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INVESTIGATION OF WEDM PERFORMANCE ON AL7075/B4C/CNT HYBRID METAL MATRIX COMPOSITE USING GRA-TAGUCHI ANALYSIS

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Abstract

This research paper focuses on the analysis of Wire Electrical Discharge Machining (WEDM) performance on Al7075/B4C/CNT hybrid metal matrix composite. This study aims to examine the impact of different machining parameters on surface roughness, material removal rate, and kerf width in the WEDM process. Experimental tests are conducted to examine the effects of parameters such as wire type, wire feed, wire tension, pulse-off time, and pulse-on time on the machining performance of the hybrid metal matrix composite. The Taguchi design of experiments technique was employed to design number of experiments required to determine the optimal input parameters and the L16 orthogonal array was chosen. To identify the ideal set of input parameters, grey relation analysis is also carried out. Ultimately, Grey Relation Analysis proposed A1B2C1D2E1 are the optimal values of the control factors for better machining responses.

Key words: Hybrid MMC, Stir casting, Wire Electrical Discharge Machining, and Grey Relation Analysis method.

1. INTRODUCTION

Since modern industries demand materials with attributes like strength, durability, light weight, and low density, researchers worldwide are focusing on the study of materials and their applications. Consequently, their attention has shifted to the creation of advanced materials such as metal matrix composites [1].Aluminum-based metal matrix composites have increasingly been utilised in various technical applications, including marine, automotive piston and cylinder components, aerospace, military, transportation, and construction sectors, where superior material strength is essential to endure elevated stresses[2].However, because of their strength and hardness, these metal matrix composites are difficult to machine using traditional machining techniques.As a result, unconventional machining techniques are necessary for the machining of AMMCs [3]. WEDM is a non-conventional machining technology that uses electrical discharges to attain the required form. The primary motivation for the development of WEDM was the necessity for the precise removal of complicated components from their respective work pieces [4]. In WEDM, an electric voltage is delivered to two electrodes separated by a dielectric fluid, resulting in a sequence of fast current discharges for material removal [5]. In the zone of machining, an increase in pulse peak current results in more electrical discharge energy. This then results in the formation of deeper craters at the machined surface, eventually increasing the Material Removal Rate (MRR) [6, 7].

In WEDM, the factors contributing to unstable process conditions include high discharge energy and an optimal pulse frequency [8]. When cutting a circular interpolation, the wire distortion is more when compared with cutting a straight cut on a component of the same thickness with same radius of wire [9]. An increase in the Ton parameter enlarges the plasma radius, resulting in an increase in crater size on the workpiece and thermal damage [10]. Enhancing conductivity alters the material removal process towards melting and re-solidification, resulting in a reduced material removal rate while simultaneously decreasing surface roughness [11]. WEDM is a time-intensive method for cutting hard materials, necessitating several costly consumables and ideal machining conditions to achieve precise components [12]. Aluminium hybrid MMCs with good mechanical properties can only be produced with suitable processing parameters when employing the stir casting technique [13].The augmentation of reinforcing input in matrix alloys enhances tensile strength and hardness while reducing the density of aluminium hybrid metal matrix composites (MMCs) [14]. Researchers have extensively studied B4C as reinforcement due of its exceptional hardness, high stiffness, and low density [15, 16]. The physical and mechanical properties of composite materials have been evaluated in several studies, demonstrating enhancement by the incorporation of ceramic particles inside various aluminium alloy matrices [17–20]. Hybrid reinforcing is a novel and effective technique for creating typical aluminum matrix composites. By combining two or more reinforcements, single reinforcement limitations would be overcome [21]. The Taguchi orthogonal approach is effective for accurately predicting reactions in any process by taking into account the number of components, interactions, and levels [22]. According to earlier research, aluminium with B4C and CNT reinforcements is relatively rare, and an Al/B4C/CNT hybrid composite can be used for a variety of purposes. This study aims to investigate the optimal WEDM parameters on stir casted hybrid composite (Al7075/B4C/CNT) using GRA-Taguchi Analysis.

2. MATERIALS AND METHODS

This study used Aluminium series 7075 (Al7075) as matrix material because of its superior corrosion resistance, excellent electrical conductivity, high strength, and favourable bending and formability properties [23]. The chemical composition and physical characteristics of Al7075 are presented in Table 1 and Table 2, respectively.

