Optimization of Abrasive Water Jet Machining Parameters on AA6061/B₄C/hBN Hybrid Composites using Grey-RSM

A Gnanavelbabu*, V Arunachalam, K T Sunu Surendran and P Saravanan
Department of Industrial Engineering, CEG Campus, Anna University, Chennai - 600025, India.

*Corresponding author email: agbabu@annauniv.edu

Abstract. Aluminium Matrix Hybrid Composites (AMHCs) possess an excellent combination of physical and mechanical properties suitable for a variety of applications in automobile and aerospace industries. Addition of solid lubricant hexagonal Boron Nitride (hBN) reduces the complexity in machining of aluminium hybrid composites. Abrasive Water Jet Machining (AWJM) is a non-traditional technique applied for the machining of alloys and composites, due to its better cutting performances. In this work, AA6061 matrix hybrid composites reinforced with B₄C (5, 10 and 15vol.%) and hBN (15vol.%) were developed through liquid metallurgy route. The composite were then machined using AWJM. Process parameters considered were abrasive flow rate, water pressure, traverse speed, percentage of reinforcement and mesh size over the responses Kerf Taper Angle (KTA) and Surface roughness (Ra). The experimental design was based on L₂₇ orthogonal array and Grey-RSM analytical tool was applied for optimization. The optimal values of parameter setting for AWJM machining process using Grey RSM methodology were 340 g/min, 200 MPa, 60.06 mm/min, 5.01% and 80 for abrasive flow rate, water pressure, traverse speed, percentage of reinforcement and mesh size were respectively.

1. Introduction
A wide range of engineering applications are imposed on Metal Matrix Composites (MMCs) due to their high specific strength, stiffness, wear resistance and dimensional stability [1]. Due to the advanced physical and mechanical properties, Aluminium Matrix Hybrid Composites (AMHCs) are majorly used for automobile and aerospace applications [2]. Aluminium alloy 6061 is the most commonly used matrix material. When it reinforced with hard Boron Carbide (B₄C) ceramic particles, the strength, hardness, wear resistance, thermal and chemical stability have been improved [3]. In addition, the solid lubricant namely hexagonal Boron Nitride (hBN), is added for improving the machinability, wear and thermal resistance of AMHCs [4]. One of the feasible and economical ways for fabricating hybrid composites is the mechanical stirring assisted casting which ensures a fine distribution of reinforcements in the matrix [5]. Machining of hybrid composites in conventional methods is a great challenge. To overcome this difficulty, many newer techniques are employed nowadays. Abrasive Water Jet Machining (AWJM) process provides a high-quality cutting for composites with a great surface finish suitable for producing various components for automotive and aerospace applications. The basic principle behind AWJM is to increase the material removal rate (MRR) from the surface by utilizing the abrasiveness of fine-grained abrasive particles flowing in a high velocity water jet. Almost any type of material can be cut by AWJM which includes hard brittle materials, soft materials etc. [6-8].
The quality of cutting on usually depends on abrasive material, work piece material, thickness of the specimen etc. and other machine controlling parameters [9]. Hence, optimization of AWJM process parameters is important for obtaining better cutting quality characteristics. Response Surface Methodology (RSM) is the popular technique for determining the optimal parameter settings. Further, Integrated Grey-Taguchi approach coupled with RSM (GT-RSM) is used for the optimization of many industrial processes. Jagadish et al. applied ANOVA and RSM for optimizing the AWJM parameters for surface roughness (Ra) and Process Time (PT) on green composites. Stand-off Distance (SoD), Nozzle Speed (NS) and Pressure within the Pumping System (PwPS) were the parameters taken for optimizing [10]. Manoj M. et al. applied Taguchi-DEAR methodology for optimizing the AWJM parameters for AA 7075 matrix based composites by considering the input parameters stand-off distance, transverse speed and Water jet pressure over MRR, Ra and taper angle [11]. Ravi Kumar et al. in their optimization study using RSM concluded that transverse speed, percentage of reinforcement and standoff distance were the significant parameters which influenced the MRR and Ra of aluminium composites [12]. Santhanakumar et al. applied Grey theory based RSM methodology for optimizing the AWJM process parameters for aluminium hybrid composites. Parameters such as SoD, traverse speed, abrasive flow rate and water pressure were considered for optimizing the responses striation zone length, angle and Ra [13].

To minimize the surface roughness (Ra) and Kerf Taper Angle (KTA) of B₄C and hBN reinforced AA6061 hybrid composites, an optimal process parameter setting is necessary for AWJM process. From the literature review, it is clearly understandable that application of Grey-RSM for acquiring optimal setting for AWJM parameters for AA6061-B₄C-hBN hybrid composites has not much been attempted. Therefore, the prime aim of this work is to apply Grey-RSM methodology in order to optimize the AWJM process parameters on the fabricated hybrid composites.

