OPTIMIZATION OF ABRASIVE WATERJET MACHINING PARAMETERS FOR AA2024-B4C-TIC HYBRID METAL MATRIX COMPOSITE USING MULTI-OBJECTIVE GREY RELATIONAL ANALYSIS

Ganesan P[1], Nandagopal K[2], Vetrivel Kumar K[3], Arul R[4]

[1] Associate Professor, Department of Mechanical Engineering, Dhanalakshmi Srinivasan College of Engineering, Coimbatore.

[2] Professor, Department of Food Technology, Dhanalakshmi Srinivasan College of Engineering, Coimbatore.

[3] Professor, Department of Mechanical Engineering, Dhanalakshmi Srinivasan College of Engineering, Coimbatore.

[4] Assistant Professor, Department of Mechanical Engineering, Dhanalakshmi Srinivasan College of Engineering, Coimbatore.

Corresponding Author:

Ganesan P, Department of Mechanical Engineering, Dhanalakshmi Srinivasan College of Engineering, Coimbatore, Tamilnadu, India.

https://orcid.org/0000-0002-1039-1557

ABSTRACT

This study aims to fabricate a hybrid aluminum 2024 (AA2024) metal matrix composite reinforced with titanium carbide (TiC) and boron carbide (B4C) particles using the stir casting method. The machining parameters of abrasive waterjet (AWJ) machining, including water jet pressure, jet traverse speed, and standoff distance, were optimized using grey relational analysis (GRA) to improve surface roughness, kerf angle, and material removal rate (MRR) of the hybrid composite. A Taguchi L27 orthogonal array was used to design the experiments. The experimental results were normalized, and grey relational coefficients were calculated. Finally, the grey relational grade was determined, and the optimal combination of AWJ parameters was identified. The results showed that the optimal AWJ parameters were water jet pressure of 260 MPa, traverse speed of 20 mm/min, and standoff distance of 1 mm.

Keywords: Abrasive waterjet machining, AA2024 metal matrix composite, Grey relational analysis, Optimization

1. INTRODUCTION

Metal matrix composites usually consist of a low-density metal, such as aluminum or magnesium, reinforced with particulate or fibers of a ceramic material, such as Boron carbide, silicon carbide or graphite, aluminum oxide etc. Aluminum (Al) alloys have been widely used in modern industry due to their light weight and inexpensive for a variety of engineering applications. Some of the typical applications are bearings, automobile pistons, cylinder liners, piston rings, connecting rods, sliding electrical contacts, turbocharger impellers, space structures, armor materials in body protection, helicopters, military vehicles, electronic substrates, bicycles, golf clubs, and a variety of other applications. Aluminum alloys are extensively used as the main engineering material in various industries such as aircraft, aerospace, and automotive industries where weight is probably the most important factor. Hence the most popular types of MMCs are aluminum alloys reinforcing with ceramic particles. Aluminum alloy ceramic particulate composites may find special applications as they exhibit a wide range of physical and mechanical properties such as higher strength. The wettability of liquid aluminium reinforced with ceramics particles such as SiC , B_4C AlN, TiB, TiN and TiC through sessile drop techniques. The surface tension of liquid aluminum varies linearly with temperature and these surface values are correlated with a melting point of the ceramics (1). The wetting tests were conducted by pressure infiltration of liquid Al-alloys into the powder specimens and corresponding threshold pressure for infiltration was used to measure the wettability(2). Al2024 alloy is easy available commercial and it's widely used for structural purpose in manufacturing sectors. it is clearly observed that lot of research has been carried out on addition of alumina, silicon carbide, boron carbide and fly ash to improve the hardness, tensile, yield strength, wear resistance, machinability, good abrasion resistance, high creep resistance(3).

