GREY INCIDENCE METHOD ON ABRASIVE WATER JET MACHINING OF AL7075/Al_2O_3 COMPOSITE

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ABSTRACT

Abrasive waterjet has been used to cut both ferrous and non-ferrous materials. The process is eco-friendly and creates minimal distortion of workpiece. The present work reports the analysis of surface roughness and kerf angle in abrasive waterjet machining of Al7075/Al_2O_3 composite. Taguchi's L9 orthogonal array is used for conducting the machining experiments with two replications. The process parameters like waterjet pressure, traverse rate, stand-off and abrasive flow rate are varied in three levels. The quality characteristics are studied and grey incidence method is applied to find out the optimal process parameters for better values of responses. Grey relational grade is employed as the quality index and analysis of variance is also performed to find the contribution of individual parameters in affecting the responses. The predicted optimal conditions are validated using proper machining trials during which noteworthy improvements are seen in kerf angle (30.8%) and surface roughness (14.32%).

Keywords: abrasive waterjet machining, Al7075/Al_2O_3 composite, L9 OA, surface roughness, grey incidence method, kerf angle, grey relational grade.

1. INTRODUCTION

The abrasive waterjet machining (AWJM) process can cut hard to machine materials including ceramics. The process merits includes zero heat affected zone, less chatter and environment friendliness. A high pressure water jet carrying the abrasives is focussed on the workpiece through a nozzle to obtain the desired cut. The abrasives receive the momentum from waterjet and act as individual cutting edges while targeting the workpiece. The process is versatile but presence of striations in machined surface along with surface roughness and kerf angle needs further study [1]. Metal matrix composites (MMCs) have superior mechanical properties and have abilities to substitute general engineering materials but the hard reinforcements create problems in machining including quick wear of cutting tools [2]. The water pressure indicates the energy content of the jet and ensures momentum transfer to the abrasives. Traverse rate indicates the speed of travel of the nozzle across the workpiece surface and stand-off indicates the distance between the nozzle tip and work surface. The flow rate of abrasives indicates the availability of multiple cutting edges to perform the required machining. Generally garnet of defined mesh size was used as abrasives [3]. AWJM could be used to cut both ductile and brittle materials; however setting of process variables were found to affect the responses. Selection of optimal levels of machining parameters could improve the surface texture of machined parts [4]. Along with surface hardness, kerf profile was also considerably affected by the design variables and improvement in kerf profile including the kerf angle requires an optimal setting of machining parameters [5].

Generally garnet was used as the abrasive to cut both ferrous and non-ferrous materials. An optimal amount of abrasive recharging improves the process economy and increases the jet penetration. However a decrease in cutting efficiency was observed with recharged abrasives [6]. The quality characteristics of the process like surface roughness and kerf angle depends on variables like traverse rate, stand-off and abrasive flow rate. Multi response optimization could be used for an offline quality control. Techniques employed for parameter design includes grey relational analysis, principal components analysis, TOPSIS, response surface method, genetic algorithm, neural networks, particle swarm optimization, ant colony optimization and fuzzy logic [7]. The optimal process parameters were designed used various techniques either in their own format or as a combined approach involving more than one method like Taguchi based RSM, grey based RSMetc. These methodologies could use the merits of both techniques to predict the optimal parameters [8, 9, 10]. Grey relational analysis is a statistical approach employed for multi response optimization. The technique uses signal to noise ratio, grey relational coefficient and grey relational grade as the quality indices to identify the optimal setting of parameters [11]. Desirability based RSM could also predict the optimal conditions within the experimental domain. However RSM was observed to lose its computing power in irregular regions of domain [12]. Simulated annealing algorithm and fuzzy logic could not cope with the process dynamics as genetic algorithm but setting of its own parameters in genetic algorithm requires extensive knowledge.