Table 1. Al 7075 ChemicalComposition

Element	Zn	Mg	Cu	Al
Weight%	5.7	2.4	1.4	Bal

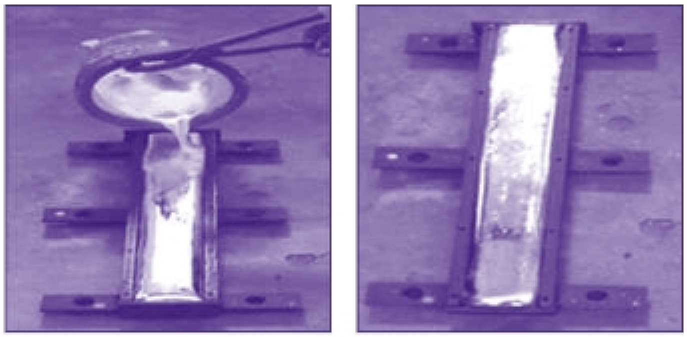
Table 2. Al 7075 PhysicalProperties

Properties	Ultimate strength	Tensile strength	Poisson' sratio	Hardness	Melting point
Values	572 Mpa	503 Mpa	0.33	87 HRB	477 °C

In order to prepare the aluminium hybrid samples, the stir casting process (Fig.1) is used and it consists stirrer with motor setup, a furnace having opening at top, a crucible made up of graphite and thermocouple (K-type). The stirrer material, stirrer speed, and stirrer design are crucial variables in the stir casting process [24]. The optimal process factors are chosen from the previous literature to produce the hybrid composite by gradually adding the preheated hybrid reinforcement particles along with 0.2 % of magnesium as a wetting agent into the liquid aluminium alloy. In this work, preheated reinforcing particles are added in the ratio of 94.3%:5%:0.7%weight proportion. During the addition of reinforcing particles stirring process is carried out to achieve the distribution of reinforcing particles uniformly into the molten metal matrix. After this process, the molten mixture is poured into the preheated die and kept idle for some time to solidify the composite (Fig.1).

Fig. 1. Stir casting setup

(a) Graphite crucible **(b) Stir casting setup**



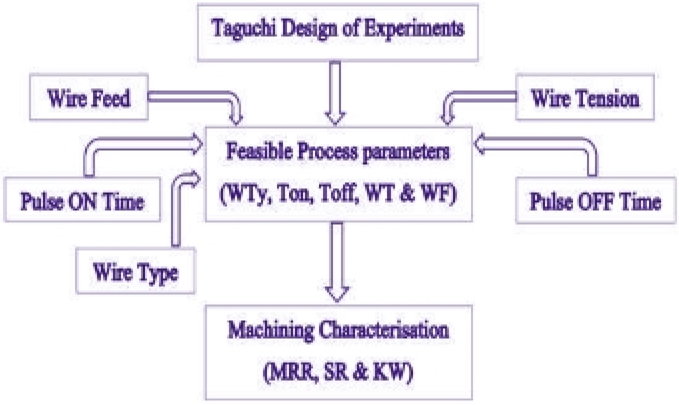
(c) Open pouring **(d) Mould with solidify material**

2.1 Design of Experiments (DoE): After fabricating the hybrid composite, the WEDM experiment was conducted on it by using Taguchi orthogonal concept. The process of designing the experiments by considering the factors and its levels encompassed under Taguchi orthogonal concept called be as Design of Experiments.In this work, five different WEDM parameters at two levels each are used as control factors (Table 3) based on the literature because choosing the right process parameters is crucial to achieving desired component [25].Fig. 2 shows the theme of work and as per the DoE concept, L16 orthogonal array is selected which is shown in Table 4.

Table 3.Machining parameters and their levels

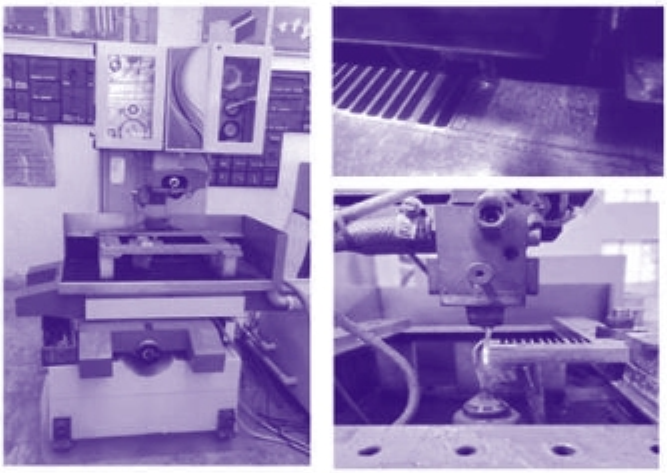
Symbol	I/pparameters	Units	Level1	Level2
A	Wiretype (WTy)	-	Brass	Zn coated Brass
B	Pulseon time (Ton)	µs	105	110
C	Pulseoff time (Toff)	µs	30	35
D	Wiretension (WT)	kgf	8	10
E	Wirefeed (WF)	mm/min.	35	40