The effect of B4C and SiC reinforcement content on mechanical and corrosion behavior of AA2024-B4C/SiC hybrid nano composite was examined. The corrosion test results show that corrosion current density of AA20240-4 wt% B4C/SiC hybrid nanocomposite sample corrosion current rate of AA2024 alloy was almost 14 times higher than AA2024-4 wt% of B4C/SiC hybrid nanocomposites. Mechanical tests showed that the hardness value of hybrid nanocomposites increases as increased reinforcement content and AA2024-5 wt% B4C/SiC hybrid nanocomposite has a maximum hardness(4). The production of light weight, low cost and high performance aluminium based composites has undergone significant evolution, Boron Carbide (B_4C) were introduced into Al-2024 alloy produced by stir casting method. The B4C particles is coated with TiB2 via sol-gel process and reinforced in Al-2024 alloy by stir casting process to produce composite. Stir casting technique is gaining importance due to its easy setup, low cost, uniform dispersion of reinforcement compare to other techniques. Hardness, porosity and tensile behavior of alloy and composites were evaluated and found that both hardness and tensile strength increases with increases in percentage of reinforcement. On the other hand a slight increasing amount of porosity is observed with increasing the B4C particles of the composites(5)

The wetting behaviors of TiC substrates by commercial aluminum alloys such as AA1010, AA2024, AA6061, AA7075 and its relation to phase formation at the metal-ceramic interface were studied. The wettability of TiC by pure AA1010 was better than the other aluminium alloys and AA7075/TiC and AA6061/TiC composites exhibited poor wettability (6). Aluminum MMC is reinforcing with the different volume fraction of SiC, Al2O3 and B4C were fabricated using stir casting route. While comparing all reinforcing matrix B4C reinforced Al composite exhibit a better interfacial bonding (7). AA2024-B4C composites produced by stir casting method considering the effect of particle content and particle size on properties. The results indicated that the increasing particle volume fraction decreases the specific wear rate and the larger particle is very effective in reducing the wear compared to smaller ones. Increasing the volume fraction of B4C in AA2024 alloy increases hardness, porosity and also decreases the yield rate and density of AMCs(8).

Non- traditional machining processes are needed to machine the materials difficult to cut. The machining of ceramic reinforced composites is difficult and nonviable using conventional machining because the addition of ceramic particles increases the hardness of composite and also the presence of ceramic particles reduces the tool life. In these cases, non-traditional machining processes which utilize various energy forms as tools instead of traditional physical tools have greater advantage (9). The effect of abrasive water jet process parameters such as water jet pressure, water jet diameter, abrasive material, particle size, abrasive flow rate, traverse rate and number of passes on the cutting of ductile material were investigated both theoretical and experimental, finally a model developed to optimize the machining parameters of high-quality ductile materials(10). The effect of cutting parameters on machining of graphite/epoxy laminate was investigated. The surface roughness varying as a function of depth of cut and the mathematical model were developed for surface roughness and kerf taper angle(11). The effect of machining parameters for AWJM of hybrid AMMC using the Taguchi technique was carried out, and the optimal parameters for surface roughness, kerf angle and MRR were determined. The percentage of contribution for each input such as water jet pressure, traverse rate, and standoff has been found by ANOVA(12).

The performance of the AWJM process and is influenced by (i) operational parameters such as jet pressure, standoff distance, nozzle traverse rate, the angle of cutting (ii) abrasive parameters such as abrasive type, size, shape, abrasive flow rate (iii) hydraulic parameters such as pump pressure, water flow rate and (iv) nozzle parameters such as nozzle diameter(13). AWJM process parameters such as hydraulic pressure, abrasive mass flow rate, standoff distance and traverse rate are optimized by using grey relational analysis(14).The effects of process parameters on the geometrical characteristics and the topography were investigated in the milling of SS304 material using Abrasive Water Jet machining technique. The optimum control of the input variables includes traverse speed, abrasive flow rate; abrasive size and standoff distance each at three levels is considered for experimentation. Achieving the quality of the channel was determined by using grey relational analysis was employed to minimize and maximize the response parameters as per the required parameters such as surface roughness, taper, impact force, vibration are minimized. The grey coefficients and grades of the experimental data, a traverse speed of 3000 mm/min, a diameter of 0.125 mm of the abrasive particle at 0.49 kg/min abrasive flow rate and a standoff distance of 4mm gives optimum machining conditions for the mandatory output(15).The effect of individual process parameters are water Jet Pressure, Standoff Distance and Traverse Speed, these parameters holds higher degree of influence over output responses. The influence analysis shows the notable increment in the metal removal process with the increased SOD, TS and water pressure. Moreover, the optimal combination of process parameters and their contribution are determined through Grey Relational Analysis (16).