From the existing literature, it was found that the study of machining characteristics of Al7075/Al_2O_3 composite using an environment friendly process like abrasive waterjet machining was limited. The main design variables were identified as waterjet pressure, traverse rate, stand-off and abrasive flow rate. However the research on study of surface roughness and kerf angle in AWJM of Al7075/Al_2O_3 composite requires attention in literature. Hence the work was focused towards application of grey incidence method for parameter design in AWJM of Al7075/Al_2O_3 composite.

2. MACHINING SETUP AND EXPERIMENTAL DESIGN

The process of stir casting was used to form Al7075/Al_2O_3composite plate after melting Al7075 in a graphite crucible and adding preheated particles of Al_2O_3 (average particle size-80 micron) in weight fraction of 10% [9]. Continuous stirring was ensured during solidification to fabricate composite with uniform distribution of reinforcements. The scanning electron microscope image shown in Figure-1, displays the distribution of reinforcements (Al_2O_3) in matrixmaterial of fabricated composite plate. The AWJM trials were performed in an abrasive waterjet cutter (German make-S3015), built with an intensifier unit capable of producing high pressure waterjet. Garnet (120 mesh) was used as abrasive and the jet was focussed at right angles to work surface. The experimental trial involving AWJM is shown in Figure-2. Based on the review of existing literature and industrial expertise, the following parameters were selected for performing the AWJM trials: waterjet pressure, traverse rate, stand-off and abrasive flow rate. The level of parameters were chosen from the pilot trials conducted by varying the process parameters. The process parameters and their range is shown in Table-1.

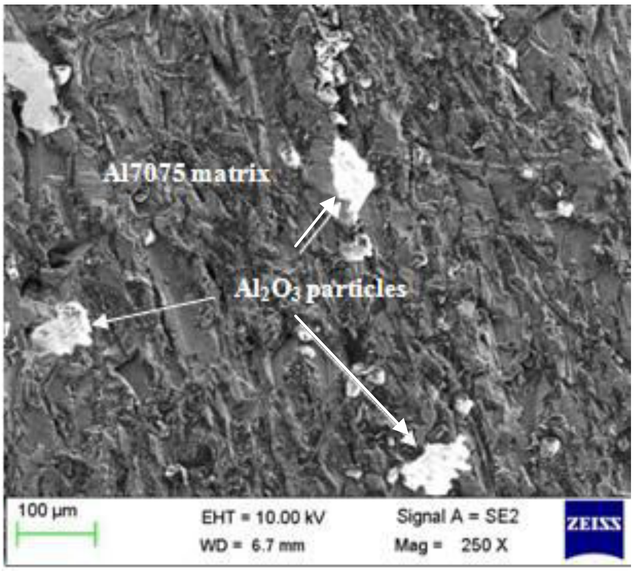

Figure-1. SEM image displaying Al_2O_3 particles in Al7075 matrix.

Table-1. AWJM parameters.

Symbol	Parameters	Units	Level 1	Level 2	Level 3
A	Waterjet pressure	MPa	200	250	300
B	Traverse rate	mm/min	100	125	150
C	Stand-off	mm	1	2	3
D	Abrasive flow rate	g/min	150	200	250

Figure-2. Experimental trial of AWJM.

Taguchi's L9 orthogonal array was used to design the AWJM trials. Surface roughness (SR) and kerf angle (KA) were studied after each trial. Two replicative cuts were performed at random to remove pattern effects [8]. The workpiece machined during each trial with button hole cuts is shown in Figure-3. Surface finish (Ra) was recorded using a surfcoder (SE3500-model), for an evaluation length of 4 mm and probe speed of 0.1 mm/s. SR values noted at three places were averaged for further analysis. Optical microscope with M-B ruler 4.0 software was used to find the KA after each cut. The results are shown in Table-2.