Fig. 2. Theme of Work



2.2 Machining of hybrid composite and measurement of responses: In this work, a series of WEDM experimentsisexecuted on Al 7075/B4C/CNT hybrid MMC by using RATNAPARKHI 2530 pro smart cut WEDM machine and it is shown in Fig. 3.The most crucial step in machining the hardest materials is choosing the WEDM process parameters. This will prevent wire breakage and recast layers,and also improving surface integrity and geometrical precision. In light of the literature review, trial experiments, and machine setup limitations, the process parameter has been carefully selected [26, 27].

Fig. 3. EDMM achineand Working Positions



All the axes in this machine was servo controlled and set up run by a CNC code with an accuracy of 1 µm. An electrode wire that was utilized has 0.25 mm dia. Both the tool and the work piece may experience material erosion as a result of local melting and vaporization brought on by the high energy density during machining. Deionized water supplied continuously at the sparking area in order to remove any eroded particles from the machined area. For the machining, 26mm× 13mm × 4 mm hybrid MMC work material is considered (Fig.4 (c)). Table 4 shows the L16 experimental layout for WEDM process parameters.

Table 4. Taguchi Design of Experiments

Exp. run	Wiretype	Pulseon time	Pulseoff time	Wiretension	Wirefeed
1	1	105	30	8	35
2	1	105	30	10	40
3	1	105	35	8	40
4	1	105	35	10	35
5	1	110	30	8	40
6	1	110	30	10	35
7	1	110	35	8	35
8	1	110	35	10	40
9	2	105	30	8	40
10	2	105	30	10	35
11	2	105	35	8	35
12	2	105	35	10	40
13	2	110	30	8	35
14	2	110	30	10	40
15	2	110	35	8	40
16	2	110	35	10	35

As shown in Table 4, the WEDM experiments are conducted, and the process performances such as Material Removal Rate (mm3/min.), kerf width (mm), and Surface Roughness (µm) were measured and reported. One of the most prevalent performance measures used to evaluate the geometric precision of a finished component is kerf width, which is calculated using a microscope and evaluates the material wasted during machining (Fig. 4(a)). Similarly, to measure the quality of surface, one of the prevailing process performancesis surface roughness [28] and it can be measured by using a Talysurf instrument (Fig. 4 (b)).The MRR can be calculated as follows.

$$MRR = \frac{Vol.\ of material removed}{Cutting\ time},$$

$$Volume of material removed = k_w \times l \times t,$$

$$Whereas,$$

$$k_w - Kerf width(mm),$$

$$l - Toatl path length(mm),$$

$$t - thickness of workpiece(mm).$$

Typically, this procedure is mostly dependent on the experience of operator and it is quite difficult to exploits the machine tool to work at optimal condition. In practice, adjustment of many machining parameters may be needed. In this study, the simplest and most reliable technique, Grey Relational Analysis (GRA) is employed to mitigate such complexity and investigate the process parameters affect on kerf width ,material removal rate, and surface roughness. In this work, lower surface roughness (SR), Higher the MRR, lower kerf width (k_w) are the requirements for optimizing the WEDM process parameters.

