

An Experimental Study on Multi-Criteria Parameters Optimization of Process for Al6351/SiC/Gr Metal Matrix Composites Using AHP-TOPSIS Approach

Sneha H. Dhoria^{1*}, K. Venkata Subbaiah², V. Durga Prasada Rao³

Abstract

This research focuses on optimizing the process parameters of Wire Electrical Discharge Machining (WEDM) for a hybrid Metal Matrix Composite (MMC) comprising Al6351 aluminum alloy reinforced with 4% SiC and 6% graphite (Gr), fabricated via squeeze casting. This technique enables the formation of dense, defect-free composites with uniform reinforcement distribution, enhancing both mechanical properties and structural integrity. Microstructural characterization using Scanning Electron Microscopy (SEM) confirmed the even dispersion and bonding of reinforcements. The expected phases were confirmed by X-ray diffraction (XRD) analysis, which also confirmed thermal compatibility by removing any undesired intermetallic formations. An L27 orthogonal array was employed to design the WEDM experiments by varying parameters such as pulse-on time, pulse-off time, wire feed, spark voltage, and wire tension. The performance was evaluated based on multiple responses—dimensional deviation (DD), surface roughness (SR), kerf width (K), and material removal rate (MRR). To achieve optimal machining conditions, the study used the AHP-TOPSIS technique. AHP was applied to assign objective weights to each response, while TOPSIS was used to determine the best parameter settings based on closeness coefficients. This hybrid approach effectively handles multi-response optimization and provides a more accurate and systematic alternative to conventional methods.

Keywords: Al6351, SiC, Gr, Squeeze casting, WEDM, AHP-TOPSIS

*Author for Correspondence

Sneha H. Dhoria

¹Research Scholar, Department of Mechanical Engineering, Andhra University, Visakhapatnam, Andhra Pradesh, India

²Senior Professor, Department of Mechanical Engineering, Andhra University, Visakhapatnam, Andhra Pradesh, India

³Professor, Department of Mechanical Engineering, SRKR Engineering College, Bhimavaram, Andhra Pradesh, India

Received Date: April 01, 2025

Accepted Date: May 13, 2025

Published Date: July 24, 2025

Citation: Sneha H. Dhoria, K. Venkata Subbaiah, V. Durga Prasada Rao. An Experimental Study on Multi-Criteria Parameters Optimization of Process for Al6351/SiC/Gr Metal Matrix Composites Using AHP-TOPSIS Approach. Journal of Polymer & Composites. 2025; 13(Special Issue 5): S303–S319p.

INTRODUCTION

Composites are a popular choice for achieving desired properties or improving material properties to meet the requirements of the intended application [1]. Researchers are currently focused on producing new and tougher materials tailored for specific applications and studying their machinability. In modern times, the deployment of metal matrix composites (MMCs) has increased substantial traction in the automobile, aerospace, and defense industries due to their improved properties [2,3]

The Aluminum-based MMCs are particularly suitable for various engineering applications, such as bicycle frames, vehicle drive shafts, automotive pistons, and cylinder liners, as they possess high strength, high thermal conductivity, excellent damping properties, and low density [4]. However, the exceptional qualities and properties of these composites make their conventional machining

complex. The manufacturing industry places great importance on machining processes, with cost and quality as the main benchmarks.

Squeeze casting is one of the best among all the fabrication process, as it may produce high-density, flawless composites with a consistent distribution of reinforcing particles, which improves their mechanical qualities and structural soundness. WEDM stands out as one of the well-known non-conventional machining method, especially when dealing with challenging-to-machine materials like graphite, copper, aluminum, and various others [5]. The choice of appropriate process factors is a crucial aspect of the Wire electro discharge machining process, as improper choices can lead to problems like short-circuiting, wire breakage, and reduced production rates [6]. The precision and accuracy of WEDM have made it a widely accepted machining process, particularly influential in the micromachining of conductive materials [7].

Optimizing process parameters is crucial for sustainable manufacturing. Several researchers have focused on optimizing WEDM parameters for machining different composites. To minimize the wastage of resources, a methodical approach is necessary and experimental design methods like Response Surface Methodology, Fractional Factorial design, and Taguchi techniques are commonly used to extract valuable information. In modern manufacturing, experimental results play a key role in optimizing input process parameters. To achieve multi response optimization, researchers have explored various methods such as GRA [8-10], Heat transfer search algorithm [11, 12], TLBO [13], PSO and Genetic Algorithms [14, 15], Artificial Neural Networks (ANN) [16], and more. These approaches aim to find a trade-off solution among multiple variables, ultimately identifying the optimal process parameters. [16]. Multi-Criteria Decision-Making (MCDM) approaches are vital tools for assessing and ranking alternatives based on specific criteria. Some of the primary techniques used in this context are WSM, WPM, ELECTRE, PROMETEE, AHP, ANP, and TOPSIS. Among these, AHP, ANP, and TOPSIS find widespread applications in pre-planning and evaluating decision criteria across various fields. AHP employs a compensating technique to assist in taking decisions, especially in situations involving certainty or uncertainty, where there is a need to choose or rank alternatives from a large number of options [17-19]. This study employs two popular MCDM methods: AHP to assign weights to the criteria and TOPSIS to rank the alternatives based on their closeness to the ideal solution.

Ramraji et al. [20] examined the impact of wire materials and particle reinforcement on the WEDM machining of AA6061-TiB₂ composite. Their results, which were obtained through experimentation using the Taguchi methodology, showed that the percentage of reinforcement particles was important, affecting machinability by 34.2% and surface quality by 62.04%. While plain brass wire offered better surface quality, zinc-coated brass wire demonstrated superior machining rates when wire materials were compared. A desirability analysis, which showed a sturdy link among the results of predicted and experimental, was conducted to attain an ideal balance between several objectives.

Kanayo Alaneme et al. [21] examined Zn-27Al composites reinforced with silicon carbide, rice husk debris, and graphite. As the RHA content increased and SiC content decreased, the composites displayed a reduction in hardness, rigidity, and yield strength. At the composition of 40% RHA and 40% SiC, the composites experienced the most significant decline, with rigidity decreasing by 8.5% and yield strength by 9.6% respectively.

Varghese and Pradeep et al. [22] fabricated aluminium lattice composites (AMCs) with a fixed 10 wt% of silicon carbide (SiC) and varying graphite content (2-6 wt%) by considering AA6063 as base metal. The contact and wear properties of the composites were compared to an unreinforced aluminium composite (AA6063) under dry sliding conditions by the nail to circle technique with typical loads and constant speed. The wear resistance of the composite increased up to 4% graphite content before starting to decline. The rough surfaces were examined by SEM.

Jayaganthan et al. [23] conducted an optimization study on WEDM of Mg/HNT/Zr MMC to enhance the MRR and Ra. Hybrid composites were produced using powder metallurgy, varying weight percentages of Zr (0.5% and 1%) and HNT (5% and 10%) in magnesium. The machining process was done by considering Taguchi's L27 DOE, with attributes like pulse OFF/ON time, reinforcement weight percentage, wire feed (WF) being considered. To assess the optimized machining parameters, Taguchi-coupled grey relational analysis was employed, and ANOVA results revealed the contributions of certain factors to composite machining. The regression model indicated that the predicted values for Ra and MRR were in close conformity with the experimental values. The study identified the most effective combinations of parameters for minimizing MRR and surface roughness are lower weight percentage of reinforcements, superior pulse - on - time, superior wire feed, and lesser pulse OFF time.

Muniappan et al. [24] explored the effect of diverse types of coated wire electrodes, namely diffused coated, zinc coated, and brass, on the WEDM characteristics of the Al/Silicon Carbide/Graphite hybrid composite. The hybrid composite was fabricated through stir casting method. The researchers utilized the Taguchi experimental design strategy with six process parameters. The output parameters, such as speed of cut, roughness, and kerf were calculated for each experiment.

Soundarajan.R et al. [25] conducted an investigation by developing A413 with 12 wt% B₄C composites with the stir cum squeeze casting technique. To enable efficient parameter selection during the machining of these developed composites using the WEDM, a systematic design approach employing the RSM was adopted. ANOVA analysis indicated that Ton and IP strongly impacted the MRR in WEDM, while Toff had a relatively lesser influence on MRR. However, Toff played a significant role in achieving optimal surface roughness (SR), highlighting its importance in optimizing both MRR and SR during the WEDM process.

