Abrasive water jet machining of Al5083/ ZrO_2/ B_4C hybrid aluminium metal matrix composite and optimization of its process parameters

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ABSTRACT

KEYWORDS

Abrasive Water Jet Machining,
Material Removal Rate,
Surface Roughness,
Taguchi- Genetic Algorithm,
Optimization of Process Parameters.

In this work, Abrasive water jet machining experiments are conducted on Al 5083/ B_4C/ ZrO_2 metal matrix composites. Experiments are conducted according to Taguchi's experimental design (OA27) for different combinations of nozzle diameter, stand-off distance, jet pressure, abrasive flow rate, and traverse speed. The experimental data of material removal rate and surface roughness are recorded for these runs and are analysed using Taguchi - Genetic algorithm method for identification of optimal process parameters. Further, ANOVA is conducted to determine the contribution of each of these parameters on machining responses. This work is more useful for maximizing MRR thereby the machining process will be done much faster and at the same time, minimizing the Surface Roughness so as to obtain a smoother finish. The confirmation test is done at optimal parameters combinations and results are satisfactory.

1. Introduction

Machining is widely used manufacturing process in the industries. The abrasive jet machining process is a non-traditional machining process which operates without much shock and heat. Abrasive jet machining is used for variety of operations like cutting, cleaning, and etching operations. The nozzles direct abrasive jet in a controlled way onto the work material. The high velocity abrasive particles strike the surface of the material and remove the material from the work piece by micro-cutting action as well as brittle fracture of the work material. Certain process parameters affect the performance of the AJM Selvam et al. (2017), Kumar and Kant (2019), Niranjan et al. (2018) such as particle size, shape, pressure of jet, stand-off distance, jet velocity, jet diameter, nozzle shape, nozzle distance etc. (Niranjan et al., 2018; Jegaraj & Babu, 2005). A high-velocity jet of water with abrasive particles gives eco-friendly and relatively economical machining options for cutting, which make leading machining technology in a short span. The nozzle is the most important part in the abrasive jet setup. The process is mainly used to cut difficult and deep shapes in hard and brittle materials which are sensitive to heat. Different types of abrasives having a range of grit size can be used depending on work piece material and the operation which needs to be performed. Abrasive particle of SiC, Aluminium oxide (alumina) of average grit size 10 – 50µm is commonly used for cutting operations, moreover when work-piece is hard. Whereas for very hard work-piece silicon carbide (SiC) is preferred because it is harder than alumina. Size of abrasives has a great impact on quality of finish as well as material removal rate. Larger grit size produces larger cavity and thus MRR improves with the kind of surface finish. Whereas, fine abrasives reduce MRR but improve surface finish and accuracy (Kumar & Shukla, 2012; Balasubramaniam et al., 2000).

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Lohar and Kubade (2016) reviewed the research work carried out from the inception to the development of AWJM within past few years. It reports on the AWJM research relating to performance measures improvement, monitoring and process control, process variables optimization. A wide range of AWJM industrial applications for variety of materials are reported with variations and also discussed the future trend of research work in the area of AWJM Madhu and Balasubramanian (2015) presented several experiments that have been conducted by many researchers to assess the influence of abrasive jet machining (AJM) process parameters such as type of abrasive Particle, Abrasive Particle size, Jet pressure, Nozzle tip distance. Various experiments were conducted to assess the influence of abrasive jet machine. Khan et al. (2021) presented an overview of previously carried research on process parameters and development of Abrasive Jet Machining and Abrasive Water Jet Machining. Further challenges and scope of future development in abrasive jet machining are also projected. The influence of input process parameters, erodent/abrasive materials and bulk material properties along response on kerf wall inclination, material removal rate and surface quality are discussed in detail. In addition, the electron microscopic images are used to discuss the wear mechanism on different materials. The information discussed in the paper will support young researchers to understand the AWJ process and its scope. Soni and Patel (2016) studied on parameters which mainly affect the quality of cutting are traverse speed, hydraulic pressure, stand-off distance, abrasive flow rate and types of abrasive. Important quality parameters in AWJM are Material Removal Rate (MRR), Surface Roughness (SR).

The objective of this work is to conduct an experimental investigation of the process that can be used for a better understanding of the process. The factors affecting water jet and abrasive water jet performance are found from review and the effect of same is to be experimentally investigated. From the literature it is revealed that many researchers had conducted their works on different parameters of AJM in their own directions to analyse machining responses for identification of optimal parameters. The present work has been done with the objective to optimize the machining parameters in abrasive water jet machining of Al 5083/B_4C/Zro_2 metal matrix composite which is developed by the authors, by analysing the machining responses for finding the optimal values for a set of parameters.

2. Experimental Work

Table 1
Parameters and their levels.