(a) Microscope used to measure kerf width

(b) Talysurf measuring instrument with Knob position

(c) Machined specimen and its cut pieces

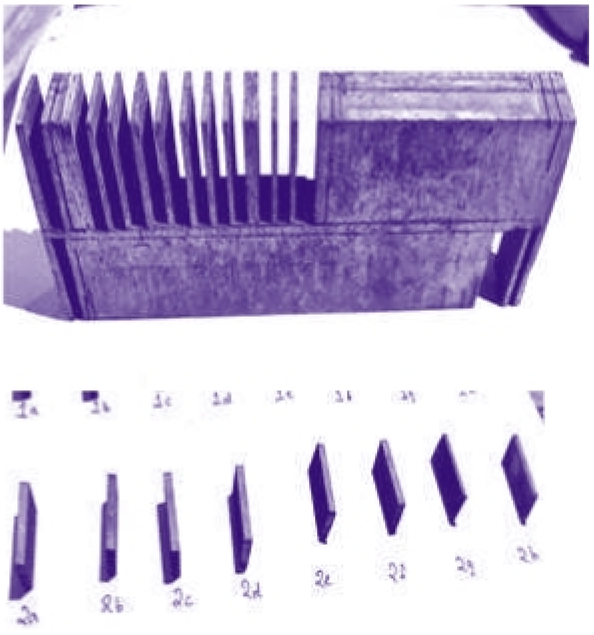


Fig. 4. Tools used to measure the responses and machined samples of workpiece

2.3 Grey Relational Analysis (GRA): Taguchi technique is an effective technique for creating high-quality systems at the lowest possible cost using orthogonal arrays (OA). The Taguchi approach works well for optimizing a single response [29], but optimizing several performance characteristics is not the same as optimizing just one. The multi-response optimization characteristics are complex, in which some factors may required higher the better and some factors may required lower the better [30] . This work uses the Taguchi method along with GRA for multi-response optimization and procedural steps as follows [31].

Step (I): Data pre-processing and Normalization

The results from experiment are linearly normalized between 0 and 1 as the initial stage in GRA technique. The normalization process is based on objectives of higher-the-better (HB), lower-the-better (LB) and nominal-the-better (NB), which are calculated by using the Equations (1),(2) and (3) respectively.

$$X_i(k) = \frac{y_i(k) - min. y_i(k)}{max.\ y_i(k) - min.\ y_i(k)} ------------- (1)$$

$$X_i(k) = \frac{max.\ y_i(k) - y_i(k)}{max.\ y_i(k) - min.\ y_i(k)} ------------- (2)$$

$$X_i(k) = \frac{\|y_i(k) - y_o\|}{max. y_i(k) - y_o} ---------------- (3)$$

Where, $X_i(k)$ is the value after normalization and $. y_i(k)$, $max. y_i(k)$ are the smallest and largest values of $y_i(k)$ for the k^{th} response.

Step (ii): Determination of Deviation Sequence and Grey Relational Coefficient

The grey relational coefficient $\xi_i(k)$ can be calculated as:

The grey relational coefficient $\xi_i(k) = \frac{\Delta_{min.} + \Psi\Delta_{max.}}{\Delta_{0i}(k) + \Psi\Delta_{max.}} -- (4)$

Deviation sequence $\Delta_{oi} = \|x_0(k) - x_i(k)\| ------ (5)$

Where, Ψ is the characteristic coefficient, ranges from $0 \leq \Psi \geq 1$ and its value in work is 0.5. $\Delta_{min.}$ $\Delta_{max.}$ are the inimum and maximum response for Δ_{0i}.

Step (iii): Calculation of Grey Relational Grade

Grey relational grade is very important parameter to evaluate the overall multiple response characteristics. It is the mean of the grey relational coefficients, it can be calculated as follows

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) ------------------------------------ (6)$$

where n is the process performance number. The experimental values $X_i(k)$ are closer to the ideal normalized values $x_0(k)$ when higher the grey relational grade.

3. RESULTS AND DISCUSSIONS

The signal-to-noise (S/N) ratio is used to describe response parameters based on the Taguchi technique. There are different types of S/N ratios to remove errors while recording experimental characteristic values. In this work, MRR is sought as higher-the-better, surface roughness and kerf width is sought as lower-the-better. Hence, the maximization quality characteristic and minimization quality characteristiccan be calculated by using following equations and represented in Table 5.

(i) Lower the better

$$S/_N\,ratio = -\log 10\left(\frac{1}{n}\right)\sum\frac{1}{y_{ij}^2} -------------------- (7)$$

(ii) Higher the better

$$S/_N\,ratio = -\log 10\left(\frac{1}{n}\right)\sum y_{ij}^2 ------------------ (8)$$

After calculating the S/N ratios of WEDM responses, the normalization of the S/N ratio is the beginning step in the GRA method. A linear normalization of the S/N ratio in the range of 0 to 1, it is calculated by using the Equations (1) and (2) and is tabulated in Table 6.

Table 5. WEDM response and its S/N ratio values

Exp. run	MRR	$S/_N$ ratio of MRR	SR	$S/_N$ ratio of SR	k_w	$S/_N$ ratio of k_w
1	19.67	25.88	2.95	-9.40	4.66	-13.36
2	19.43	25.77	2.94	-9.38	4.33	-12.72
3	20.59	26.27	2.87	-9.18	4.32	-12.70
4	21.67	26.72	3.42	-10.69	5.14	-14.21
5	40.49	32.14	3.80	-11.60	5.48	-14.77
6	37.57	31.49	3.23	-10.18	4.28	-12.62
7	36.71	31.29	3.62	-11.19	4.31	-12.68
8	35.15	30.92	3.28	-10.31	4.30	-12.66
9	27.44	28.76	3.06	-9.72	4.24	-12.54