2. Materials and Methodology
AA6061 is the widely used aluminium alloy which has good corrosion resistances, high strength to weight ratio, dimensional stability and is chosen as the matrix material. Boron Carbide (B₄C) with an APS (Average Particle Size) of 10-25 µm and hexagonal Boron Nitride (hBN) with an APS of 5µm were used as the reinforcements. The volumetric composition of the materials for fabricating the hybrid composites through stir casting is given in table 1.

| S. No. | AA6061 (Vol.%) | B₄C (Vol.%) | hBN (Vol.%) |
|-------|---------------|-------------|-------------|
| 1     | 80            | 5           | 15          |
| 2     | 75            | 10          | 15          |
| 3     | 70            | 15          | 15          |

The various input parameters of the machine along with their levels considered for optimization is given in Table 2. Standoff distance (1.5mm), impinging angle (90°) and focusing tube length (75mm) were kept constant throughout the study. Responses considered for this study were Surface roughness (Ra) and Kerf Taper Angle (KTA).
The cutting of hybrid composites of size 100 mm x 100 mm and thickness 10 mm was carried out in an AWJM machine (Make: OMAX-2626). The image of the AWJM machine and specimen after AWJM process are shown in figure 1a and b. The cutting quality of the specimens was analysed by measuring the kerf width, kerf taper angle and surface roughness. Video measurement system (VMS2010 F) was utilized for the measurement of kerf width. The samples after AWJM process placed in VMS in order to find the bottom and top kerf width. Using the kerf width and sample thickness, KTA is calculated by equation 1. The effect on various AWJM parameters on the surface finish was studied. A non-contact profilometer was utilized for measuring surface roughness value (Ra).

\[ \theta = \tan^{-1}\left(\frac{(w_t-w_b)}{2t}\right) \]  

\( w_t = \text{Top kerf width} , \ w_b = \text{Bottom kerf width} , \ t = \text{Thickness of the work piece} . \)

3. Result and Discussion

AWJM was performed on the hybrid composites as per the L27 orthogonal array and the experimental results obtained are shown in table 3. The optimization of parameters was done by Grey-Response Surface Methodology (G-RSM) using design expert software. In grey relational analysis the optimization was performed until the Grey Relational Grade (GRG) obtained. When GRG value is higher, it indicates that the parameter is nearest to the optimal value. In G-RSM, the GRG values representing the multiple responses were taken as single performance and are used in the generation of responses surface graphs.

| S.No | A  | B  | C  | D  | E  | KTA (°) | Ra (µm) |
|------|----|----|----|----|----|---------|---------|
| 1    | 80 | 240| 125| 60 | 5  | 0.40067 | 3.6032  |
| 2    | 80 | 240| 125| 60 | 10 | 0.38137 | 3.6185  |
| 3    | 80 | 240| 125| 60 | 15 | 0.35827 | 3.6248  |
| 4    | 80 | 340| 200| 90 | 5  | 0.39036 | 3.6189  |
| 5    | 80 | 340| 200| 90 | 10 | 0.37395 | 3.6288  |
| 6    | 80 | 340| 200| 90 | 15 | 0.37286 | 3.6392  |
| 7    | 80 | 440| 275| 120| 5  | 0.50227 | 3.6299  |
| 8    | 80 | 440| 275| 120| 10 | 0.43827 | 3.6392  |
| 9    | 80 | 440| 275| 120| 15 | 0.30935 | 3.6507  |
| 10   | 100| 240| 125| 120| 5  | 0.60836 | 3.6353  |
| 11   | 100| 240| 125| 120| 10 | 0.46925 | 3.6448  |
| 12   | 100| 240| 125| 120| 15 | 0.40089 | 3.6532  |
| 13   | 100| 340| 200| 60 | 5  | 0.45416 | 3.5948  |
### 3.1. Grey Relational Grade (GRG)

The S/N ratio, Normalized S/N ratio, Grey Relational Coefficient (GRC) and GRG for each trial were calculated and the values obtained are shown in table 4. A large GRG among the trials is considered as optimal value. The highest GRG value obtained was 0.735 on 16th trial.