Grey relational analysis applied to maximize MRR and minimize surface roughness whereas control variable is taken to be transverse speed, standoff distance, abrasive flow rate, and water pressure. The optimum parameter setting and the most significant parameter are found with the assistance of S/N ratio(17). Taguchi L25 orthogonal array is used to optimize the process parameters to attain the optimal joint strength and quality of joint in the welded samples and also it is used to identify the most influential process parameter in this welding process (18). Aluminum based hybrid composite with Silicon Carbide and Boron Carbide particles are prepared through the stir casting process and subjected to Abrasive Water Jet Machining. AWJM parameters such as the pressure, standoff distance and traverse speed are considered as the input process parameters and the output response such as kerf angle, MRR and surface roughness are measured and optimized using Grey Relational Analysis. ANOVA and the F-test are accomplished to understand the contribution and the significant level of importance of each input parameter over the output response. The experimental result shows that, it contributed more to affecting the performance of traverse speed and the standoff distance, with a contribution of 62.14% and 18.43% respectively (19).To explore the machining performance, experiments were conducted on the internal surface of tubes made of AA2024 in the various number of AFM cycles for studying and observing its behavior on the surface roughness and material removal characteristics with an empirical approach(20).

To identify the optimum level of parameters, conducted confirmation experiments have been conducted and calculated the percentage improvements in the specified objectives for different applications, but this study deals with the optimization of machining parameters AA2024-B_4C-TIC hybrid composite. Grey relational theory can provide an efficient solution to the uncertainty in multi-input and discrete data problems. It had been effectively applied to optimize the multi-response processes through the set of process parameters. It is an effective method to analyze relational degree between discrete sequences. The advantage of the above method is that many factors can be analyzed using fewer data. GRA can be used to find out the relationship ofthe reference sequence with other sequences or the relational degree existing between the variations of any two different sequences.

2. EXPERIMENTAL SETUP

AA2024 is an aluminium alloy with copper as the primary alloying element. As the alloy has high strength, fatigue resistance, good machinability and surface finish capabilities it is widely used in aircraft structures, fittings, hydraulic valve bodies, gears, pistons, rectifier parts, worm gears, fasteningdevices, veterinary and orthopedic equipment, shafts missile parts and munitions. AA2024 is an aluminum alloy having a chemical composition as given in Table 1.

Table 1 Chemical composition of AA2024

Cu	Mg	Mn	Fe	Si	Zn	Cr	Ti	Al
4.85	1.31	0.667	0.254	0.11	0.079	0.033	0.008	Bal

Boron Carbide is one of the hardest and low-density materials by- products in the production of metal borides and gray in color, abundantly available and having hardness values of 2750 HV, which is greater than to that of SiC. Titanium carbide is a tremendously hard ceramic material and it has the appearance of black powder. It has a hardness value of 2470 HV, which is equal to that of SiC and used extensively for cutting tools because of its combination of wear resistance and high hardness, heat shield coating for atmospheric reentryof spacecraft.

The stir casting setup of composite preparation is as shown in Figure 1. The selected particles are B_4C having an average particle size of 150µm and density of 2.5278g/cm^3; TiC having an average particle size of 150µm and a density of 4.52g/cm^3. The hybrid composites were produced by two-step stir casting process. First AA2024 alloy was melted in a resistance furnace to a temperature of 640°C and then cooled to 490°C. The alloy was in slurry state and the slurry was stirred by a stirrer to create a vortex. While stirring the slurry, the two preheated ceramic particles were added in equal volume percentage to it. Now the slurry with ceramic particles was again heated to 650°C and stirring was carried out for 10 minutes with the average stirring rate of 300 rev/min. The molten mixture was poured into the dies and then cooled. The procedure was followed to prepare specimens of composites with particles of 5% (2.5%B_4C+2.5% TiC), to the size of 100mm x 100mm x 15mm.

Figure1 Stir casting setup

The experiments were conducted on water Jet cutter (Model DWJ1313-FB) which was equipped with SL-V50 pressure pump with the designed pressure of 300 MPa, traverse speed of 0-60mm/min. The experiments were conducted according to the below orthogonal array with their factors and their levels as mentioned in Table 2.