Suja Sundaram [26] incorporated TiO₂ nano-reinforced particles into Al6351 at varying weight fractions (4–12%) using the stir casting technique. The study analyzed the influence of feed, speed, and depth of cut on material removal rate (MRR) and surface roughness (SR). To determine the best machining parameters, two different optimization techniques were successfully implemented.

This work is dedicated to addressing the machining difficulties encountered in WEDM of a newly developed aluminium matrix composite (AMC) known as Al6351-6% Gr/4%SiC. Despite the superior mechanical properties of AMCs, their effective integration in industrial applications faces challenges due to the limited literature available on WEDM specifically for this material, especially concerning four crucial responses. To overcome these challenges, the researchers conduct a systematic investigation and adopt a multi-objective optimization approach, namely AHP-TOPSIS. The main objective is to resolve conflicting responses related to the output parameters. While multi-objective optimization is a powerful tool capable of providing optimal solutions, its systematic application in this specific context has not been extensively explored in previous studies.

EXPERIMENTATION

Materials and Methods

Al6351, a medium-strength heat-treatable aluminum alloy, was selected as the matrix material for the development of the hybrid metal matrix composite (MMC) owing to its superior properties, including excellent weldability, corrosion resistance, and good machinability. These characteristics make Al6351 highly suitable for structural and precision machining applications in the aerospace, automotive, and marine industries. To enhance its mechanical and tribological properties, the matrix was reinforced with 4 wt.% silicon carbide (SiC)—a hard ceramic known for its high wear resistance—and 6 wt.% graphite (Gr), which provides solid lubrication and improved machinability. The reinforcing particles, with an average size of 30µm, were uniformly mixed with the molten Al6351 alloy maintained at 750°C to ensure proper wetting and dispersion. The molten composite slurry was then poured into a preheated H13 steel die to maintain thermal consistency and reduce shrinkage defects. Immediately after pouring, a hydraulic ram applied a pressure of 100 MPa during solidification, ensuring a dense, defect-free microstructure.

The squeeze casting technique, known for producing near-net-shape components, also aids in minimizing porosity and improving the bonding between the matrix and reinforcements. This controlled fabrication process is critical for achieving the desired mechanical integrity and homogeneous distribution of reinforcements in the composite, laying a strong foundation for subsequent machining and performance evaluation studies. The resulting Al6351/6%Gr/4%SiC composite, known for its excellent wear resistance and thermal properties [27], was fabricated in $10\text{ mm} \times 10\text{ mm} \times 10\text{ mm}$ dimensions for WEDM performance evaluation. Figure 1 illustrates the detailed fabrication work plan for the development of the Al6351/4%SiC/6%Gr hybrid metal matrix composite (MMC) using the squeeze casting process. This carefully controlled fabrication methodology is essential not only for achieving the desired microstructural characteristics and material integrity but also for establishing a reliable basis for investigating the composite's machinability, surface quality, and wear performance under advanced manufacturing techniques.

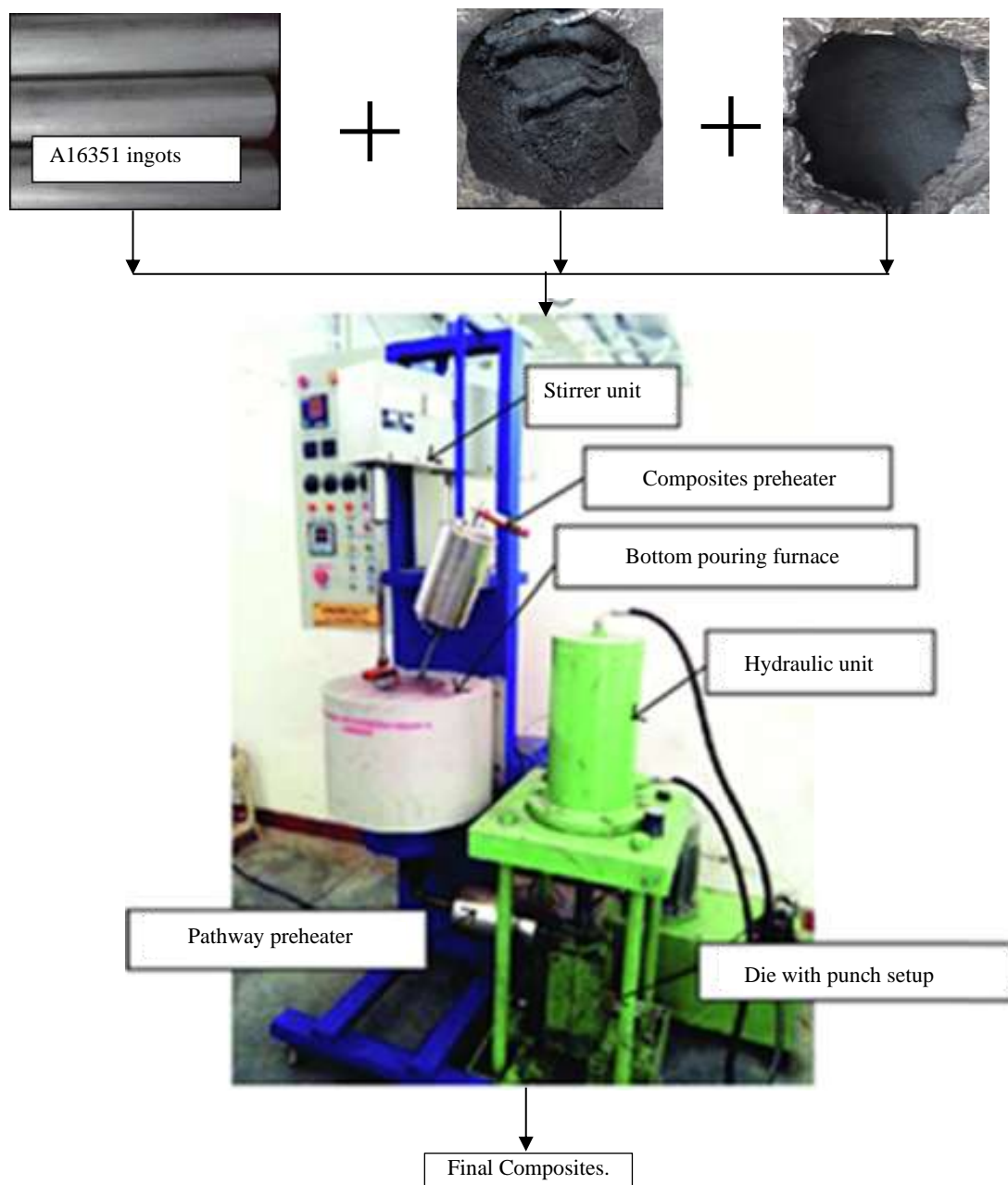


Figure 1. Fabrication Work Plan.

Characterization

SEM Analysis

The morphology, distribution, and interaction between the surfaces of the reinforcement particles within the aluminum matrix were assessed using Scanning Electron Microscopy (SEM) to analyze the microstructural characteristics of the produced Al6351/6%Gr/4%SiC hybrid metal matrix composite. A heterogeneous however even distribution of silicon carbide (SiC) and graphite (Gr) particles established in the Al6351 matrix is revealed by the SEM micrograph, as seen in Figure 2 and Figure 3. Because of their higher atomic number and distinctive sharp-edged morphology, the SiC particles are easily visible as bright, angular phases. In addition to supporting load transfer, their stiff, irregular structure greatly enhances hardness and wear resistance.

The graphite particles, on the other hand, show up as layered, darker, flaky areas also known for their lubricating qualities, these particles are evenly distributed throughout the matrix and are useful for improving surface finish and minimizing tool wear in machining operations like WEDM. With little indication of porosity, agglomeration, or debonding, the SEM image also shows strong interfacial bonding between the reinforcements and matrix. The squeeze casting method, which applies pressure during solidification to encourage close contact between the matrix and reinforcement particles, is responsible for the successful bonding. This process lowers shrinkage defects and improves the integrity of the composite. By integrating the lubricating properties of graphite with the mechanical strength of SiC, the observed microstructure validates the successful creation of a well-bonded, dual-reinforced hybrid composite system, improving the material's overall performance and machinability.

