x_{11} & x_{12} & x_{13} & \cdots & x_{1m} \\
    x_{21} & x_{22} & x_{23} & \cdots & x_{2m} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    x_{n1} & x_{n2} & x_{n3} & \cdots & x_{nm}
\end{bmatrix}
\]

Step II: The decision matrix is then normalized by the following expression (Equation 3) and tabulated in Table 6.

\[
N_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}^2} \quad \text{where } j = 1,2,3,\ldots,m
\]  

(3)

Step III: Evaluate weighted normalized matrix Uij by the following expression (Equation 4) and tabulated in Table 7.

\[
U_{ij} = W_j * N_{ij} \quad \sum_{j=1}^{n} W_j = 1
\]  

(4)

Step IV: Determination of the positive and negative unique solutions from the following expressions (Equation 5).

\[
U^+ = \left\{ \left\lceil \sum_{i}^{\text{min}} U_{ij} j e f l \right\rceil, \left\lceil \sum_{i}^{\text{max}} j e f l i = 1,2,\ldots,m \right\rceil \right\} = \{u_1^+, u_2^+, u_3^+, \ldots, u_n^+ \}
\]  

(5)

\[
U^- = \left\{ \left\lceil \sum_{i}^{\text{min}} U_{ij} j e f l \right\rceil, \left\lceil \sum_{i}^{\text{max}} j e f l i = 1,2,\ldots,m \right\rceil \right\} = \{u_1^-, u_2^-, u_3^-, \ldots, u_n^- \}
\]  

(6)

Step V: Calculating Euclidean distance from the unique positive and negative value (Equation 7 and 8) shown in Table 8.

\[
E_i^+ = \sqrt{\sum_{j=1}^{n} \left[ U_{ij} - u_j^+ \right]^2} \quad i = 1,2,3,\ldots,m
\]  

(7)

\[
E_i^- = \sqrt{\sum_{j=1}^{n} \left[ U_{ij} - u_j^- \right]^2} \quad i = 1,2,3,\ldots,m
\]  

(8)

Step VI: Calculating the nearness of the performance index by the following expression (Equation 9).

\[
P_i = \frac{E_i^-}{E_i^+ + E_i^-} \quad i = 1,2,3,\ldots,m
\]  

(9)

Step VII: Ranking is allocated according to the performance index from Table 9.

Whereas ideal positive, negative Euclidean values and corresponding performance index score characteristics of the TOPSIS method were evaluated in MS Excel 2007 software and by using Equations 5, 6, 7, 8, and 9 are represented in Table 8 and Table 9. The maximum performance score is the relative closeness to the standard solution to achieve the optimal input parameters.

From Table 9, experiment number 1 encounters the highest score and it is ranked first. Machining of AL 6061 MMC on EDM to achieve the optimal input conditions are I-9, P-On20, P-Off50 and TL-1.5.

### Table 6 Normalization matrix

| MRR   | TWR  | SR   | SCD |
|-------|------|------|-----|
| 0.1680| 0.1219| 0.1772| 0.1363|
| 0.1648| 0.1590| 0.1787| 0.1281|
| 0.1458| 0.1219| 0.1707| 0.0958|
| 0.1711| 0.1803| 0.1854| 0.1428|
| 0.1490| 0.1696| 0.1726| 0.1084|
| 0.1553| 0.1803| 0.1818| 0.1346|
| 0.1474| 0.1060| 0.1855| 0.1807|
| 0.1236| 0.1590| 0.1947| 0.2016|
| 0.1521| 0.1643| 0.1905| 0.1794|
| 0.1917| 0.1590| 0.1904| 0.1769|
| 0.1775| 0.1590| 0.1787| 0.1259|
| 0.1902| 0.1590| 0.1869| 0.1616|
| 0.1997| 0.1590| 0.1868| 0.1598|
| 0.1902| 0.2121| 0.1926| 0.1847|
| 0.1981| 0.2227| 0.1891| 0.1648|
| 0.1711| 0.1590| 0.2082| 0.2597|
### Normalization