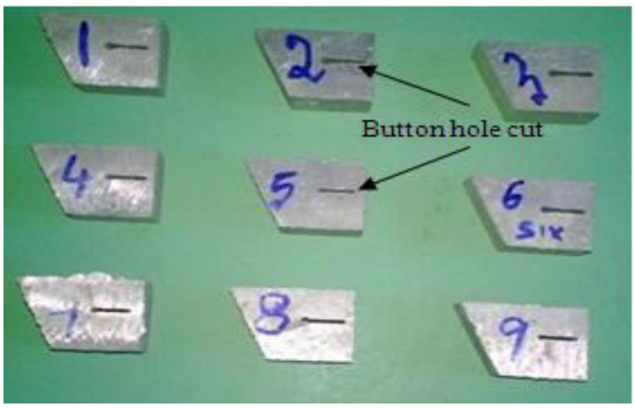

Figure-3. Workpiece machined during the designed trials.

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Table-2. AWJM trialsand measured responses.

Exp. No	Control parameter levels				Responses			
	A	B	C	D	SR (μm)		KA (deg)	
1	1	1	1	1	3.022	3.068	12.647	12.633
2	1	2	2	2	3.124	3.153	11.442	11.256
3	1	3	3	3	3.058	3.055	15.333	15.354
4	2	1	2	3	2.157	2.161	9.277	9.315
5	2	2	3	1	2.876	2.858	14.863	14.707
6	2	3	1	2	2.369	2.349	10.563	10.623
7	3	1	3	2	1.824	1.847	5.683	5.694
8	3	2	1	3	1.325	1.308	7.915	7.896
9	3	3	2	1	2.046	2.029	11.297	11.347

3. APPLICATION OF GREY INCIDENCE METHOD

The method of grey incidence analysis is used to solve multi response optimization problem in different manufacturing processes [7, 8, 9, 11]. It is a statistical approach which uses grey theory to arrive at the quality index. Grey incidence analysis is basically employed as an offline quality control method to deal with multiple process outputs and it uses *signal-to-noise* ratio (*S/N ratio*) for analysing the obtained responses. The abilities of grey theory in handling multiple uncertainties are described in following steps.

3.1 Pre-Processing of Responses

The *S/N ratio* was calculated for each of the obtained responses. Further normalization becomes essential before arriving at the grey relational coefficient (GRC) and grey relational grade (GRG). The *S/N ratio* (y_{ij}) for '*smaller-the-better*' and '*larger-the-better*' characteristic was calculated using Eq. (1) and Eq. (2) respectively. The target for '*smaller-the-better*' characteristic was achieving a minimum value of the response. Normalization was done to bring all the responses on a common scale using Eq. (3). Two replications were performed for each trial to improve the accuracy in analysis.

$$S/N\ Ratio(\eta) = -10\log_{10}\left(\frac{1}{r}\cdot\sum_{i=1}^{r} y_{ij}^2\right) \tag{1}$$

$$S/N\ Ratio(\eta) = -10\log_{10}\left(\frac{1}{r}\right)\sum_{i=1}^{r}\frac{1}{y_{ij}^2} \tag{2}$$

$$Z_{ij} = \frac{y_{ij} - \min(y_{ij}, i = 1,2,.....,n)}{\max(y_{ij}, i = 1,2,.....,n) - \min(y_{ij}, i = 1,2,.....,n)} \tag{3}$$

Where 'r' is the number of replications and 'm' is the number of observations.Computation of grey incidence coefficient (γ) from the normalized *S/N ratio,* using Eq (4) leads to further calculation of GRG values from Eq. (5). The calculated values are shown in Table-3. The GRG values were used as quality indices to rate the machining conditions. A larger value of GRG indicates a better combination of machining parameters to obtain good quality characteristics. From the analysis, it was observed that the machining condition of trial number 8 (GRG value of 0.80), could be a near optimal solution.

$$\gamma_i^j = \frac{\Delta\min + \xi\Delta\max}{\Delta_{oj}(i) + \xi\Delta\max} \tag{4}$$

$\Delta\min = \min_{\forall j\in i}\min_{\forall i}\left\|z_o(i) - z_j(i)\right\|$ is the smallest value of $z_j(i)$ and $\Delta\max = \max_{\forall j\in i}\max_{\forall i}\left\|z_o(i) - z_j(i)\right\|$ is the largest value of $z_j(i)$.'ξ' is the necessary discrimination coefficient whose value was chosen as 0.5 to give an equal importance to the two observed responses.