XRD Analysis

XRD analysis was performed to confirm the phase composition of the Al6351/6%Gr/4%SiC hybrid composite. As shown in Figure 4, distinct peaks at 38.5° , 44.7° , 65.1° , and 78.2° correspond to the (111), (200), (220), and (311) planes of the aluminium matrix, indicating high crystallinity. The presence of SiC is confirmed by peaks at 35.6° , 60.0° , and 71.8° corresponding to (111), (220), and (311) planes, while graphite is identified by a peak at 26.5° for the (0001) plane. The absence of secondary phases confirms good thermal compatibility among constituents. The combination of hard SiC and lubricating graphite is expected to enhance wear resistance and machinability, especially for WEDM applications.

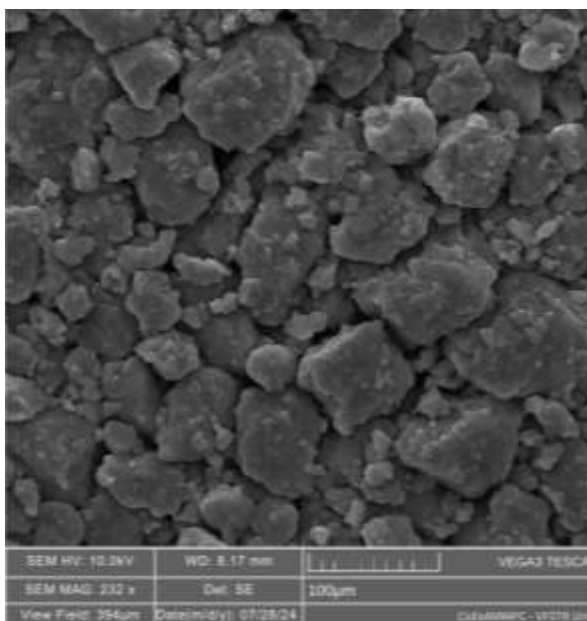


Figure 2. SEM of Al6351.

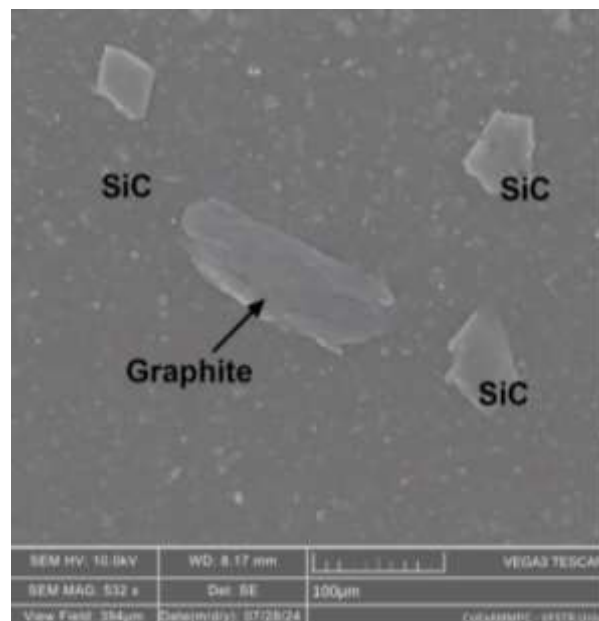


Figure 3. SEM of Al Hybrid MMC.

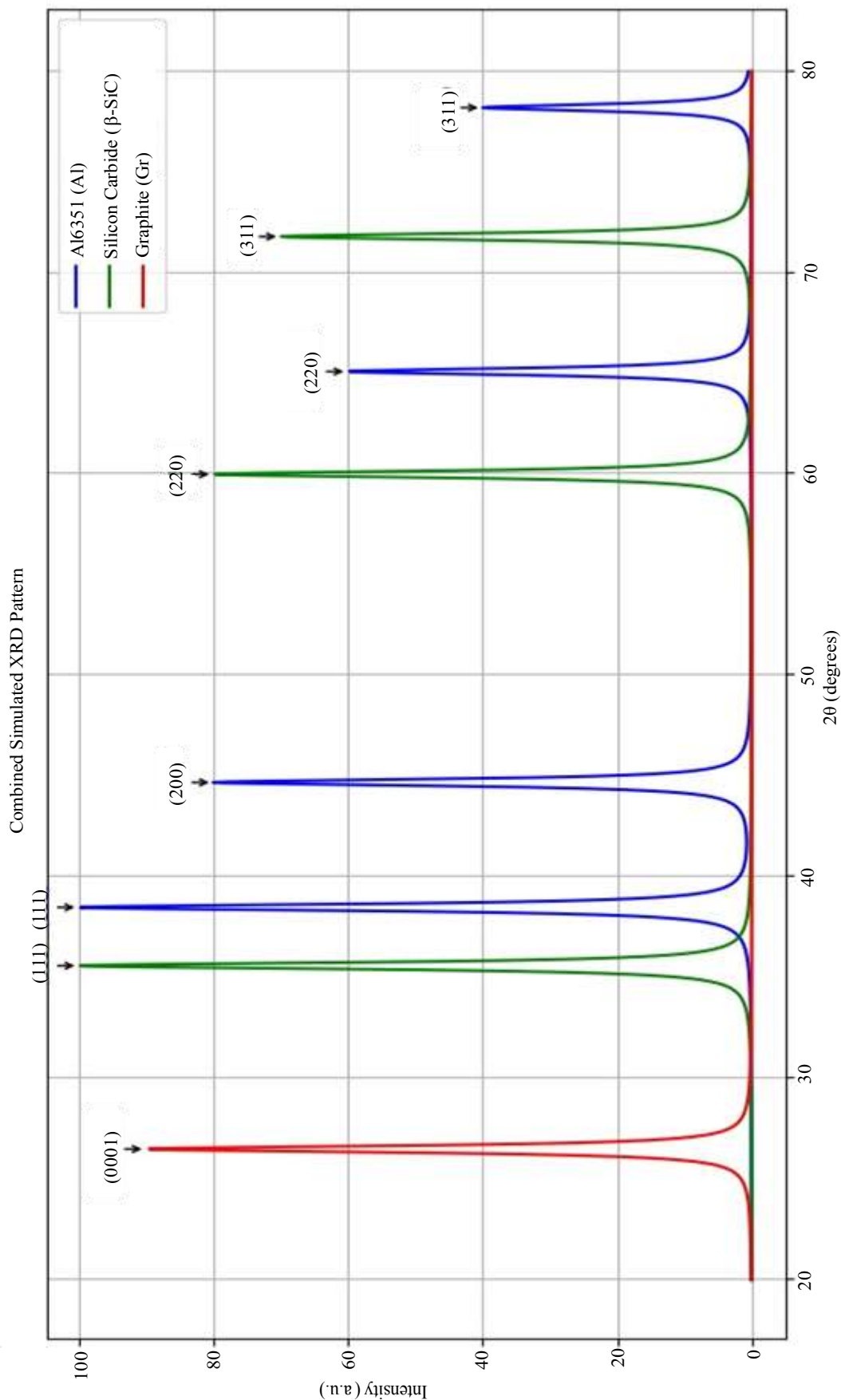


Figure 4. XRD of Hybrid MMC.

Experimental Design Using Taguchi Method

Taguchi's Design of Experiments (DOE) method, utilizing an L27 orthogonal array (OA), was employed to optimize WEDM parameters. Five key parameters, each with three levels (Table 1), were considered, leading to 27 experimental runs. The specimens were machined using an Electronica Hi-tech WEDM machine (Figure 5), with a 0.2 mm brass wire and demineralized water as the dielectric medium. This approach minimizes variance and ensures optimal process parameter selection.

Response Parameters

Dimensional deviation (DD), surface roughness (SR), kerf width (K), and material removal rate (MRR) are the response parameters analyzed in this study. Surface roughness measurements were taken four times perpendicular to the wire travel path on each machined work piece, and the mean value was used to determine SR in micrometers. Each specimen (10 × 10 × 10 mm) (Figure 6) was extracted from the Composite block and SR was measured using a Mitutoyo Surf test SJ-211 (Figure 7). Kerf width was determined using equation (1), while dimensional deviation was calculated as a percentage using equation (2). The cross-sectional dimension (observed width) of each specimen was measured with a Mitutoyo digital vernier caliper, with the actual specimen width set at 10 mm. MRR was calculated using equation (3), with cutting speed obtained from the machine's monitor display. Table 2 presents the experimental values of the output parameters.

Table 1. Machining Parameters and their Levels.