| MRR     | TWR  | SR    | SCD  |
|---------|------|-------|------|
| 0.1553  | 0.1484 | 0.2015 | 0.2299 |
| 0.1711  | 0.1590 | 0.1955 | 0.2050 |
| 0.2345  | 0.2227 | 0.1906 | 0.1838 |
| 0.2219  | 0.2227 | 0.1977 | 0.2070 |
| 0.2440  | 0.2651 | 0.1971 | 0.2033 |
| 0.2536  | 0.2704 | 0.2018 | 0.2405 |
| 0.2488  | 0.2757 | 0.1998 | 0.2079 |
| 0.2472  | 0.2651 | 0.1894 | 0.1722 |
| 0.2219  | 0.2015 | 0.2179 | 0.2933 |
| 0.2028  | 0.2121 | 0.2090 | 0.2577 |
| 0.2092  | 0.2121 | 0.2161 | 0.2769 |

### Table 7 Weighted matrix

| MRR     | TWR  | SR    | SCD  |
|---------|------|-------|------|
| 0.0420  | 0.0305 | 0.0443 | 0.0341 |
| 0.0412  | 0.0398 | 0.0447 | 0.0320 |
| 0.0364  | 0.0305 | 0.0427 | 0.0239 |
| 0.0428  | 0.0451 | 0.0463 | 0.0357 |
| 0.0372  | 0.0424 | 0.0431 | 0.0271 |
| 0.0388  | 0.0451 | 0.0455 | 0.0337 |
| 0.0368  | 0.0265 | 0.0464 | 0.0452 |
| 0.0309  | 0.0398 | 0.0487 | 0.0504 |
| 0.0380  | 0.0411 | 0.0476 | 0.0448 |
| 0.0479  | 0.0398 | 0.0476 | 0.0442 |
| 0.0444  | 0.0398 | 0.0447 | 0.0315 |
| 0.0475  | 0.0398 | 0.0467 | 0.0404 |
| 0.0499  | 0.0398 | 0.0467 | 0.0399 |
| 0.0475  | 0.0530 | 0.0481 | 0.0462 |
| 0.0495  | 0.0557 | 0.0473 | 0.0412 |
| 0.0428  | 0.0398 | 0.0521 | 0.0649 |
| 0.0388  | 0.0371 | 0.0504 | 0.0575 |
| 0.0428  | 0.0398 | 0.0489 | 0.0512 |
| 0.0586  | 0.0557 | 0.0476 | 0.0460 |
| 0.0555  | 0.0557 | 0.0494 | 0.0518 |
| 0.0610  | 0.0663 | 0.0493 | 0.0508 |
| 0.0634  | 0.0676 | 0.0505 | 0.0601 |
| 0.0622  | 0.0689 | 0.0500 | 0.0520 |
| 0.0618  | 0.0663 | 0.0474 | 0.0431 |
| 0.0555  | 0.0504 | 0.0545 | 0.0733 |
| 0.0507  | 0.0530 | 0.0522 | 0.0644 |
| 0.0523  | 0.0530 | 0.0540 | 0.0692 |

### Table 8 Best and worst value

| Euclidean distance from the ideal positive and negative value |
|---------------------------------------------------------------|
| MRR     | TWR  | SR    | SCD  |
|---------|------|-------|------|
| 0.0241  | 0.0570 | 0.0570 | 0.0570 |
| 0.0272  | 0.0525 | 0.0525 | 0.0525 |
| 0.0272  | 0.0639 | 0.0639 | 0.0639 |
| 0.0303  | 0.0468 | 0.0468 | 0.0468 |
| 0.0308  | 0.0549 | 0.0549 | 0.0549 |
| 0.0324  | 0.0478 | 0.0478 | 0.0478 |
| 0.0342  | 0.0519 | 0.0519 | 0.0519 |
| 0.0444  | 0.0376 | 0.0376 | 0.0376 |
4.5 Data analysis

To measure the influence of process parameters of Die-Sink EDM on Al MMC, 27 experimental tests were conducted (L27 orthogonal array). The responses were recorded and further multi-response optimization was attempted with the aid TOPSIS method. Here the goals are Maximization of MRR, Minimization of TWR, SR, and SCD. It has been explored that the required goal of achieving the optimal combination parameters. Then after TOPSIS method is mingled...
with the ANOVA for obtaining the favorable optimal machining conditions. Main effect plots were drawn and represented in Figure 12. From the main effect plot, it has been discovered that as current and pulse on increases performance score decreases, but for tool lift and pulse off performance score primarily decreases and then increases.