S. no	Parameter and Symbol	Levels		
		Level 1	Level 2	Level 3
1	Pressure (psi) A	25000	30000	35000
2	Abrasive flow rate B (g/min)	220	320	420
3	Feed rate C (mm/min)	87	121	155
4	Stand of distance D (mm)	2	3	4
5	Nozzle diameter E (mm)	1.2	1.4	1.6

Fig. 1. Water jet cutting on work piece.

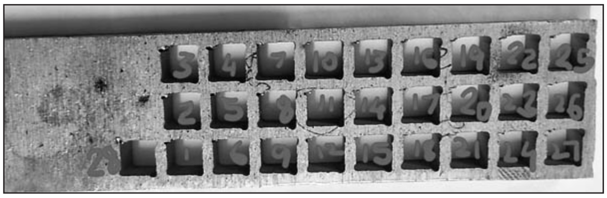

Fig. 2. Machined work piece.

In the this work, CNC Abrasive water jet cutting machine is used to cut slots on composite with the abrasive material of Garnet mesh 80 at a nozzle impingement angle of 85 degrees, the machine setup is shown in Fig.1. Experiments are conducted on composite according to Taguchi L27 orthogonal array Nagdeve et al. (2012); Ross (1988); Byrne (1986), which is prepared based on parameters (Niranjan et al., 2018; Jegaraj & Babu, 2005) and their levels (Table 1). Square slots (Fig.2) are cut on the composite for different combination of process parameters jet pressure, abrasive flow rate, nozzle diameter, traverse speed and stand of distance between nozzle tip and work surface. During operation, surface roughness and machining time are noted by using a stopwatch for each experimental run. Further, MRR is calculated as the output responses based on machining time for each experiment.

2.1 Measurement of responses

The experimental data of material removal rate, surface roughness are recorded for each experimental run for the purpose of analysing them.

- Material Removal Rate (MRR)

The MRR is the amount of material erosion from the work piece per unit time. It expresses the speed of the machining of the work piece. The material removal rate can be calculated from the volume of material removal before and after machining.

Table 2
Experimental layout and responses.

S.no	Pressure (psi)	Abrasive flow rate (g/min)	Feed rate (mm/min)	Stand of distance (mm)	Nozzle diameter (mm)	S/N ratio of	
						MRR	SR
1	25000	220	87	2	1.2	31.20153	3.849299
2	25000	220	87	2	1.4	30.67684	5.336055
3	25000	220	87	2	1.6	30.38952	5.629966
4	25000	320	121	3	1.2	29.57606	2.326771
5	25000	320	121	3	1.4	29.68272	4.208386
6	25000	320	121	3	1.6	29.97396	4.40807
7	25000	420	155	4	1.2	28.1292	1.60798
8	25000	420	155	4	1.4	28.5659	3.849299
9	25000	420	155	4	1.6	28.16042	5.882726
10	30000	220	121	4	1.2	30.31658	4.928339
11	30000	220	121	4	1.4	30.07513	7.250205
12	30000	220	121	4	1.6	29.71122	7.618133
13	30000	320	155	2	1.2	29.4263	2.709778
14	30000	320	155	2	1.4	29.63527	5.780738
15	30000	320	155	2	1.6	29.63077	7.702056
16	30000	420	87	3	1.2	28.64993	2.709778
17	30000	420	87	3	1.4	28.56581	3.985658
18	30000	420	87	3	1.6	27.95028	4.026987
19	35000	220	155	3	1.2	29.22108	1.279784
20	35000	220	155	3	1.4	29.53657	3.060893
21	35000	220	155	3	1.6	29.23318	4.716477
22	35000	320	87	4	1.2	29.61933	2.23641
23	35000	320	87	4	1.4	29.09022	2.349509
24	35000	320	87	4	1.6	29.4575	9.709045
25	35000	420	121	2	1.2	27.54456	2.292776
26	35000	420	121	2	1.4	27.68811	2.781268
27	35000	420	121	2	1.6	27.90681	6.375175

$$\text{VRR} = \frac{\text{Kerf volume}}{\text{Machining time}}$$

MRR = VRR× Density of the composite

- Surface Roughness

Surface roughness on cut slots is measured using Talysurf surface roughness tester, while measuring; stylus of the instrument is drawn across the surface at a constant speed for a set distance, the values of surface texture are given in the Table 2.

3. Analysis of Experimental Responses and Identification of Optimal Parameter Values

The experimental data of material removal rate, surface roughness (Table 2) are analysed using Taguchi S/N ratio analysis method and Taguchi-Genetic algorithm method for identification of optimization of process parameters (Iqbal et al., 2011; Pudi et al., 2020; Soni & Patel, 2016). ANOVA is performed on responses for finding the contribution of influential parameters.