Process Parameters	Notation	Units	Levels		
			1	2	3
Pulse – on- time	A	μsec	108	110	112
Pulse- off- time	B	μsec	50	55	60
Wire feed	C	mm/min	8	10	12
Spark voltage	D	V	20	24	28
Wire tension	E	Kgf	4	6	8

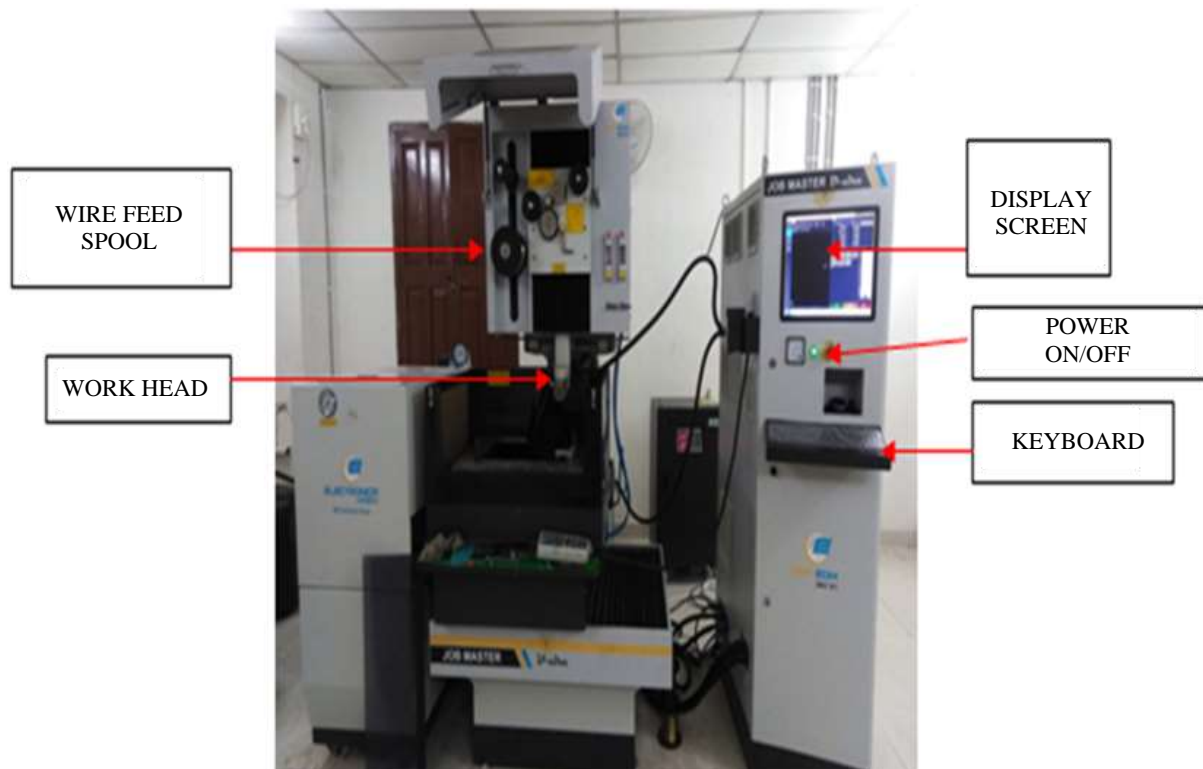


Figure 5. Wire Electrical Discharge Machine.

$$\text{Kerf width} = \frac{\text{Outer width} - \text{Inner width}}{2} \tag{1}$$

$$\text{DD} = \frac{\text{Actual Width} - \text{Observed Width}}{\text{Actual Width}} \times 100 \tag{2}$$

$$\text{MRR} = \text{Cutting speed} \times \text{Height of sample} \times \text{Kerf} \tag{3}$$

Table 2. Quality Characteristics of L₂₇ Orthogonal Array.

Expt. No.	A	B	C	D	E	MRR mm ³ /min	SR Mm	DD %	Kerf mm
1	108	50	8	20	4	17.208	5.4675	2.75	0.2525
2	108	50	8	20	6	16.73	5.1875	2.7	0.246
3	108	50	8	20	8	15.332	4.8325	2.4	0.2385
4	108	55	10	24	4	14.158	4.71	2.8	0.2875
5	108	55	10	24	6	13.245	4.7775	2.7	0.264
6	108	55	10	24	8	12.804	4.8275	2.8	0.22
7	108	60	12	28	4	12.685	4.52	2.8	0.335
8	108	60	12	28	6	9.568	4.585	2.75	0.3025
9	108	60	12	28	8	8.835	4.6925	2.6	0.2632
10	110	50	10	28	4	18.504	4.5325	3.35	0.2825
11	110	50	10	28	6	17.958	4.9625	3.2	0.2655
12	110	50	10	28	8	15.171	4.9725	3.25	0.2175
13	110	55	12	20	4	18.534	4.3575	3.1	0.2975
14	110	55	12	20	6	16.325	4.7725	3	0.2675
15	110	55	12	20	8	15.998	4.7775	2.95	0.2525
16	110	60	8	24	4	16.028	5.0725	3.05	0.315
17	110	60	8	24	6	13.822	5.125	3.3	0.28
18	110	60	8	24	8	12.824	4.855	3	0.253
19	112	50	12	24	4	24.813	4.6775	3.55	0.3075
20	112	50	12	24	6	22.791	4.59	2.9	0.2675
21	112	50	12	24	8	22.228	4.8525	2.85	0.2595
22	112	55	8	28	4	22.086	5.265	3.25	0.2875
23	112	55	8	28	6	20.225	4.63	3.2	0.25
24	112	55	8	28	8	17.682	5.0125	3	0.2325
25	112	60	10	20	4	22.215	4.58	3.25	0.2925
26	112	60	10	20	6	20.969	4.685	3	0.2725
27	112	60	10	20	8	17.21	4.39	3.3	0.283

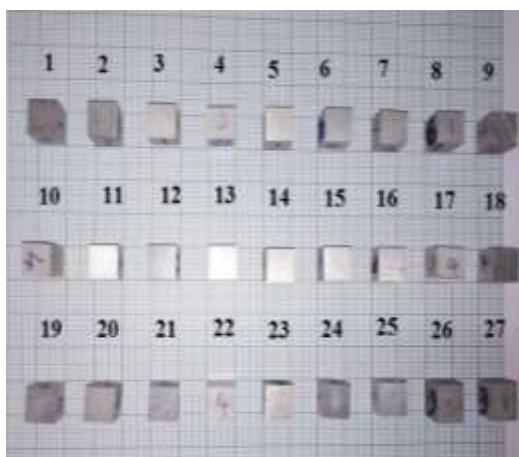


Figure 6. Specimens Produced by WEDM

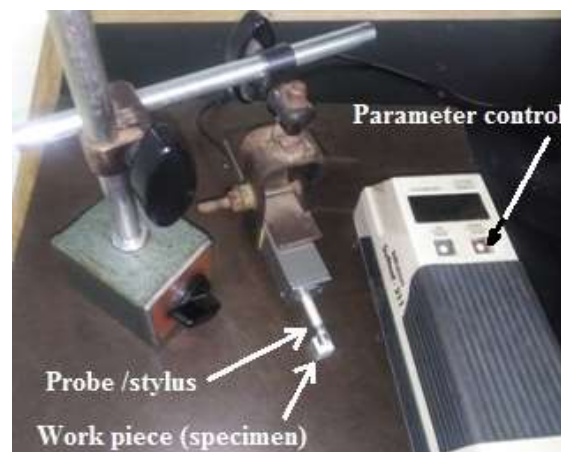


Figure 7. Measurement of SR by Surf test

Multi-Objective Optimization by AHP Method

The hybrid AHP-TOPSIS method represents a well-established approach under the umbrella of Multi-Criteria Decision-Making (MCDM) techniques. MCDM methods are widely used mathematical frameworks designed to tackle complex problems involving multiple alternatives and often conflicting criteria [28-30]. These techniques provide structured solutions by integrating both qualitative and quantitative factors into the decision-making process. Among the various MCDM methods, the Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty in the 1970s, stands out as a pioneering tool for decision analysis. AHP enables decision-makers to systematically evaluate and prioritize alternatives based on pairwise comparisons of multiple criteria [30].

Step 1: Develop a hierarchical structure as shown in Figure 8.

Step 2: Performing the pair-wise comparison by comparison scale [31], and determining the weights of the attributes is shown in Table 3.

Step 3: Once the matrix has been generated through AHP measurement, the next step is to calculate the Eigen values by the geometric process in order to obtain an accurate representation of priorities. This process entails the multiplication of elements within each row, followed by extracting the n^{th} root of the resulting product. The Eigen values or vectors are tabulated in Table 4.