| Trial No. | S/N | Normalised S/N | GRC (R1) | GRC (R2) | GRG |
|-----------|-----|----------------|----------|----------|-----|
| 1         | 7.94 | -11.13         | 0.34     | 0.14     | 0.43 | 0.37 | 0.400 |
| 2         | 8.37 | -11.17         | 0.28     | 0.41     | 0.41 | 0.46 | 0.433 |
| 3         | 8.92 | -11.19         | 0.19     | 0.52     | 0.38 | 0.51 | 0.445 |
| 4         | 8.17 | -11.17         | 0.31     | 0.41     | 0.42 | 0.46 | 0.440 |
| 5         | 8.54 | -11.20         | 0.25     | 0.58     | 0.40 | 0.55 | 0.473 |
| 6         | 8.57 | -11.22         | 0.25     | 0.76     | 0.40 | 0.68 | 0.538 |
| 7         | 5.98 | -11.20         | 0.64     | 0.60     | 0.58 | 0.56 | 0.569 |
| 8         | 7.17 | -11.22         | 0.46     | 0.75     | 0.48 | 0.67 | 0.576 |
| 9         | 10.19| -11.25         | 0.00     | 0.96     | 0.33 | 0.92 | 0.628 |
| 10        | 4.32 | -11.21         | 0.89     | 0.70     | 0.82 | 0.62 | 0.723 |
| 11        | 6.57 | -11.23         | 0.55     | 0.86     | 0.53 | 0.78 | 0.652 |
| 12        | 7.94 | -11.25         | 0.34     | 1.00     | 0.43 | 1.00 | 0.716 |
| 13        | 6.86 | -11.11         | 0.51     | 0.00     | 0.50 | 0.33 | 0.418 |
| 14        | 7.05 | -11.15         | 0.48     | 0.24     | 0.49 | 0.40 | 0.442 |
| 15        | 7.72 | -11.17         | 0.38     | 0.41     | 0.44 | 0.46 | 0.451 |
| 16        | 3.91 | -11.20         | 0.96     | 0.60     | 0.92 | 0.55 | 0.735 |
| 17        | 6.66 | -11.21         | 0.54     | 0.66     | 0.52 | 0.59 | 0.557 |
| 18        | 10.03| -11.22         | 0.02     | 0.79     | 0.34 | 0.70 | 0.521 |
| 19        | 3.62 | -11.17         | 1.00     | 0.41     | 1.00 | 0.46 | 0.730 |
| 20        | 4.06 | -11.18         | 0.93     | 0.50     | 0.88 | 0.50 | 0.691 |
| 21        | 4.65 | -11.21         | 0.84     | 0.66     | 0.76 | 0.59 | 0.678 |
| 22        | 4.18 | -11.20         | 0.91     | 0.58     | 0.85 | 0.55 | 0.700 |
| 23        | 7.23 | -11.21         | 0.45     | 0.70     | 0.48 | 0.62 | 0.549 |
| 24        | 8.03 | -11.22         | 0.33     | 0.79     | 0.43 | 0.70 | 0.565 |
3.2. Optimization

A statistical technique used widely for empirical model building is Response Surface Methodology (RSM). It provides the optimized results for different combinations of input parameters. In this study, RSM was applied on GRG values in order to find the optimum combination of parameters. The results of Analysis Of Variance (ANOVA) are shown in figure 2. The model “F value” 10.50 indicate the model significance. The p-value should be less than 0.05 shows significant. ANOVA shows that combination of parameters AB (Mesh size and Abrasive flow rate), AE (Mesh Size and Reinforcement %), BC (Abrasive Flow Rate and Water Pressure) are significant. R-sq. value 0.9131 closes to one show that the model is fit.

![Figure 2. ANOVA for GRG.](image-url)
Summary of ANOVA: Std. Dev.: 0.045, Mean: 0.57, CV %: 7.91, Press: 0.12, Adj. $R^2$: 0.8261, $R$ sq.: 0.9131, Pred. $R$ –sq.: 0.5874 and Adq. Precision: 11.046.

The generated regression equation offers the scope to study the behaviour of system by quantifying the association and thereby exploring their individual effects and interaction effects of parameters on the responses. The corresponding regression equation is shown in equation 2.

$$GRG = 0.45 + 0.014 \times A + 0.017 \times B + 0.035 \times D - 0.013 \times E - 0.089 \times A \times B + 0.058 \times A \times D - 0.037 \times A \times E + 0.12 \times B \times C - 0.091 \times B \times D - 0.016 \times B \times E - 8.839 \times E - 0.003 \times D \times E + 0.025 \times A^2 + 0.030 \times E^2$$  \hspace{1cm} (2)

3.3. Response Surface Plots

Response surface plots based on GRG with parameters are shown in the figures 3(a-c). Figure 3a shows the effect of % of reinforcement (E) and Mesh size (A) on the GRG values. The maximum GRG value was obtained at 120 mesh size and 15% reinforcement. Also, it illustrates that GRG and Mesh size are directly proportional. Figure 3 (b) represents the effects of Abrasive flow rate (B) and Water pressure (C) on GRG values. Maximum GRG obtained at highest abrasive flow rate and water pressure. At highest abrasive flow rate, and increase in water pressure increases the GRG. Figure 3 (c) represents the effects of mesh size (A) and abrasive flow rate (B) on GRG. The highest GRG values obtained at low mesh size and highest Abrasive flow rate. A significant reduction in GRG can be observed as the abrasive flow rate decreases.