3.1 Optimal parameters combination through taguchi S/N ratio analysis

Main effects of each machining parameters on MRR are shown in Fig.3. From this, S/N ratio of MRR is maximum for the parameter of jet pressure at level 1 (25000), Abrasive flow rate at level 1 (220 grams/min), Traverse Speed at level 1 (87 mm/min), Standoff distance at level 1 (2 mm), and nozzle diameter at level 1 (1.2 mm). The optimal parameter setting for the maximum MRR is identified as A1B1C1D1E1 Similarly, from main effects plot of machining parameters (Fig.4), Surface roughness (SR) is minimum for jet pressure at level 2 (30000), Abrasive flow rate at level 1 (220 grams/min), Traverse Speed at level 2 (121 mm/min), Standoff distance at level 3 (4 mm), and nozzle diameter at level 3 (1.6 mm). The optimal parameter setting for the maximum MRR is identified as A2B1C2D3E3.

3.2 ANOVA of machining responses

ANOVA of Surface Roughness and MRR (Table 3&4) has shown the order of factors influencing parameters as BACDE and EADBC respectively. It is also evident that abrasive flow rate having maximum percentage of contribution (78.04%) for MRR and diameter of nozzle having maximum percentage of contribution (53.77%) for Surface roughness. It is observed that the value of P of these parameters is less than 0.05, indicating that these are significant parameters contributing much towards machining performance.

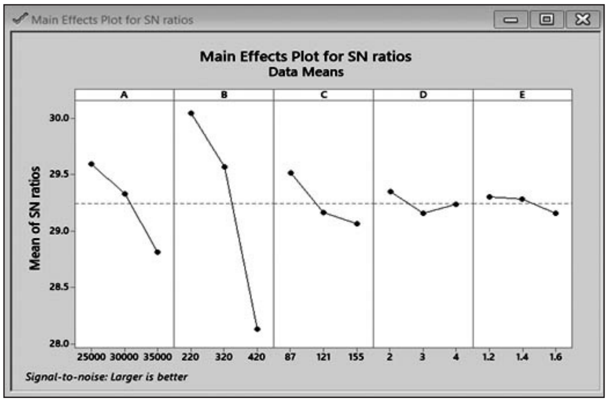

Fig. 3. Main effects plot for S/N ratios of MRR.

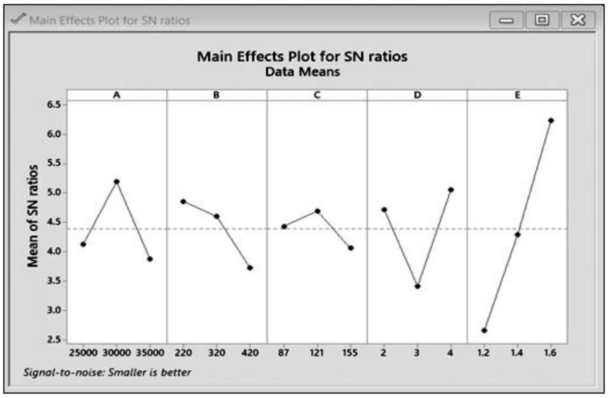

Fig. 4. Main effects plot for S/N ratios of surface roughness.

3.3 Optimal parameters combination through genetic algorithm

- Development of objective function and constraints

The optimization process has two steps. In first step, modeling of responses is done through regression for formulation of objective function. In addition, all constraints are defined using equalities and (or) inequalities. In the second step, carryout the searching process for a global minimum of objective function (eq.3), under all defined constraints (eq.4). The Regression models are developed using Minitab software for machining responses of MRR (eq.1) and SR (eq.2).

$$MRR = 0.1566 + 0.000080\times A + 0.434\times C - 0.00212\times C - 0.0168\times E - 0.018\times E - 0.90\times B^2 + 0.000006\times C^2 + 0.0011\times E^2 + 0.00067\times D^2 \quad ....(1)$$

Table 3
Analysis of variance for SN ratios of MRR.

Source	Degrees of freedom	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P- Value
A	2	0.000004	11.99%	0.000004	0.000002	18.62	0.000
B	2	0.000025	78.04%	0.000025	0.000013	121.20	0.000
C	2	0.000001	3.98%	0.000001	0.000001	6.18	0.010
D	2	0.000000	0.42%	0.000000	0.000000	0.65	0.536
E	2	0.000000	0.42%	0.000000	0.000000	0.65	0.536
Error	16	0.000002	5.15%	0.000002	0.000000		
Total	26	0.000032	100%				

Table 4
Analysis of variance for SN ratios of surface roughness.

Source	Degrees of freedom	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P- Value
A	2	0.7321	11.06%	0.7321	0.36604	4.45	0.029
B	2	0.2766	4.18%	0.2766	0.13828	1.68	0.217
C	2	0.1797	2.72%	0.1797	0.08986	1.09	0.359
D	2	0.5556	8.39%	0.5556	0.27781	3.38	0.060
E	2	3.5591	53.77%	3.5591	1.77957	21.63	0.000
Error	16	1.3161	19.88%	1.3161	0.08225		
Total	26	6.6192	100%				

Table 5
The optimum values of parameters/responses from GA.