It is because of the generation of carbide layer in-between tool and workpiece (spark gap). By observing the response for means it can be concluded that the major influence on performance score is current and pulse on time after that it is followed by P-Off and Tool lift (Table 10).

### Table 10 Response of means of a performance score

| Level | I   | P-On | P-Off | TL   |
|-------|-----|------|-------|------|
| 1     | 0.6110 | 0.6032 | 0.5392 | 0.4962 |
| 2     | 0.5523 | 0.5359 | 0.5135 | 0.5111 |
| 3     | 0.4191 | 0.4433 | 0.5297 | 0.5751 |
| Delta | 0.1919 | 0.1598 | 0.0258 | 0.0789 |
| Rank  | 1    | 2    | 4     | 3    |

The prediction of the Responses ($R_p$) of the EDM parameters can be evaluated by the following equation:

$$R_p = R_{\text{mean}} + \sum_{i=1}^{m}(R_i - R_{\text{mean}})$$

Where

- $R_p$ is the response to be predicted
- $R_{\text{mean}}$ is mean of all the response
- $R_i$ is the mean response of $i$th parameter
- $m$ is the number of input parameters.

The present investigation reveals the significant influence of input process parameters on output responses. The most optimal input parametric conditions of the EDM process for acquiring maximum MRR and minimum TWR, SR, and SCD are achieved by the TOPSIS method and presented in Table 11.

The most significant factors affecting the performance score, according to Table 12, are peak current and P-On time, followed by tool lift. The P-Off factor had a minor impact on the response performance score, which is consistent with the literature [39]. A peak current input level of 9 Amps, P-On time input level of 20 s, P-Off time input level of 50 s, and Tool Lift input level of 4.5 s are predicted to be optimal machining conditions. The results of the confirmatory tests were 0.103 g/min MRR, 0.022 g/min TWR, 4.108 m SR, and 0.0048213 m SCD, as shown in Figure 13.

It has also been verified that the deviation from the average performance score is 1.78 percent, and that it is highly interactive and accurate, i.e., with confidence.

Complete list of abbreviations is shown in Appendix I.
Table 11 Predicted and experimental values by TOPSIS method

| Response                      | Experimental Response Values (I1-POn1-POff1-TL3) |
|-------------------------------|--------------------------------------------------|
| MRR                           | 0.103 gm/min                                     |
| TWR                           | 0.022 gm/min                                     |
| SR                            | 4.108 µm                                          |
| SCD                           | 0.004821µm                                       |
| Performance index score (Pi)  | 0.7328                                            |
| Predicted Performance index score from ANOVA | 0.7461                                           |
| Deviation                     | 1.78%                                             |

Table 12 ANOVA for means of performance score

| Source | DOF | SS       | MSS      | F-ratio   | % of Contribution |
|--------|-----|----------|----------|-----------|-------------------|
| I      | 2   | 0.1741   | 0.0870   | 87.00     | 50.7288           |
| P-On   | 2   | 0.1159   | 0.0579   | 57.92     | 33.8192           |
| P-Off  | 2   | 0.0030   | 0.0015   | 1.53      | 0.8746            |
| TL     | 2   | 0.0316   | 0.0158   | 15.82     | 9.3294            |
| Residual Error                  | 18  | 0.0180   | 0.0010   |           | 5.2478            |
| Total                             | 26  | 0.3428   |          | 100       |                   |

F ratio from the table with the significance level of 0.05 and DOF (2, 18) is 3.55.

Figure 13 SEM Photograph of machined surface for validation

Limitations
The limitations of the above work are as follows
1. The effect of high temperature on metallurgical aspects during machining on work surface.
2. The development of residual stress on the work sample machined surface.

The EDM process causes these limitations. The transfer of high thermal energy during machining on the work sample is the mechanism of EDM machining. During P-On time, there is a sudden heating due to high thermal energy, and during P-Off and TL time, there is a flushing of dielectric fluid causes quenching of the work surface, resulting in high residual stresses and metallurgical changes.