10	35.82	31.08	3.34	-10.47	4.27	-12.60
11	30.16	29.58	3.23	-10.19	4.29	-12.64
12	31.89	30.07	3.76	-11.51	4.20	-12.46
13	28.20	29.00	3.01	-9.59	4.25	-12.56
14	32.86	30.33	2.90	-9.26	4.24	-12.54
15	27.03	28.63	2.45	-7.81	4.50	-13.06
16	29.89	29.51	2.81	-8.99	4.30	-12.66

Table 6. Data Pre-Processing Values of WEDM performance measures

Exp. run	Normalized values of S/N ratios		
	MRR	SR	Kw
1	0,017268	0,419525	0.38961
2	0	0.414248	0.112554
3	0,078493	0,361478	0.103896
4	0.149137	0.759894	0.757576
5	1	1	1
6	0.897959	0.62533	0.069264
7	0.866562	0.891821	0.095238
8	0.808477	0.659631	0.08658
9	0.469388	0.503958	0.034632
10	0.833595	0.701847	0.060606
11	0.598116	0.627968	0.077922
12	0.675039	0.976253	0
13	0.507064	0.469657	0.04329
14	0.715856	0.382586	0.034632
15	0.44898	0	0.25974
16	0.587127	0.311346	0.08658

After determining the data pre-processing values of WEDM responses, the deviation sequence values are calculated by using Equation (5) for determining the grey relation coefficient values with the help of Equation (4) and the values is tabulated in Table 7.

Table 7. Values of deviation sequence and Grey relation coefficients

Exp. run	Deviation Sequence Values			Grey Relation Coefficient Values		
	MRR	SR	Kw	MRR	SR	Kw
1	0.982732	0.580475	0.61039	0.337215	0.462759	0.450292
2	1	0.585752	0.887446	0.333333	0.46051	0.360374
3	0.921507	0.638522	0.896104	0.351739	0.439166	0.35814
4	0.850863	0.240106	0.242424	0.370134	0.675579	0.673469
5	0	0	0	1	1	1
6	0.102041	0.37467	0.930736	0.830508	0.571644	0.34947
7	0.133438	0.108179	0.904762	0.789343	0.822126	0.355932
8	0.191523	0.340369	0.91342	0.723042	0.594976	0.353752
9	0.530612	0.496042	0.965368	0.485149	0.501987	0.341211
10	0.166405	0.298153	0.939394	0.750294	0.626446	0.347368

11	0.401884	0.372032	0.922078	0.554395	0.573374	0.351598
12	0.324961	0.023747	1	0.606089	0.95466	0.333333
13	0.492936	0.530343	0.95671	0.503557	0.485275	0.343239
14	0.284144	0.617414	0.965368	0.637638	0.447462	0.341211
15	0.55102	1	0.74026	0.475728	0.333333	0.403141
16	0.412873	0.688654	0.91342	0.547721	0.420644	0.353752

The final step in GRA method is to determine the Grey Grade values for evaluating the overall multiple response characteristics. In this method, the parameter combination is closer to the optimal parameter combination when the grey relational grade is higher. Table 8 shows the grey relation grade values and their order of ranks.

Table 8. Grey Relational Grade and their order of ranks

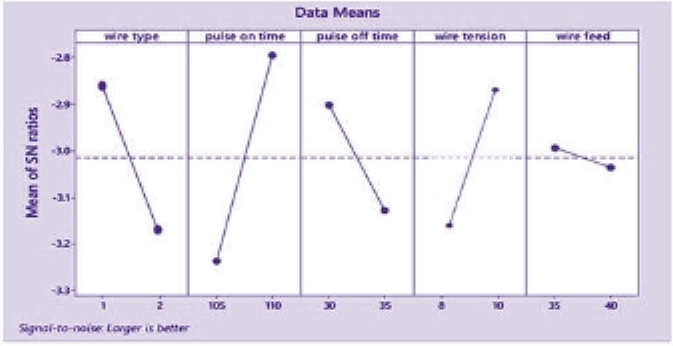
Exp. run	Process parameters					GRG	Rank
	WTy	Ton	Toff	WT	WF		
1	1	105	30	8	35	0.743	3
2	1	105	30	10	40	0.681	14
3	1	105	35	8	40	0.692	13
4	1	105	35	10	35	0.583	16
5	1	110	30	8	40	0.666	15
6	**1**	**110**	**30**	**10**	**35**	**0.758**	**1**
7	1	110	35	8	35	0.735	4
8	1	110	35	10	40	0.733	5
9	2	105	30	8	40	0.700	11
10	2	105	30	10	35	0.730	7
11	2	105	35	8	35	0.702	10
12	2	105	35	10	40	0.693	12
13	2	110	30	8	35	0.709	9
14	2	110	30	10	40	0.746	2
15	2	110	35	8	40	0.733	6
16	2	110	35	10	35	0.723	8