Table 2 OA with control factors

Experimental no.	Water jet pressureMPa	Transverse speed mm/min	Standoff distance mm
1	220	20	1
2	220	20	2

3	220	20	3
4	220	30	1
5	220	30	2
6	220	30	3
7	220	40	1
8	220	40	2
9	220	40	3
10	240	20	1
11	240	20	2
12	240	20	3
13	240	30	1
14	240	30	2
15	240	30	3
16	240	40	1
17	240	40	2
18	240	40	3
19	260	20	1
20	260	20	2
21	260	20	3
22	260	30	1
23	260	30	2
24	260	30	3
25	260	40	1
26	260	40	2
27	260	40	3

Experimental set up of an abrasive water jet cutting process is shown in Figure 4.1. The garnet with 80 mesh size was used as abrasive particles. The water jet impinged vertically downward direction on the work piece. The orifice assembly has a 0.7mm diameter size carbide nozzle. The mass flow rate of abrasive particles was maintained at 3.1 lit/min for entire machining.

Figure 2 Abrasive water jet cutters

The most influencing parameters such as jet pressure, traverse speed and standoff distance were selected in machining of hybrid composites. The average surface roughness was measured on the water jet machined surfaceusing a Mitutoyo Surface tester (Model SJ401). The kerf width at the top and bottom are measured with the help of an optical microscope and the kerf angle iscalculated using the equation 4.1. The experiments were conducted based on an L_{27} orthogonal array. Each trial was repeated three times and the average of three values was recorded. The measurement of the average surface roughness ofworkpiece was measured using Mitutoyo Surf test- SJ401 measurement device. The measurements were taken at a distance of the 10mm top of the cut surface. The MRR is found using the Equation 4.2.

$$\text{Kerf Angle} = \tan^{-1}\frac{w_1 - w_2}{2t} \qquad (1)$$

$$\text{MRR} = \left(\frac{w_1 + w_2}{2}\right) \times \text{thickness of work piece } (t) \times \text{cutting velocity}(v)$$

3. MULTI-OBJECTIVE GREY RELATIONAL METHOD

In Grey relational analysis the first step is to perform the Grey relational generation in which the results of the experiments are normalized in the range between 0 and 1 due to different measurement units. Data preprocessing converts the original sequences to a set of comparable sequences. Normalizing the experimental data for each quality characteristic is done according to the type of performance response(20). Thus, the normalized data processing for surface roughness and kerf angle corresponding to smaller the-better criterion can be expressed as Equation 3,

$$x_i\,(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{3}$$

The normalized data processing for MRR corresponding to larger-the-better criterion can be expressed as Equation 4,

$$x_i\,(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{4}$$

where, i = 1, 2, 3, ..., m, m is the number of experimental runs in Taguchi orthogonal array, in the present work L9 orthogonal array is selected then m = 9. k = 1, 2, ... n, n is the number of quality characteristics or process responses, in the present study surface roughness, kerf angle and materialremoval rate are selected, then n = 3.

Normalized value OF SR, KA and MRR

Min y_i (k) is the smallest value of y_i (k) for the k^{th} response. Max y_i (k) is the largest value of y_i (k) for the k^{th} response. x_i (k) is the value of Greyrelational generation.

4. RESULTS AND DISCUSSION

The experimental results and the corresponding normalized values are presented in Table 3. The grey relational coefficients and the overall grey relational grade for each experiment are shown in Table 4.

Table 3 Experimental and normalised values

EXP No.	Experimental values			Normalized values		
	SR	KA	MRR	SR	KA	MRR
1	3.524	0.4432	206.8	0.7248	0.5800	0.0000
2	3.635	0.4602	207.9	0.5097	0.4100	0.0521
3	3.693	0.4718	209.2	0.3973	0.2940	0.1137
4	3.687	0.4586	208.1	0.4089	0.4260	0.0616
5	3.764	0.4778	209.3	0.2597	0.2340	0.1185
6	3.706	0.4854	210.8	0.3721	0.1580	0.1896
7	3.712	0.4700	209.6	0.3605	0.3120	0.1327
8	3.802	0.4902	210.6	0.1860	0.1100	0.1801
9	3.887	0.5012	213.1	0.0213	0.0000	0.2986