5. Conclusion
In this work, a study was executed to investigate the multi-response optimization of EDM process parameters in the machining of SiC and B4C particle reinforced Al-6061 HMMC by application of the TOPSIS method. Minitab software is employed for surface plots and it reveals that the maximum of MRR
as 0.160 gm/min is obtained at process parameters settings of I-15 Amps, P-On-50 µs, P-Off-50 µs, and TL-1.5 s, the minimum of TLWR as 0.0203 gm/min is achieved at process parameters settings of I-9 Amps, P-On-100 µs, P-Off-50 µs and TL-4.5 s and minimum of SR of 4.094 µm and SFCD of 0.0042 µm were attained at process parameters settings of I-9 Amps, P-On-20 µs, P-Off-200 µs, TL-4.5 s. TOPSIS multi-objective optimization reveals the significant impact of process parameters on output performances. Peak current and P-On are very significant factors that affect the responses performance score. It is due to the availability of high thermal energy from spark discharges. During tool lift time, the shielding layer of ceramic particles and debris is flushed away by dielectric fluid between the tool and workpiece. Thus, TL is also a significant parameter on responses performance score. The most optimal input parametric conditions of the EDM process for acquiring maximum MRR as 0.103 gm/min and minimum TWR as 0.022 gm/min, SR 4.108 µm and SCD as 0.0048 µm were achieved at I-9 Amps, P-On-20 µs, P-Off-50 µs, and TL-4.5 s. The prediction responses performance score and experimental responses performance score has a very less deviation of 1.78% which is very highly interactive and also within the confidence level. This study will be beneficial to the production industries in choosing effective machining conditions of a novel Hybrid MMC of the die-Sink EDM for manufacturing the components in modern engineering applications like ship buildings, aerospace, and automobile applications.

The following work can be attempted in future in the following ways:
1. The influence metallurgical aspects of generated temperature during machining on work surface.
2. The influence sudden heating and quenching on residual stresses.
3. Influence of temperature on machining and work life. So more sensors are arranged to measure temperature at each level of machining.

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Conflicts of interest
The authors have no conflicts of interest to declare.

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### Appendix I

| S.No. | Abbreviation | Description                                      |
|-------|--------------|--------------------------------------------------|
| 1     | ANOVA        | Analysis of Variance                             |
| 2     | B4C          | Boron Carbide                                    |
| 3     | CP           | Current Peak                                     |
| 4     | DEAR         | Data Envelopment Analysis Ranking                |
| 5     | DOE          | Design of Experiments                            |
| 6     | DOF          | Degrees of Freedom                               |
| 7     | EDM          | Electric Discharge Machine                       |
| 8     | EDS          | Energy-dispersive Spectroscopy                   |
| 9     | EDX          | Energy-dispersive X-ray Spectroscopy             |
| 10    | FESEN        | Field Emission Scanning Electron Microscope      |
| 11    | GRA          | Grey Relational Analysis                         |
| 12    | HMMC         | Hybrid Metal Matrix Composite                    |
| 13    | I            | Pulse Current                                    |
| 14    | MMC          | Metal Matrix Composite                           |
| 15    | MRR          | Metal Removal Rate                               |
| 16    | OA           | Orthogonal Array                                 |
| 17    | P-Off        | Pulse Off duration                              |
| 18    | P-On         | Pulse On duration                               |
| 19    | PSO          | Particle Swarm Optimization                      |
| 20    | Rp           | Responses                                        |
| 21    | RSA          | Response Surface Methodology                     |
| 22    | SCD          | Surface Crack Density                            |
| 23    | SEM          | Scanning Electron Microscope                     |
| 24    | SC           | Silicon Carbide                                  |
| 25    | SN           | Signal to Noise ratio (K)                        |
| 26    | SR           | Surface Roughness                                |
| 27    | SVR          | Support Vector Regression                        |
| 28    | TL           | Tool Lift time                                   |
| 29    | TOPSIS       | Technique of Order Preference Similarity to the Ideal Solution |
| 30    | TWR          | Tool Wear Rate                                   |
| 31    | WEDM         | Wire cut Electric Discharge Machine              |
| 32    | WR           | Wear Ratio                                       |

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