It is observed from the GRA analysis that the order of grey grade rankings proposed the 6th experimental process parameters set combinations would be the optimal input parameters for getting the feasible WEDM performances measures on Al7075/B4C/CNT hybrid composite. Furthermore, this grey relation grade values are analyzed by using Taguchi method to identify the most influential process parameter among all WEDM parameters on performance measures and this analysis is tabulated in Table 9.

Table 9. Response table for S/N ratios of Grey Relation Grade

Level	Wire Type	Pulse ON Time	Pulse OFF Time	Wire Tension	Wire Feed
1	-3.139	-3.236	-2.902	-2.980	-2.995
2	-2.892	-2.795	-3.129	-3.051	-3.036
Delta	0.247	0.442	0.227	0.071	0.041
Rank	**2**	**1**	**3**	**4**	**5**

Fig. 5. Main effects plot for S/N ratios of Grey Relation Grade Values



From the Table 9, it is observed that pulse ON time is the most influential process parameter on WEDM performance measures on Al7075/B4C/CNT composite followed by wire type, pulse OFF time, wire tension and wire feed. From the Fig. 5, it is observed that A1B2C1D2E1 would be the optimal process parameter combinations.

4. CONCLUSION

This study involves the preparation of Al7075/B4C/CNT composites through the stir casting method, with a wire electrical discharge machine employed to extract rectangular pieces from the Al7075/B4C/CNT workpiece, which has a thickness of 13 mm. An electrode wire with a diameter of 0.25mm, along with de-ionized water as the dielectric medium, is utilised for machining by adjusting various influential process parameters. The influence of process parameters on performance metrics such as MRR, SR, Kerf Width has been examined and the following conclusions are derived from this study:

- The Grey Relational Analysis indicates a high grey relational grade of 0.758 for the following influential parameters: Brass material wire, 110µs pulse on time, 30µs pulse off time, 10 kgf wire tension, and 35 mm/min wire feed.
- Through the optimal combinations of process parameters, the achievable performance metrics are noted as follows: Surface roughness: 3.23 µm; Kerf width: 4.28 mm; Material removal rate: 37.57 mm^3/min.
- This analysis concludes that the most influential parameter is pulse ON time, while wire feed is the least influential in the WEDM of Al7075/B4C/CNT composite.
- This study observed a reduction in material removal rate attributed to a lower mixture of de-ionized water. Additionally, wire breakage was noted due to porosity in Hybrid AMMC, and excessive tool wear was linked to the high hardness of the workpiece.