Machining Parameters	Optimized value
Pressure (psi), A3 (A at level-3)	35000
Abrasive flow rate (g/min), B3 (B at level-3)	420
Feed rate (mm/min), C3 (C at level-3)	155
Stand of distance (mm), D3 (D at level-3)	4
Nozzle diameter (mm), E1 (E at level-3)	1.2
MRR (mm^3/min)	34.054
SR (µm)	0.414

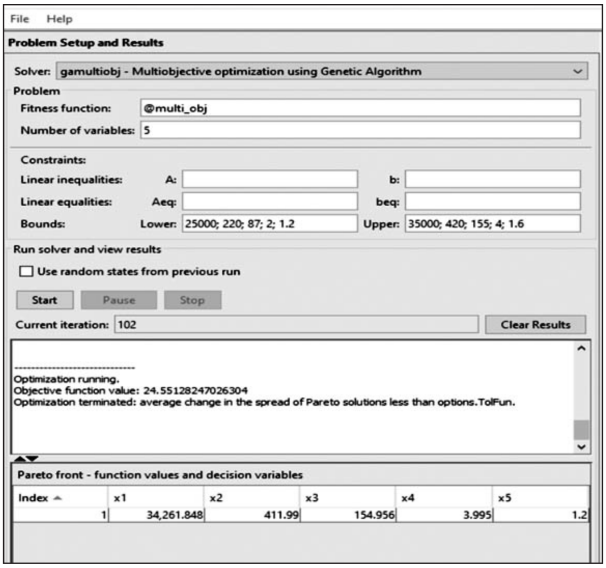

Fig. 4. Screen shot of GA toolbox of Mat lab with selected options and solution.

Table 6
Results of confirmation experiment.

S.no	Pressure (psi)	Abrasive flow rate (g/min)	Feed rate (mm/min)	Stand of distance (mm)	Nozzle diameter (mm)	MRR (mm^3/sec)	SR (µm)
1	35000	420	154	4	1.2	36.3142	0.542

$SR = -1.2474 - 0.000027 \times A + 3.660 \times B - 0.03324 \times C + 0.2078 \times D + 0.8056 \times E - 6.24 \times B^2 + 0.000101 \times C^2 + 0.00412 \times D^2 - 0.02829 \times E^2$ ....(2)

Objective function:

$f(c) = 1.404 + 0.000107 \times A - 3.226 \times B + 0.03112 \times C - 0.3758 \times D - 0.8236 \times E + 5.34 \times B^2 - 0.000095 \times C^2 - 0.00302 \times D^2 + 0.02896 \times E^2$ ....(3)

Subjected to

$25000 \leq A \leq 35000,\quad 210 \leq B \leq 450,\quad 87 \leq C \leq 155, 1 \leq D \leq 3,\quad 1.2 \leq E \leq 1.6$ ....(4)

Where

A=Pressure (x1)

B=Abrasive flow rate (x2)

C=Feed rate (x3)

D=Stand of distance (x4)

E=Nozzle diameter (x5)

Searching for optimum values of objective function with GA

The developed models (eq. 3, 4) are solved by using genetic algorithm tool box. The obtained results are shown in the Table.5; the optimization process is terminated for minimal value of objective function. The GA parameters and solution of this problem are shown in the Fig.4. From GA the optimum solution obtained as A3B3C3D3E1. This result is verified experimentally.

4. Confirmation Test

The confirmation test is conducted for the optimal parameters at its levels to evaluate quality characteristics in AJM of Composite. The confirmation test results are given in Table 6. The optimal process parameter set A3B3C3D3E1 gave good multiple performance characteristics.

5. Conclusions

In this work, an experimental study on material removal rate, surface roughness in abrasive water jet machining of a developed composite is conducted successfully and optimisation study is done on process parameters. The following conclusions are drawn from results.

- The effect of influential parameters on MRR, SR is studied and the optimal parameter settings for the maximum MRR and minimum SR individually are identified using Taguchi S/N ratio analysis. These are the ideal machining conditions for AWJM of developed composites.
- ANOVA on Surface Roughness and MRR is performed and the order of influential parameters is identified. It is also evident here that abrasive flow rate having maximum percentage of contribution for MRR, and diameter of nozzle having maximum percentage of contribution towards surface roughness.
- The optimization technique Genetic algorithm applied for identifying the best combination of input parameters with the goal of maximizing the MRR, as higher is the MRR value, the machining process will be much faster, and as a result the cycle time will be less. At the same time, minimizing the Surface Roughness so as to obtain a smoother finish for defined machined surface.

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