10	3.408	0.4265	211.7	0.9496	0.7470	0.2322
11	3.502	0.4378	213.2	0.7674	0.6340	0.3033
12	3.611	0.4419	214.8	0.5562	0.5930	0.3791
13	3.526	0.4368	213.1	0.7209	0.6440	0.2986
14	3.636	0.4516	214.9	0.5078	0.4960	0.3839
15	3.715	0.4586	216.3	0.3547	0.4260	0.4502
16	3.646	0.4521	214.7	0.4884	0.4910	0.3744
17	3.721	0.4686	216.5	0.3430	0.3260	0.4597
18	3.898	0.4814	218.5	0.0000	0.1980	0.5545
19	3.382	0.4012	217.6	1.0000	1.0000	0.5118
20	3.442	0.4234	218.3	0.8837	0.7780	0.5450
21	3.612	0.4476	220.1	0.5543	0.5360	0.6303

Table 3 continued

22	3.415	0.4265	218.5	0.9360	0.7470	0.5545
23	3.519	0.4321	220.9	0.7345	0.6910	0.6682
24	3.714	0.4562	224.2	0.3566	0.4500	0.8246
25	3.588	0.4398	220.2	0.6008	0.6140	0.6351
26	3.695	0.4517	222.4	0.3934	0.4950	0.7393
27	3.808	0.4709	227.9	0.1744	0.3030	1.0000

The normalized values of surface roughness and material removal rate calculated by Equations 3 and 4. The experimental values and normalized values of SR, TWR, and MRR are given in Table 3.

Grey Relational Co-Efficient and Grey Relational Grade Analysisof SR, KA, and MRR

The second step is to calculate the Grey relational coefficient based on the normalized experimental data to represent the correlation between the desired and actual experimental data. The overall Grey relational grade is then computed by averaging the Grey relational coefficient corresponding to each performance characteristic. As a result, the optimal combination of process parameters is evaluated considering the highest Grey relational grade. Based on the normalized experimental data the Grey relation coefficient can be calculated using the Equations 5 and 6.

$$\xi_i - \frac{\Delta_{min} - \zeta\Delta_{max}}{\Lambda_{oi}(k) + \zeta\Lambda_{max}} \tag{5}$$

$$\Delta_{oi}(k) = (x_o(k) - x_i(k) \tag{6}$$

Here Δ_{max} and Δ_{min} are 1and 0, where $\Delta_{oi}(k) = (x_o(k) - x_i(k)$ is a difference of the absolute value between $x_o(k)$ and $x_i(k)$, $x_o(k)$ is the reference sequence of the k^{th} quality characteristics.

Δ_{min} and Δ_{max} are respectively the minimum and maximum values of the absolute differences (Δ_{oi}) of all comparing sequences. ζ is a distinguishing coefficient, $0 \leq \zeta \leq 1$, the purpose of which is to weaken the effect of Δ_{max} when it gets too large and thus increases the difference significance of the relational coefficient. In the present case, $\zeta = 0.5$ is used due to the moderate distinguishing effects and good stability of outcomes (20).

After the optimal level of AWJM parameters has been identified, a verification test needs to be carried out in order to check the accuracy of the analysis. The estimated Grey relational grade is used to predict the improvement of the performance characteristic by using optimum combination of turning parameters. The estimated Grey relational grade can be calculated by the following equation. Finally, the average value of the grey-relational coefficient for n comparison sequences is obtained as given Equation 7.

$$\gamma(X_i) = (^1/_n)\gamma(X_o(p), X_i(p)) \qquad (7)$$

Where n = number of responses

$$\gamma(X_i) = (^1/_n)\gamma(X_i(SR) + X_i(KA) + X_i(MRR) \text{ , n=3} \qquad (8)$$