Table 3. Weights of Attributes

	MRR	SR	DD	KERF
MRR	1	1/3	1/4	1/7
SR	3	1	1/4	1/5
DD	4	4	1	1/3
KERF	7	5	3	1

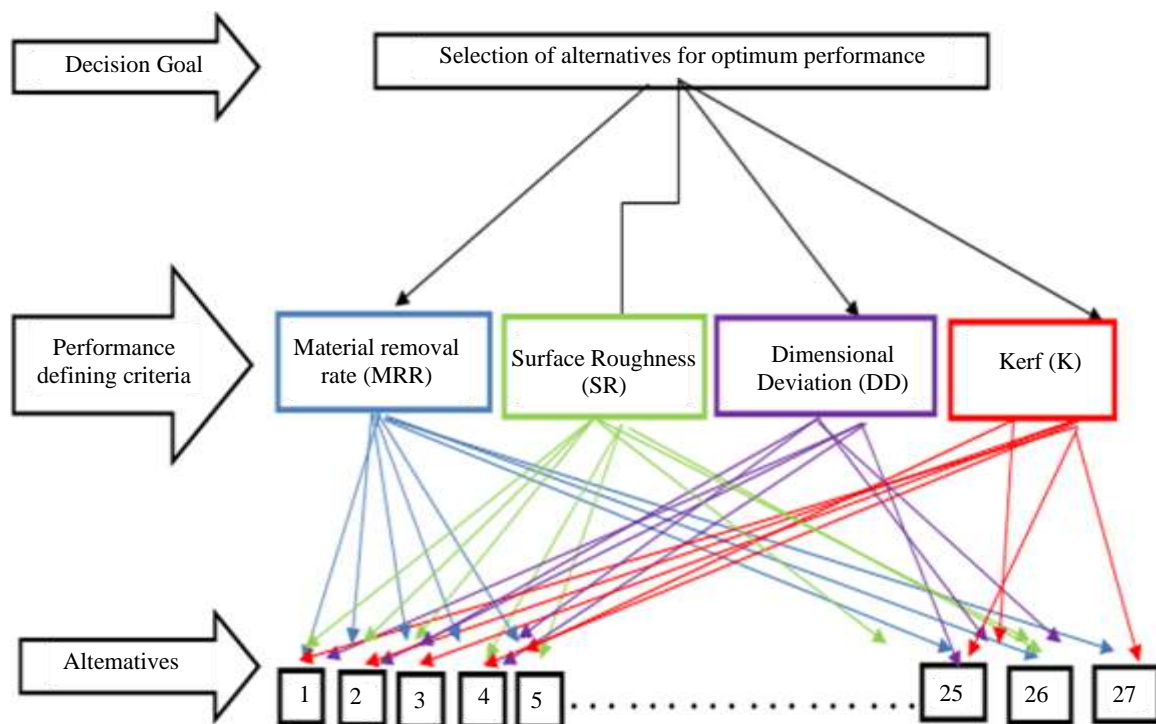


Figure 8. AHP Hierarchical Structure.

$$EV_{MRR} = \sqrt[4]{1 * (\frac{1}{3}) * (\frac{1}{4}) * (\frac{1}{7})} = 0.3220$$

$$EV_{SR} = \sqrt[4]{3 * 1 * (\frac{1}{4}) * (\frac{1}{5})} = 0.6220$$

$$EV_{DD} = \sqrt[4]{4 * 4 * 1 * (\frac{1}{3})} = 1.5158$$

$$EV_{Kerf} = \sqrt[4]{7 * 5 * 3 * 1} = 3.2010$$

Step 4: The resulting priority vector for MRR, SR, DD, and Kerf is presented in Table 4, and it is derived using the following formula:

$$PV = \frac{\text{Eigen value of the output parameter}}{\text{Total sum of the column elements}}$$

Table 4. Eigen Values and Weightages (Pv_i)

	Eigen Values	Priority values/ Weightages (Pv _i)
MRR	0.3200	0.0565
SR	0.6220	0.1099
DD	1.5158	0.2679
Kerf	3.2010	0.5657
Total (T_i)	5.6588	

Step 5: In order to calculate the principal vector, it is necessary to multiply the sum of each column by the corresponding priority vector. The formula for determining the principal vector is provided by Equation 4.

$$\lambda_{max} = \sum_{i=1}^n T_i * P_{vi} \tag{4}$$

Step 6: The Calculation of the consistency index is given by eq.5

$$C.I = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

Where n= number of output parameters = 4, λ_{max}= 4.138

Step 7: To determine the consistency of pair-wise comparisons, the consistency ratio (C.R.) is considered by dividing the Consistency Index (CI) by a randomly chosen consistency number [31]. As per Saaty's guidelines, a C.R. value of ≤ 0.1 is considered acceptable for consistency, and the Random Index (R.I.) is used to find out the appropriate random value based on the matrix size.

$$CI = \frac{\text{Consistency Index}}{RI}$$

Ideally, the CR value must be around 10% for acceptance, but sometimes 20% is also acceptable. In this case, the CR is fewer than 10%, indicating that the pair wise comparison matrix is accepted, and the weightages for output parameters are assigned the same priority values or weightages. Specifically, W_{MRR}= 0.0565, W_{SR}= 0.1099, W_{DD}= 0.2679, and W_{KW}= 0.5657.

AHP –TOPSIS Process

The AHP-TOPSIS method combines AHP for weighting criteria and TOPSIS for ranking alternatives based on their proximity to the ideal solution. The AHP-TOPSIS process flow chart is as shown in the Figure 9. After constructing the decision matrix, Equation (6) is utilized to normalize it. Through this

normalization process, the attribute dimensions are changed into non-dimensional attributes, allowing for meaningful comparisons across all attributes. The AHP-TOPSIS methodology comprises the analysis and formulation of data into a decision matrix containing 'm' attributes and 'n' alternatives.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (6)$$

x_{ij} =decision matrix values related to output parameters, m = attributes. Repeat the process for all the output parameters. Following normalization, the calculation of the weighted normalized decision matrix is carried out using equation 7. This matrix, which incorporates the AHP weights with the TOPSIS normalization matrix, is then generated. The results from 27 experiments involving the normalized decision matrix and the weighted normalized decision matrix are displayed in Table 5.