3.4. Desirability analysis

The results of desirability analysis are shown in figure 4. In the figure 4, the dots indicate the level of the parameter and heights indicate the desirability. The obtained desirability value form the analysis is
0.950. This indicates a higher degree of closeness, as 1 is the desirable value. The optimal level of AWJM parameters obtained is Mesh size - 80, abrasive flow rate - 340, water pressure- 200, Transverse speed-60.6 and reinforcement % - 5.01.

![Desirability analysis.](image)

**Figure 4.** Desirability analysis.

4. Conclusion
Fabrication and parametric optimization of AWJM process on three different AA6061-B4C-hBN hybrid composites were successfully carried out using the analytical tools G-RSM. The predicted and the experimentally obtained values of grey relational grade were matched well demonstrating a better model fitness. The optimal parameter setting for AWJM machining process using Grey RSM methodology were: Mesh size=80, Abrasive flow rate=340 g/min, Water pressure=200 MPa, Traverse speed =60.06 mm/min, % reinforcement=5.01 Vol.%. 

**Acknowledgement**
This research work was supported by Science and Engineering Research Board (SERB), Govt. of India (Grant No.: EEQ/2017/000382).

**References**
[1] Nicholls C J, Boswell B, Davies I J, Islam M N, “Review of machining metal matrix composites”, International Journal of Advanced Manufacturing Technology, vol. 90(9-12), pp. 2429-2441, 2017.

[2] Michael Oluwatosin Bodunrin, Kenneth Kanayo Alaneme, Lesley Heath Chown, “Aluminium matrix hybrid composites: A review of reinforcement philosophies; mechanical, corrosion and tribological characteristics”, Journal of Materials Research and Technology, vol. 4(4), pp. 434-445, 2015.

[3] Kaikai Wang, Xiaopei Li, Qilin Li, Guogang Shu, Guoyi Tang, “Hot deformation behavior and microstructural evolution of particulate-reinforced AA6061/B4C composite during compression at elevated temperature”, Materials Science and Engineering: A, vol. 696, pp. 248-256, 2017.
[4] Pagidi Madhukar, N Selvaraj, C S P Rao, G B Veeresh Kumar, “Tribological behavior of ultrasonic assisted double stir casted novel nano-composite material (AA7150-hBN) using Taguchi technique”, Composites Part B: Engineering, Vol. 175, Article 107136, 2019.

[5] Ramanathan Arunachalam, Pradeep Kumar, Krishnan Rajaraman, Muraliraja, “A review on the production of metal matrix composites through stir casting – Furnace design, properties, challenges, and research opportunities”, Journal of Manufacturing Processes, vol. 42, pp. 213-245, 2019.

[6] S B Supriya, S Srinivas, “Machinability studies on stainless steel by abrasive water jet - Review”, Materials Today: Proceedings, Vol. 5(1), pp. 2871-2876, 2018.

[7] R Senthil Kumar, S Gajendran, R Kesavan, “Estimation of Optimal Process Parameters for Abrasive Water Jet Machining Of Marble Using Multi Response Techniques”, Materials Today: Proceedings, Vol.5(5), pp. 11208-11218, 2018.

[8] Padmakar J Pawar, Umesh S Vidhate, Mangesh Y Khalkar, “Improving the quality characteristics of abrasive water jet machining of marble material using multi-objective artificial bee colony algorithm”, Journal of Computational Design and Engineering, Vol. 5(3), pp. 319-328, 2018.

[9] A Gnanavelbabu, K Rajkumar, Saravanan P, “Investigation on the Cutting Quality Characteristics of Abrasive Waterjet Machining on AA6061-B4C-hBN Hybrid Metal Matrix Composites”, Materials and Manufacturing Processes, vol. 33(12), pp. 1313-1323, 2018.

[10] Jagadish, Sumit Bhownik, Amitava Ray, “Prediction and optimization of process parameters of green composites in AWJM process using response surface methodology”, International Journal of Advanced Manufacturing Technology, vol. 87(5-8), pp. 1359-1370, 2016.

[11] M Manoj, G R Jinu, T Muthuramalingam, “Multi Response Optimization of AWJM Process Parameters on Machining TiB2 Particles Reinforced Al7075 Composite Using Taguchi-DEAR Methodology”, Silicon, vol. 10(5), pp. 2287-2293, 2018.

[12] K Ravi Kumar, V S Sreebalaji, T Pridhar, “Characterization and optimization of Abrasive Water Jet Machining of aluminium/tungsten carbide composites”, Measurement, vol. 117, pp. 57-66, 2018.

[13] M Santhana kumar, R Adalarasan, M Rajmohan, “Parameter design for cut surface characteristics in abrasive waterjet cutting of Al/SiC/Al2O3 composite using grey theory based RSM”, Journal of Mechanical Science and Technology, vol. 30(1), pp. 371-379, 2016.