REFERENCES

1. *K Anand Babu, Jeyapaul, R., Gugulothu, B., Selvaraj, S., &Varatharajulu, M. (2023). A Retrospective Investigation on Hybrid Metal Matrix Composites: Materials, Processing Methods, and Properties of Composites. Iranian Journal of Chemistry and Chemical Engineering, 42(6), 1842-1870. https://doi.org/10.30492/IJCCE.2022.5534*
2. *Babu, K.A., Jeyapaul, R. (2022). An Investigation into the Wear Behaviour of a Hybrid Metal Matrix Composite Under Dry Sliding Conditions Using Taguchi and ANOVA Methods. J Bio TriboCorros 8, 15. https://doi.org/10.1007/s40735-021-00608-2*
3. *Kumba, A. B., & Venkata Ramaiah, P. (2019). Optimization in wire-cut edm of aluminium hybrid metal matrix composite using Taguchi coupled Deng's similarity-based approach. UPB Sci Bull Ser D Mech Eng, 81, 169-186.*
4. *Slătineanu, L.; Dodun, O.; Coteaţă, M.; Nagîţ, G.; Băncescu, I.B.; Hriţuc, A. Wire Electrical Discharge Machining—A Review. Machines 2020, 8, 69. https://doi.org/10.3390/machines8040069*
5. *Anand Babu, K., Jeyapaul, R. (2021). Process Parameters Optimization of Electrical Discharge Wire Cutting on AA6082/Fly Ash/Al2O3 Hybrid MMC Using Taguchi Method Coupled with Hybrid Approach. J. Inst. Eng. India Ser. C 102, 183–196. https://doi.org/10.1007/s40032-020-00640-0*
6. *Kumar, A., Grover, N., Manna, A. et al. (2022). Multi-Objective Optimization of WEDM of Aluminum Hybrid Composites Using AHP and Genetic Algorithm. Arab J Sci Eng 47, 8031–8043. https://doi.org/10.1007/s13369-021-05865-4*
7. *Andrea Gommeringer, Ulrich Schmitt-Radloff, Philipp Ninz, Frank Kern, Fritz Klocke, Sebastian Schneider, Maximilian Holsten, Andreas Klink.(2018). ED-machinable Ceramics with Oxide Matrix: Influence of Particle Size and Volume Fraction of the Electrical Conductive Phase on the Mechanical and Electrical Properties and the EDM Characteristics, Procedia CIRP, Volume 68, pp. 22-27.https://doi.org/10.1016/j.procir.2017.12.016.*
8. *T. Bergs, U. Tombul, T. Herrig, M. Olivier, A. Klink, F. Klocke. (2018). Analysis of Characteristic Process Parameters to Identify Unstable Process Conditions during Wire EDM, Procedia Manufacturing, Volume 18, pp. 138-145, https://doi.org/10.1016/j.promfg.2018.11.018.*
9. *A. Conde, J.A. Sanchez, S. Plaza, M. Ostolaza, I. de la Puerta, Z. Li,(2018). Experimental Measurement of Wire-lag Effect and Its Relation with Signal Classification on Wire EDM, Procedia CIRP, Volume 68, pp. 132-137,https://doi.org/10.1016/j.procir.2017.12.035.*
10. *Joshi, K., Bhandarkar, U., Samajdar, I., and Joshi, S. S. (2018). Microstructural Characterization of Thermal Damage on Silicon Wafers Sliced Using Wire-Electrical Discharge Machining. ASME. J. Manuf. Sci. Eng. 140(9): 091001. https://doi.org/10.1115/1.4039647*
11. *Ulrich Schmitt-Radloff, Andrea Gommeringer, Patrick Assmuth, Frank Kern, Fritz Klocke, Maximilian Holsten, Sebastian Schneider. (2018). Effects of Composition on Mechanical and ED-machining Characteristics of Zirconia toughened Alumina – Titanium Carbide (ZTA-TiC) Composite Ceramics. Procedia CIRP, Volume 68, pp. 17-21, https://doi.org/10.1016/j.procir.2017.12.015.*
12. *G. Wälder, D. Fulliquet, N. Foukia, F. Jaquenod, M. Lauria, R. Rozsnyo, B. Lavazais, R. Perez. (2018). Smart Wire EDM Machine. Procedia CIRP, Volume 68, pp. 109-114. https://doi.org/10.1016/j.procir.2017.12.032.*
13. *Anand Babu. K and Venkataramaiah. P. (2018). Influence of Flyash/SiCp/Al2O3 on mechanical characteristics of Al-Mg based hybrid metal matrix composites synthesised by stir casting process. ARPN Journal of Engineering and Applied Sciences, 13 (6), 2080-2089. http://www.arpnjournals.org/jeas/research_papers/rp_2018/jeas_0318_6898.pdf*
14. *Anand Babu K. P. Venkataramaiah. (2018). Selection of optimum aluminium hybrid metal matrix composite using Fuzzy AHP-VIKOR method. International Journal of Research and Analytical Reviews, Volume 5, Issue 4, pp. 246-254. http://www.ijrar.org/IJRAR1944027.pdf*
15. *Kennedy, A.R. The microstructure and mechanical properties of Al-Si-B4C metal matrix composites. Journal of Materials Science 37, 317–323 (2002). https://doi.org/10.1023/A:1013600328599*
16. *Guttikonda Manohar, K.M. Pandey, S.R. Maity. (2021).*

Effect of sintering mechanisms on mechanical properties of AA7075/B4C composite fabricated by powder metallurgy techniques. Ceramics International, Volume 47, Issue 11, pp. 15147-15154, https://doi.org/10.1016/j.ceramint.2021.02.073.