$$V_{ij} = W_i * r_{ij} \quad (7)$$

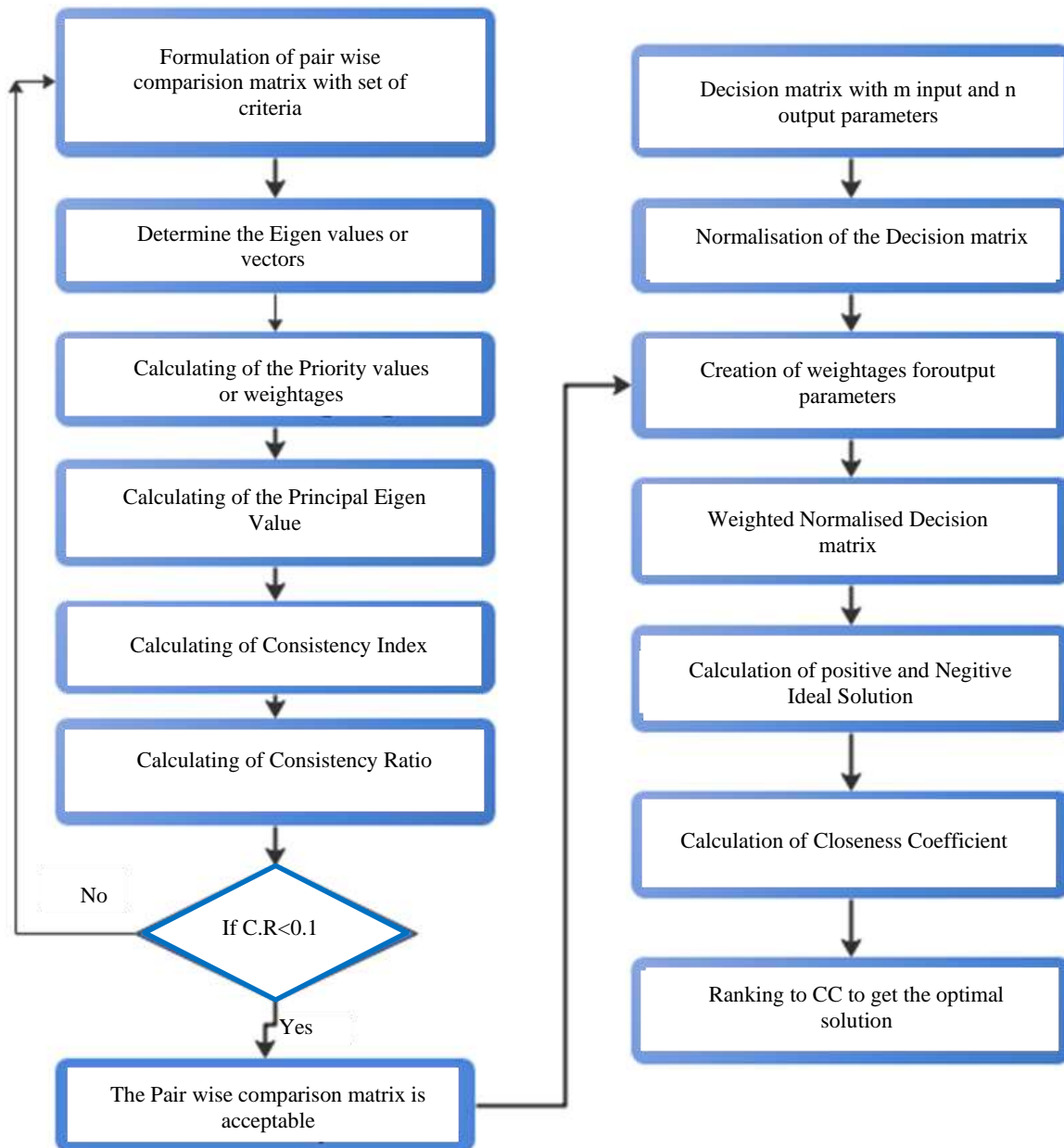


Figure 9. Flow Chart of AHP-TOPSIS

Table 5. Decision Matrix, Normalized Decision Matrix, Weighted Normalized Matrix.

Decision Matrix					Normalization Matrix				Weighted Normalized Matrix			
Expt. No	MRR	SR	DD	KERF	MRR	SR	DD	KERF	MRR	SR	DD	KERF
1	17.208	5.4675	2.75	0.2525	0.1909	0.2187	0.1762	0.1790	0.0108	0.0240	0.0472	0.1012
2	16.73	5.1875	2.7	0.246	0.1856	0.2075	0.1730	0.1744	0.0105	0.0228	0.0463	0.0986
3	15.332	4.8325	2.4	0.2385	0.1701	0.1933	0.1537	0.1690	0.0096	0.0212	0.0412	0.0956
4	14.158	4.71	2.8	0.2875	0.1571	0.1884	0.1794	0.2038	0.0089	0.0207	0.0481	0.1153
5	13.245	4.7775	2.7	0.264	0.1470	0.1911	0.1730	0.1871	0.0083	0.0210	0.0463	0.1059
6	12.804	4.8275	2.8	0.22	0.1421	0.1931	0.1794	0.1559	0.0080	0.0212	0.0481	0.0882
7	12.685	4.52	2.8	0.335	0.1407	0.1808	0.1794	0.2374	0.0080	0.0199	0.0481	0.1343
8	9.568	4.585	2.75	0.3025	0.1062	0.1834	0.1762	0.2144	0.0060	0.0202	0.0472	0.1213
9	8.835	4.6925	2.6	0.2632	0.0980	0.1877	0.1666	0.1866	0.0055	0.0206	0.0446	0.1055
10	18.504	4.5325	3.35	0.2825	0.2053	0.1813	0.2146	0.2002	0.0116	0.0199	0.0575	0.1133
11	17.958	4.9625	3.2	0.2655	0.1993	0.1985	0.2050	0.1882	0.0113	0.0218	0.0549	0.1065
12	15.171	4.9725	3.25	0.2175	0.1683	0.1989	0.2082	0.1542	0.0095	0.0219	0.0558	0.0872
13	18.534	4.3575	3.1	0.2975	0.2056	0.1743	0.1986	0.2109	0.0116	0.0192	0.0532	0.1193
14	16.325	4.7725	3	0.2675	0.1811	0.1909	0.1922	0.1896	0.0102	0.0210	0.0515	0.1073
15	15.998	4.7775	2.95	0.2525	0.1775	0.1911	0.1890	0.1790	0.0100	0.0210	0.0506	0.1012
16	16.028	5.0725	3.05	0.315	0.1778	0.2029	0.1954	0.2233	0.0100	0.0223	0.0523	0.1263
17	13.822	5.125	3.3	0.28	0.1534	0.2050	0.2114	0.1985	0.0087	0.0225	0.0566	0.1123
18	12.824	4.855	3	0.253	0.1423	0.1942	0.1922	0.1793	0.0080	0.0213	0.0515	0.1014
19	24.813	4.6775	3.55	0.3075	0.2753	0.1871	0.2274	0.2180	0.0156	0.0206	0.0609	0.1233
20	22.791	4.59	2.9	0.2675	0.2529	0.1836	0.1858	0.1896	0.0143	0.0202	0.0498	0.1073
21	22.228	4.8525	2.85	0.2595	0.2466	0.1941	0.1826	0.1839	0.0139	0.0213	0.0489	0.1040
22	22.086	5.265	3.25	0.2875	0.2451	0.2106	0.2082	0.2038	0.0138	0.0231	0.0558	0.1153
23	20.225	4.63	3.2	0.25	0.2244	0.1852	0.2050	0.1772	0.0127	0.0204	0.0549	0.1002
24	17.682	5.0125	3	0.2325	0.1962	0.2005	0.1922	0.1648	0.0111	0.0220	0.0515	0.0932
25	22.215	4.58	3.25	0.2925	0.2465	0.1832	0.2082	0.2073	0.0139	0.0201	0.0558	0.1173
26	20.969	4.685	3	0.2725	0.2327	0.1874	0.1922	0.1931	0.0131	0.0206	0.0515	0.1093
27	17.21	4.39	3.3	0.283	0.1910	0.1756	0.2114	0.2006	0.0108	0.0193	0.0566	0.1135

After acquiring the PIS and NIS, we move forward with evaluating the distance of each alternative from these solutions by applying equations (8) and (9). The outcomes of these computations are documented representing the Positive Separation Ideal Solution (PSIS) and Negative Separation Ideal Solution (NSIS). With the separations now determined, our next step involves computing the closeness coefficient using equation (10). The resulting coefficients are likewise tabulated in Table 6.

$$D_i^+ = \sqrt{\sum_{j=1}^m (V_{ij} - V_j^+)^2} \tag{8}$$

$$D_i^- = \sqrt{\sum_{j=1}^m (V_{ij} - V_j^-)^2} \tag{9}$$

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{10}$$

The closeness coefficient, derived from the AHP-TOPSIS analysis, plays a significant role in the Taguchi method for identifying the optimal process parameter settings in wire electrical discharging machining on an AMC composite. In this context, the closeness coefficient acts as a quality characteristic of the "Higher the better" type. To assess the influence of various parameter levels, the closeness coefficient is computed for each parameter and organized in Table 6

Table 6. PIS, NIS, and Closeness Coefficient of Al MMC.

Exp No	A	B	C	D	E	SI ⁺	SI ⁻	Closeness Coefficient (CC _i)
1	1	1	1	1	1	0.0167	0.0362	0.6840
2	1	1	1	1	2	0.0140	0.0389	0.7352
3	1	1	1	1	3	0.0105	0.0437	0.8061
4	1	2	2	2	1	0.0297	0.0235	0.4414
5	1	2	2	2	2	0.0207	0.0323	0.6086
6	1	2	2	2	3	0.0104	0.0480	0.8214
7	1	3	3	3	1	0.0482	0.0137	0.2218
8	1	3	3	3	2	0.0359	0.0193	0.3499
9	1	3	3	3	3	0.0212	0.0333	0.6106
10	2	1	2	3	1	0.0310	0.0226	0.4211
11	2	1	2	3	2	0.0242	0.0292	0.5467
12	2	1	2	3	3	0.0160	0.0476	0.7482
13	2	2	3	1	1	0.0345	0.0186	0.3506
14	2	2	3	1	2	0.0232	0.0292	0.5570
15	2	2	3	1	3	0.0179	0.0351	0.6622
16	2	3	1	2	1	0.0411	0.0127	0.2359
17	2	3	1	2	2	0.0304	0.0227	0.4277
18	2	3	1	2	3	0.0192	0.0344	0.6414
19	3	1	3	2	1	0.0412	0.0153	0.2710
20	3	1	3	2	2	0.0219	0.0308	0.5848
21	3	1	3	2	3	0.0187	0.0337	0.6431
22	3	2	1	3	1	0.0319	0.0214	0.4016
23	3	2	1	3	2	0.0192	0.0355	0.6494
24	3	2	1	3	3	0.0131	0.0426	0.7653
25	3	3	2	1	1	0.0335	0.0201	0.3747
26	3	3	2	1	2	0.0245	0.0280	0.5338
27	3	3	2	1	3	0.0308	0.0224	0.4211

Based on Table 6 results, the closeness coefficients (CC_i) of various experiments, it can be observed that the values range from approximately 0.2218 to 0.8214. A higher closeness coefficient indicates a better performance or a closer proximity to the ideal solution. Among the experiments, Experiment 6 stands out with the highest closeness coefficient (CC_i = 0.8214), suggesting that it is the most favourable or closest to meeting the desired criteria or objectives. On the other hand, Experiment 7 has the lowest closeness coefficient (CC_i = 0.2218), indicating that it is the least favourable or farthest from the ideal solution among the experiments. The remaining experiments fall within the intermediate range of closeness coefficients, signifying varying degrees of performance relative to the ideal solution.