Table 4 Grey relational analyses for Aluminium hybrid MMC

Grey Relational Co-efficient			Grey Relational Grade	RANK
SR	KA	MRR		
0.6450	0.5435	0.3333	0.5073	14
0.5049	0.4587	0.3453	0.4363	19
0.4534	0.4146	0.3607	0.4096	22
0.4583	0.4655	0.3476	0.4238	20
0.4031	0.3949	0.3619	0.3867	25
0.4433	0.3726	0.3816	0.3991	24
0.4388	0.4209	0.3657	0.4084	23
0.3805	0.3597	0.3788	0.3730	26

0.3381	0.3333	0.4162	0.3625	27
0.9085	0.6640	0.3944	0.6556	4
0.6825	0.5774	0.4178	0.5592	8
0.5298	0.5513	0.4461	0.5090	13
0.6418	0.5841	0.4162	0.5474	10
0.5039	0.4980	0.4480	0.4833	15
0.4365	0.4655	0.4763	0.4595	17
0.4943	0.4955	0.4442	0.4780	16
0.4322	0.4259	0.4806	0.4462	18
0.3333	0.3840	0.5288	0.4154	21
1.0000	1.0000	0.5060	0.8353	1
0.8113	0.6925	0.5236	0.6758	3
0.5287	0.5187	0.5749	0.5408	11
0.8866	0.6640	0.5288	0.6931	2
0.6532	0.6180	0.6011	0.6241	5
0.4373	0.4762	0.7404	0.5513	9
0.5560	0.5643	0.5781	0.5662	7
0.4518	0.4975	0.6573	0.5356	12
0.3772	0.4177	1.0000	0.5983	6

Finally, the grades were considered for optimizing the multi-response AWJM parameter. The results are given in the Table 4. The higher grey relational grade implied the better product quality. Hence on the basis of grey relational grade, the factor effect is estimated as the optimal value water jet pressure 260 Mpa, traverse speed 20 mm/min and standoff distance as 1mm. Grey relational analysis has been used for optimizing the AWJM performance parameter of Aluminum hybrid MMC. The result indicates that higher grey relational grade implied the better product quality. Finally, the grades were considered for optimizing the multi-response AWJM parameter. The higher grey relationalgrade implied the better product quality. Hence on the basis of grey relational grade, the factor effect is estimated and the optimal value water jet pressure 260 Mpa, traverse speed 20 mm/min and standoff distance as 1mm.

5. CONCLUSION

In this study, an AA2024-B4C-TiC hybrid metal matrix composite was fabricated using the stir casting method. The abrasive waterjet machining parameters, including water jet pressure, traverse speed, and standoff distance, were optimized using the multi-objective grey relational analysis approach to improve the surface roughness, kerf angle, and material removal rate of the hybrid composite.

The key findings of this study are:

1. The optimal AWJ machining parameters were identified as water jet pressure of 260 MPa, traverse speed of 20 mm/min, and standoff distance of 1 mm, which resulted in the highest grey relational grade.
2. The grey relational analysis effectively combined the multiple response characteristics and identified the optimal parameter settings to achieve the best overall machining performance.
3. The proposed methodology can be applied to optimize the AWJ machining of other metal matrix composites and non-traditional machining processes.

REFERENCES

1. Rhee, SK 1970, “Wetting of ceramics by liquid aluminum”, Journal of the American Ceramic Society, vol. 53, no. 7, pp. 386-89.

2. Oh, SY, Cornie, JA & Russell, KC 1989, “Wetting of ceramic particulates with liquid aluminum alloys: Part II, Study of wettability”, Metallurgical Transactions A, vol. 20, no. 3, pp. 533-541.

3. Kumaraswamy, H. S., V. Bharat, and T. Krishna Rao. "Influence of Mechanical &tribological Behaviour of Al 2024 MMC Fabricated by Stir Casting Technique-A Review." Materials Today: Proceedings 5.5 (2018): 11962-11970.

4. Karabacak, Abdullah Hasan, et al. "Corrosion and Mechanical Properties of Novel AA2024 Matrix Hybrid Nanocomposites Reinforced with B 4 C and SiC Particles." Silicon (2022): 1-13.

5. Lokesh, G. N., et al. "Effect of hardness and tensile behaviour of Al-2024/TiB2 coated B4C particles synthesized by stir casting route." Manufacturing Technology Today 20.1-2 (2021): 41-47.