17. *Akhileshwar Nirala, S. Soren, Navneet Kumar, D.R. Kaushal. (2020). A comprehensive review on mechanical properties of Al-B4C stir casting fabricated composite. Materials Today: Proceedings, Volume 21, Part 3, pp. 1432-1435. https://doi.org/10.1016/j.matpr.2019.09.172.*

18. *Peng-Xiang Zhang, Hong Yan, Min Zeng. (2023). Decorating nano Ni on the surface of CNTs and their wettability behaviors analysis with aluminum alloy. Materials Letters, Volume 335, 133795,https://doi.org/10.1016/j.matlet.2022.133795.*

19. *F. Ibrahim, M., R. Ammar, H., M. Samuel, A., S. Soliman, M., Songmene, V., & H. Samuel, F. (2021). Why Al-B4C Metal Matrix Composites? A Review. IntechOpen. doi: 10.5772/intechopen.95772*

20. *Sharma, N. K., Misra, R. K., & Sharma, S. (2017). Experimental characterization and numerical modeling of thermo-mechanical properties of Al-B4C composites. Ceramics International, 43(1), 513–522. http://dx.doi.org/10.1016/j.ceramint.2016.09.187.*

21. *Nirala, A., Soren, S., Kumar, N. et al. (2023). Micro-mechanical and tribological behavior of Al/SiC/B4C/CNT hybrid nanocomposite. Sci Rep 13, 13147. https://doi.org/10.1038/s41598-023-39713-2.*

22. *J Viswanath, CH Lakshmi Tulasi, K Anand Babu. (2018). Optimizing the process parameters of AWJM using Taguchi Method And ANOVA on Inconel 625. ARPN Journal of Engineering and Applied Sciences, Volume. 13, Issue. 5, pp. 1578-1586.http://www.arpnjournals.org/jeas/research_papers/rp_2018/jeas_0318_6839.pdf*

23. *K. Anand Babu, P. Venkataramaiah, SaideepthiYerrathota. (2018). Material Selection for Preparation of Aluminium Hybrid Mmcs, Materials Today: Proceedings, Volume 5, Issue 5, Part 2, pp.12209-12222. https://doi.org/10.1016/j.matpr.2018.02.198.*

24. *K. Anand Babu, P. Venkataramaiah, K. Dharma Reddy. (2018). Mechanical characterization of aluminium hybrid metal matrix composites synthesized by using stir casting process. Materials Today: Proceedings, Volume 5, Issue 14, Part 2, pp. 28155-28163. https://doi.org/10.1016/j.matpr.2018.10.058.*

25. *M. Varatharajulu&MuthukannanDuraiselvam& G. Jayaprakash & N. Baskar & S. Vijayaraj & K. Anand Babu. (2023). A Retrospective Analysis On Drilling Operation And Its Parameters: A Critical Review. Surface Review and Letters (SRL), Vol. 30 (10), pp. 1-33, https://doi.org/10.1142/S0218625X23300101*

26. *Anand Babu, K. and Venkataramaiah, P. (2015). Multi-response Optimization in Wire Electrical Discharge Machining (WEDM) of Al6061/SiCp Composite Using Hybrid Approach. Journal for Manufacturing Science and Production, vol. 15, no. 4, pp. 327-338. https://doi.org/10.1515/jmsp-2015-0010*

27. *Amitesh Goswami, Jatinder Kumar. (2014). Investigation of surface integrity, material removal rate and wire wear ratio for WEDM of Nimonic 80A alloy using GRA and Taguchi method. Engineering Science and Technology, an International Journal, Volume 17, Issue 4, pp. 173-184. https://doi.org/10.1016/j.jestch.2014.05.002.*

28. *Anand Babu, K., Vijaya Kumar, G., & Venkataramaiah, P. (2015). Prediction of Surface Roughness in Drilling of Al 7075/10% - SiCp Composite under MQL Condition using Fuzzy Logic. Indian Journal of Science and Technology, 8(12). https://doi.org/10.17485/ijst/2015/v8i12/75053*

29. *Anand Babu K and Venkataramaiah P. (2018). Optimization of material factors in the casting of aluminium hybrid metal matrix composites using Taguchi coupled Entropy-VIKOR approach. International Journal of Applied Engineering Research, 13 (22), pp. 16111-16116. https://www.ripublication.com/ijaer18/ijaerv13n22_93.pdf*

30. *Das, M. K., Kumar, K., Barman, T. K., & Sahoo, P. (2015). Optimization of WEDM Process Parameters for MRR and Surface Roughness using Taguchi-Based Grey Relational Analysis. International Journal of Materials Forming and Machining Processes (IJMFMP), 2(1), 1-25. http://doi.org/10.4018/ijmfmp.2015010101.*

31. *Rajender Kumar, Puneet Katyal, Shiwani Mandhania. (2022). Grey relational analysis based multiresponse optimization for WEDM of ZE41A magnesium alloy. International Journal of Lightweight Materials and Manufacture, Volume 5, Issue 4,2022, pp. 543-554,https://doi.org/10.1016/j.ijlmm.2022.06.003.*

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