$$GRG_i = \sum_{i=1}^{n}(\gamma_{ij}) \tag{5}$$

3.2 Parameter Effects on Responses

The effects of variation of process parameters are studied for changes in observed responses (Figure-4). The water pressure becomes important to energize the abrasive jet by transferring the necessary momentum. A higher value was desired as shown in Figure-4a. Traverse rate was significant in ensuring the complete cut and has ability to affect kerf. Hence a lower level of traverse rate was preferred (Figure-4b). An optimal stand-off ensures lesser rebound and hence a reduced nozzle wears with minimal jet divergence [9, 10]. A lower level of stand-off was preferred as observed from Figure-4c. A high level of abrasive flow rate was essential for better surface finish as inferred from Figure-4d. Hence an increased waterjet pressure and abrasive flow rate along with low levels of stand-off and traverse rate was observed to produce better responses as shown in Figure-4.

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Table-3. S/N ratio and GRG values.

Trial	S/N ratio		Normalized S/N ratio		GRC		GRG
	SR	KA	SR	KA	SR	KA	
1	-9.6713	-22.0348	0.0349	0.1954	0.3413	0.3832	0.3623
2	-9.9345	-21.0993	0.0000	0.3039	0.3333	0.4180	0.3757
3	-9.7045	-23.7186	0.0305	0.0000	0.3402	0.3333	0.3368
4	-6.6851	-19.3658	0.4306	0.5051	0.4676	0.5025	0.4851
5	-9.1486	-23.3966	0.1042	0.0374	0.3582	0.3418	0.3500
6	-7.4546	-20.5006	0.3286	0.3734	0.4269	0.4438	0.4353
7	-5.2753	-15.1002	0.6175	1.0000	0.5665	1.0000	0.7833
8	-2.3886	-17.9586	1.0000	0.6683	1.0000	0.6012	0.8006
9	-6.1820	-21.0784	0.4973	0.3063	0.4986	0.4189	0.4588