6. Aguilar, EA, Leon, CA, Contreras, A, López, VH, Drew, RA & Bedolla, E 2002, "Wettability and phase formation in TiC/Al-alloys assemblies", Composites Part A: Applied Science and Manufacturing, vol. 33, no. 10, pp. 1425-1428.

7. Shorowordi, KM, Laoui, T, Haseeb, AS, Celis, JP & Froyen, L 2003 "Microstructure and interface characteristics of B_4C, SiC and Al_2O_3 reinforced Al matrix composites: A comparative study", Proceedings ICME, 4th International Conference on Mechanical Engineering, pp. 738- 743.

8. Canakci, A & Arslan, F 2012, "Abrasive wear behaviour of B_4C particle reinforced Al2024 MMCs", The International Journal of Advanced Manufacturing Technology, vol. 63, no. 5, pp. 785-795.

9. Ganesan, P., Sivakandhan, C., Marichamy, S., Madan, D., Stalin, B., & Dhinakaran, V. (2020), "Taguchi optimization of AWJM process parameters on aluminium hybrid composite. In Advances in Industrial Automation and Smart Manufacturing: Select Proceedings of ICAIASM 2019 (pp. 347-355). Singapore: Springer Singapore.

10. Youssef, HA & El-Hofy, H 2008, Machining technology: Machine tools and operations. CRC Press.

11. Hashish, M & Du Plessis, MP 1979, "Prediction equations relating high- velocity jet cutting performance to standoff distance and multi passes", Journal of Engineering Ind., vol. 101, no. 3, pp. 311-318.

12. Ramulu, M & Arola D 1994, "The influence of abrasive waterjet cutting conditions on the surface quality of graphite/epoxy laminates", International Journal of Machine Tools and Manufacture, vol. 34, no. 3,pp. 295-313.

13. Ganesan, P., Babu, K. V., Marichamy, S., & Madan, D. (2019). "AWJM parametric investigation on hybrid composite produced through two step stir casting process", Materials Research Express, 6(10), 106567.

14. Kechagias, J, Petropoulos, G & Vaxevanidis, N 2012, " Application of Taguchi design for quality characterization of abrasive waterjet machining of TRIP sheet steels", The International Journal of Advanced Manufacturing Technology, vol. 62, no. 5, pp. 635-643.

15. Azmir, MA & Ahsan, AK 2008, "Investigation on glass/epoxy composite surfaces machined by abrasive waterjet machining", Journal of materials processing technology, vol. 198, no. 1, pp. 122-128.

16. Gupta, TV, Ramkumar, J, Tandon, P & Vyas, NS 2014, "Application of grey relational analysis for geometrical characteristics in abrasive waterjet milled channels. Measurements", vol. 393, pp. 1-6.

17. Singh, D & Chaturvedi, V 2014, "Investigation of optimal processing condition for abrasive waterjet machining for stainless steel AISI 304 using grey relational analysis coupled with S/N ratio", In Applied Mechanics andMaterials, vol. 592, no. 1, pp. 438-443.

18. K.Nandagopal, C.Kailasanathan, 2016, "Analysis of mechanical properties and optimization of gas tungsten Arc welding (GTAW) parameters on dissimilar metal titanium (6Al4V) and aluminium 7075 by Taguchi and ANOVA techniques" Journal of Alloys and Compounds, vol. 682, pp. 503-516.

19. Kumaran, ST, Uthayakumar, M, Kumar, VK, Sundaram, AM & Rajaselvam, EM 2015, "Parametric optimization of AWJM in AA6351- SiC-B4C hybrid composite using grey relational analysis", Applied Mechanics and Materials, vol. 766, no. 1, pp. 38-43.

20. Choopani, Y., Khajehzadeh, M., & Razfar, M. R. (2023). "An experimental study on the abrasive flow machining of aluminum alloy (AA 2024)". SN Applied Sciences, 5(5), 151.

21. Lin, ST, Horng, SJ, Lee, BH, Fan, P, Pan, Y, Lai, JL, Chen, RJ & Khan MK 2011, "Application of grey-relational analysis to find the most suitable watermarking scheme", International Journal of Innovative Computing,Information and Control, vol. 7, no. 9, pp. 5389-5401.