Main effects plot for means

Moreover, a main effects plot for means is employed to study the effects of these parameters on the response characteristics. This combined approach aids in determining the most favourable parameter settings that lead to enhanced machining performance for the given composite material. Figure 10 presents the main effects plot for means based on the closeness coefficient. Parameter E shows the

highest influence, with a significant rise in mean response at higher levels. Parameters B and C also affect the response notably, showing decreasing trends. Parameters A and D have minimal impact within the tested range. This analysis helps identify the most influential factors for optimizing multi-response performance.

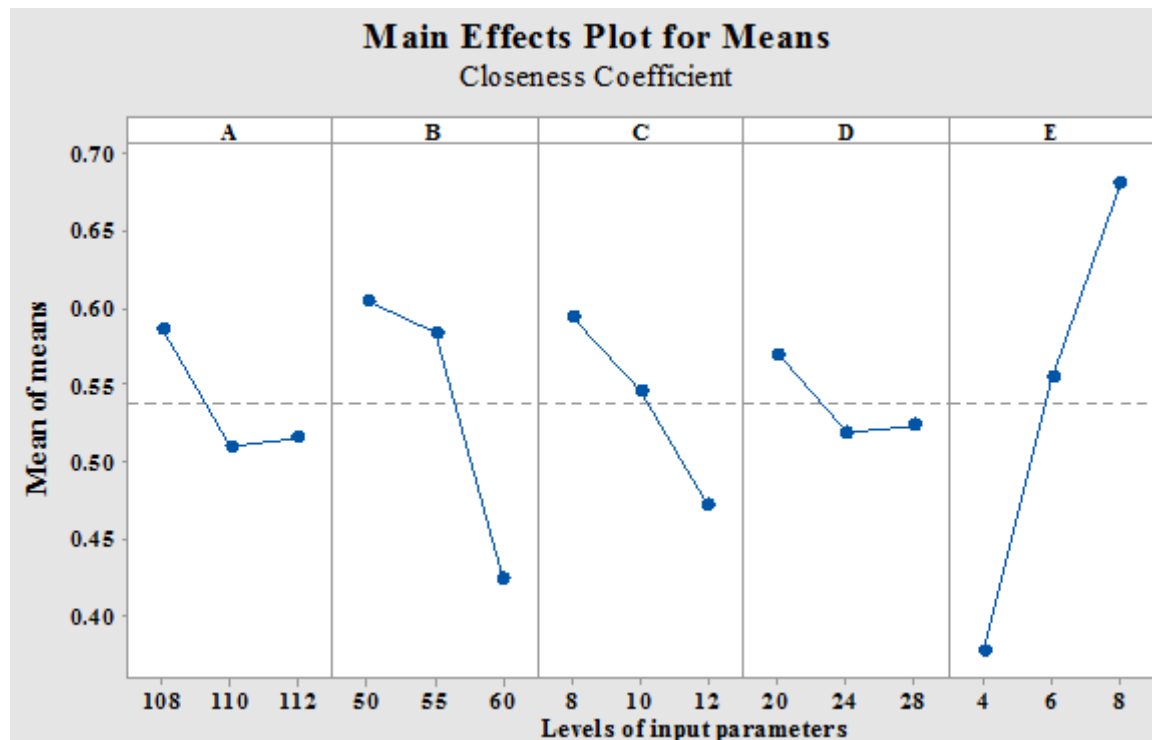


Figure 10. Main Effects Plot for Response Means.

Table 7. Response Table for S/N ratios of Closeness coefficient

Level	A	B	C	D	E
1	-5.273	-4.773	-5.069	-5.233	-8.938
2	-6.314	-4.988	-5.544	-6.305	-5.297
3	-6.147	-7.974	-7.121	-6.196	-3.499
Delta	1.041	3.201	2.052	1.071	5.438
Rank	5	2	3	4	1

The Table 7 response table clearly indicates that wire tension exerts the most significant impact on the WEDM of the prepared composite, making it the most influential parameter. Following closely in importance are Pulse off time, Wire feed, Spark voltage, and pulse on time, in descending order of their effects on the machining process.

CONCLUSIONS AND DISCUSSIONS

In this work Al6351/SiC/Gr hybrid metal matrix composites were processed through Squeeze casting process.

- The SEM analysis confirms uniform dispersion of SiC and graphite in the Al6351 matrix with minimal defects. XRD results validate the presence of distinct crystalline phases without secondary formations, confirming successful composite fabrication..
- The study successfully optimizes the process parameters of Wire Electrical Discharge Machining (WEDM) for Al6351/6%Gr/4%SiC hybrid metal matrix composite (MMC) using the AHP-TOPSIS methodology.

- The integration of an L27 orthogonal array provides a structured experimental approach, enabling a comprehensive analysis of key machining responses, including surface roughness (SR), material removal rate (MRR), dimensional deviation (DD), and kerf width (K).
- The application of AHP-TOPSIS overcomes the limitations of conventional optimization techniques by effectively handling multi-response optimization and enhancing decision-making accuracy through weight-based response evaluation.
- The analysis of closeness coefficients (CCi) confirms a significant variation in machining performance across different experimental runs, with values ranging from 0.2218 to 0.8214. Experiment 6 emerges as the optimal parameter combination, exhibiting the highest CCi value of 0.8214, ensuring superior machining efficiency and precision.
- The findings of this research contribute to the advancement of WEDM machining strategies for hybrid composites, providing a reliable framework for improving process efficiency, accuracy, and surface integrity.
- The proposed optimization approach can be extended to other composite materials and machining processes, offering a valuable tool for industrial applications requiring high-precision manufacturing.

Acknowledgements

The authors declare that there are no acknowledgements to be made for this study. All research and writing were conducted independently without external support or contributions.

Declaration of Interest

Authors declare that there are no conflicts of interest associated with this publication all authors have contributed to the research and writing of this manuscript, and no financial or personal relationships could be perceived as influencing the work reported in this manuscript.

REFERENCES

1. Low IM, Dong Y, editors. Composite materials: manufacturing, properties and applications. 1st ed. Amsterdam: Elsevier; 2021. 688 p. ISBN: 9780128205129.
2. Uthayakumar M, Prabhakaran G, Aravindan S, Sivaprasad JV. Influence of cutting force on bimetallic piston machining by a cubic boron nitride (CBN) tool. *Materials and Manufacturing Processes*. 2012 Oct 1; 27(10):1078-83. <https://doi.org/10.1080/10426914.2012.677913>
3. Dhoria, S. H.; Durga Prasada Rao, V.; Venkata Subbaiah, K. Assessment of Mechanical and Tribological Properties of Aluminium Hybrid Metal Matrix Composites: A Review. *Research Review International Journal of Multidisciplinary* 2019, 4(5), 1049-1056.
4. Monica V, Lakshmikanth G, Lathicashree S, Senthilkumar N, Muniappan A, Deepanraj B. An experimental analysis and optimization of heat treatment parameters of Al6061 alloy for improved mechanical properties. *International Journal of Mechanical and Production Engineering Research and Development*. 2019; 9(Special Issue):46-59.
5. Phate MR, Toney SB, Phate VR. Multi-parametric optimization of WEDM using artificial neural network (ANN)-based PCA for Al/SiCp MMC. *Journal of the Institution of Engineers (India): Series C*. 2021 Feb; 102(1):169-81. <http://dx.doi.org/10.1007/s40032-020-00615-1>
6. Lal K, Trehan R. Review of wire breakage causes and mitigation strategies in wire electrical discharge machining. *Machining Science and Technology*. 2025 Mar 5:1-47. <https://doi.org/10.1080/10910344.2025.2475463>.
7. Kumar N, Kumari S, Abhishek K, Nandi G, Ghosh N. Study on various parameters of WEDM using different optimization techniques: A review. *Materials Today: Proceedings*. 2022 Jan 1;62:4018-24. <http://dx.doi.org/10.1016/j.matpr.2022.04.596>.
8. Sheth M, Gajjar K, Jain A, Shah V, Patel H, Chaudhari R, Vora J. Multi-objective optimization of inconel 718 using Combined approach of taguchi—Grey relational analysis. In *Advances in Mechanical Engineering: Select Proceedings of ICAME 2020 2021* (pp. 229-235). Springer Singapore. http://dx.doi.org/10.1007/978-981-15-3639-7_27.

9. Rathi P, Ghiya R, Shah H, Srivastava P, Patel S, Chaudhari R, Vora J. Multi-response optimization of Ni55. 8Ti shape memory alloy using taguchi–grey relational analysis approach. *In Recent Advances in Mechanical Infrastructure: Proceedings of ICRAM 2019 2020* (pp. 13-23). Springer Singapore. https://doi.org/10.1007/978-981-32-9971-9_2
10. Patel S, Fuse K, Gangvekar K, Badheka V. Multi-response optimization of dissimilar Al-Ti alloy FSW using Taguchi-Grey relational analysis. *Key Engineering Materials*. 2020 Apr 6;833:35-9. <http://dx.doi.org/10.4028/www.scientific.net/KEM.833.35>.
11. Chaudhari R, Vora JJ, Prabu SM, Palani IA, Patel VK, Parikh DM. Pareto optimization of WEDM process parameters for machining a NiTi shape memory alloy using a combined approach of RSM and heat transfer search algorithm. *Advances in manufacturing*. 2021 Mar;9:64-80. <http://dx.doi.org/10.1007/s40436-019-00267-0>.
12. Vora J, Patel VK, Srinivasan S, Chaudhari R, Pimenov DY, Giasin K, Sharma S. Optimization of activated tungsten inert gas welding process parameters using heat transfer search algorithm: With experimental validation using case studies. *Metals*. 2021 Jun 19;11(6):981. <https://doi.org/10.3390/met11060981>.
13. Chaudhari R, Khanna S, Vora J, Patel VK, Paneliya S, Pimenov DY, Giasin K, Wojciechowski S. Experimental investigations and optimization of MWCNTs-mixed WEDM process parameters of nitinol shape memory alloy. *Journal of Materials Research and Technology*. 2021 Nov 1;15:2152-69. <https://doi.org/10.1016/j.jmrt.2021.09.038>.
14. Nain SS, Garg D, Kumar S. Investigation for obtaining the optimal solution for improving the performance of WEDM of super alloy Udimet-L605 using particle swarm optimization. *Engineering science and technology, an international journal*. 2018 Apr 1;21(2):261-73. <https://doi.org/10.1016/j.jestch.2018.03.005>.
15. Sharma N, Khanna R, Gupta RD. WEDM process variables investigation for HSLA by response surface methodology and genetic algorithm. *Engineering science and technology, an international journal*. 2015 Jun 1;18(2):171-7. <https://doi.org/10.1016/j.jestch.2014.11.004>.
16. Phate MR, Toney SB. Modeling and prediction of WEDM performance parameters for Al/SiCp MMC using dimensional analysis and artificial neural network. *Engineering Science and Technology, an International Journal*. 2019 Apr 1;22(2):468-76. <http://dx.doi.org/10.1016/j.jestch.2018.12.002>.
17. Haddad M, Sanders D. Selection of discrete multiple criteria decision making methods in the presence of risk and uncertainty. *Operations Research Perspectives*. 2018 Jan 1;5:357-70.
18. Vassoney E, Mammoliti Mochet A, Desiderio E, Negro G, Pilloni MG, Comoglio C. Comparing multi-criteria decision-making methods for the assessment of flow release scenarios from small hydropower plants in the alpine area. *Frontiers in Environmental Science*. 2021 Apr 16;9:635100. <http://dx.doi.org/10.3389/fenvs.2021.635100>.
19. Babu RD, Gurusamy P, Bejaxhin AB, Chandramohan P. Influences of WEDM constraints on tribological and micro structural depictions of SiC-Gr strengthened Al2219 composites. *Tribology International*. 2023 Jul 1;185:108478. <http://dx.doi.org/10.1016/j.triboint.2023.108478>.
20. Ramraji K, Rajkumar K, Selvakumar G. Investigations on the influence of particle reinforcement and wire materials on the surface quality and machining characteristics of AA6061-TiB₂ alloy in WEDM. *Surface Topography: Metrology and Properties*. 2021 Aug 27;9(3):035029. <http://dx.doi.org/10.1088/2051-672X/ac1f7c>
21. Alaneme KK, Ajayi OJ. Microstructure and mechanical behavior of stir-cast Zn–27Al based composites reinforced with rice husk ash, silicon carbide, and graphite. *Journal of King Saud University-Engineering Sciences*. 2017 Apr 1;29(2):172-7. <http://dx.doi.org/10.1016/j.jksues.2015.06.004>.
22. Varghese AN, Pradeep PV. Experimental investigation of wear characteristics on AL/SiC/GR composite material. *International Journal on Theoretical and Applied Research in Mechanical Engineering (IJTARME)*. 2014;3(3).
23. Jayaganthan A, Manickam M, Prathiban S, Amarnath M, Subramanian K, Babu M, Dharmadurai P, Adamassu Y. Multiobjective Optimization of WEDM Parameters on the Mg-HNT-Zr Hybrid

- Metal Matrix Composite Using Taguchi-Coupled GRA. *Advances in Materials Science and Engineering*. 2022; 2022(1):1920810. <http://dx.doi.org/10.1155/2022/1920810>.
24. Anandan D, Aravind D, Dhanraj K, Abinesh R, Barathkumar P. Performance of wire electrodes on machining of hybrid Aluminium composite. *International Journal of Applied Engineering Research*.; 10(65):2015.
 25. Soundararajan R, Ramesh A, Mohanraj N, Parthasarathi N. An investigation of material removal rate and surface roughness of squeeze casted A413 alloy on WEDM by multi response optimization using RSM. *Journal of alloys and compounds*. 2016 Nov 15; 685:533-45. <http://dx.doi.org/10.1016/j.jallcom.2016.05.292>.
 26. Sundram S, Raman MS, Balamuralitharan S. Influence of process parameters on machining studies on stir casted MMCs with AA6351 and TiO₂ by grey and desirability approaches. *Materials Today: Proceedings*. 2023 Jan 1; 77:551-6. <http://dx.doi.org/10.1016/j.matpr.2023.01.091>
 27. Dhoria SH, Rao VD, Subbaiah KV. Mechanical and wear behaviour of 6351 Al/Gr/SiC composites fabricated by squeeze casting. *Materials Today: Proceedings*. 2019 Jan 1;18:2107-13. <http://dx.doi.org/10.1016/j.matpr.2019.06.326>
 28. Soota T, Rajput SK. Optimization and measurement of kerf width and surface roughness of AISI 316L. *Forces in Mechanics*. 2022 Feb 1; 6:100071. <http://dx.doi.org/10.1016/j.finmec.2022.100071>.
 29. Tosun N, Cogun C, Tosun G. A study on kerf and material removal rate in wire electrical discharge machining based on Taguchi method. *Journal of materials processing technology*. 2004 Oct 30;152(3):316-22. <http://dx.doi.org/10.1016/j.jmatprotec.2004.04.373>.
 30. Saaty TL. The analytic hierarchy process mcgraw hill, New York. *Agricultural Economics Review*. 1980;70(804):10-21236.
 31. Ram Prasad AV, Ramji K, Kolli M, Vamsi Krishna G. Multi-response optimization of machining process parameters for wire electrical discharge machining of lead-induced Ti-6Al-4V alloy using AHP-TOPSIS method. *Journal of Advanced Manufacturing Systems*. 2019 Jun; 18(02):213-36. <http://dx.doi.org/10.1142/S0219686719500112>.