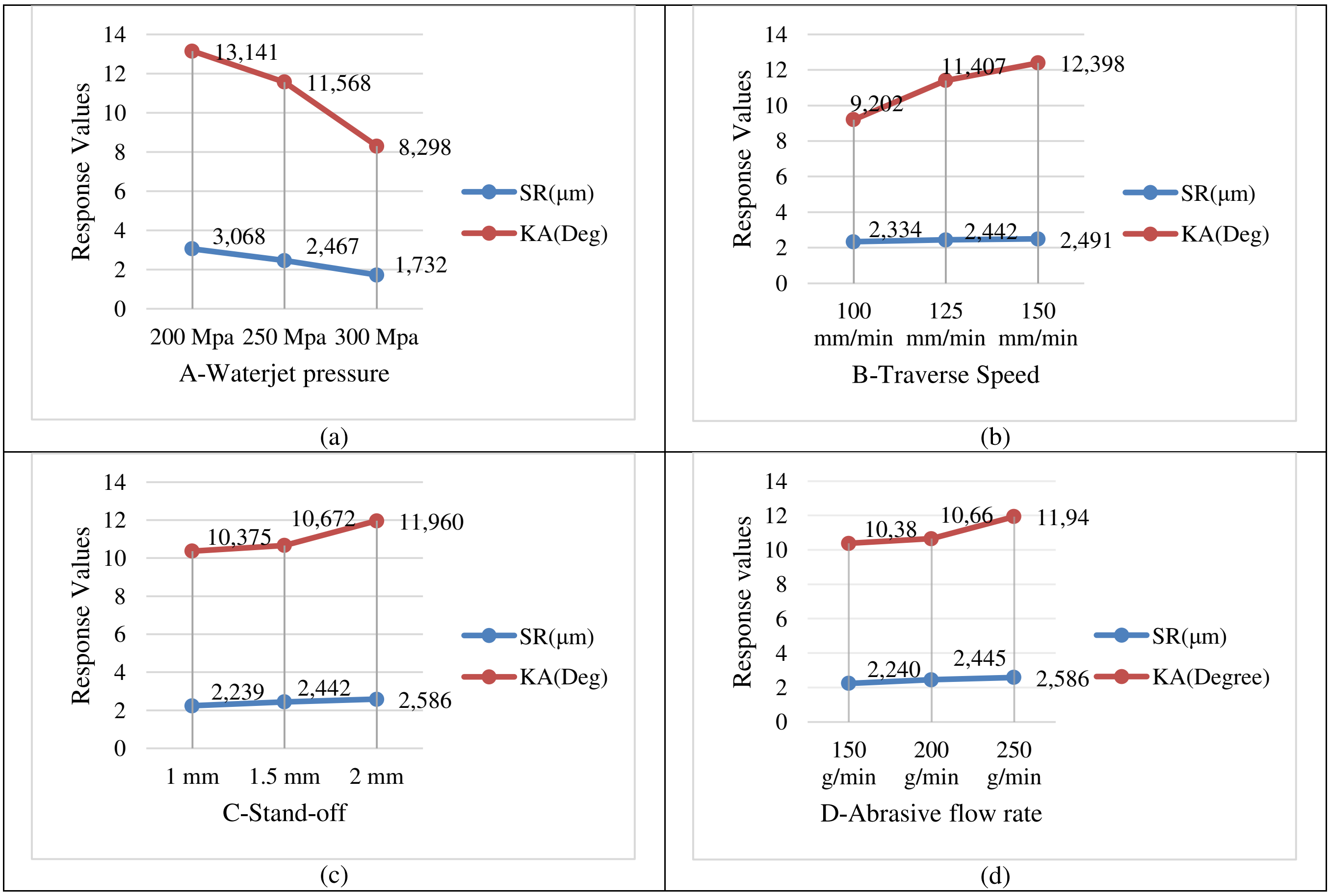

Figure-4. Effect of AWJM parameters on response values-SR and KA (a) waterjet pressure (b) traverse rate (c) stand-off (d) abrasive flow rate.

3.3 ANOVA

Analysis of variance (ANOVA) was performed to find the contribution of various parameters on GRG values representing the two responses. The waterjet pressure was found out as the primary and most significant parameter affecting SR and KA with a total contribution of 67.45%, while the contribution of abrasive flowrate in affecting the responses was 16.47%.The nozzle-workpiece stand-off was the least significant factor affecting the studied responses. Hence it is pooled with experimental error (Table-4). However an indepth analysis was essential in identifying the effects of interactions among various machining parameters.

Table-4. Pooled ANOVA.

Source	SS	DoF	MS	F	% Contribution
A	0.1746	2	0.087	13.459	67.45
B	0.0287	2	0.014	2.209	11.07
D	0.0426	2	0.021	3.286	16.47
Error	0.0130	2	0.006		5.01
Total	0.2587	17			100

4. TESTING OF OPTIMAL LEVEL OF PARAMETERS

The optimal parameter setting was identified by grey incidence analysis as: waterjet pressure-300 MPa, traverse rate- 100 mm/min, stand-off- 1 mm and abrasive flow rate- 250 g/min. The responses obtained with predicted optimal setting was compared with those obtained with the initial setting of parameters (waterjet pressure-300 MPatraverse rate- 125 mm/min, stand-off- 1 mm and abrasive flow rate- 250 g/min). The initial settings of parameters correspond to the cutting conditions in trial number 8 producing the largest value of GRG. A considerable improvement was observed in both surface finish (14.32%) and kerf angle (30.8%) as shown in Table-5, validating the approach used for parameter design.

Table-5. Validation of predicted optimal AWJM parameter setting.

Responses	Initial parameter setting	Optimal parameter setting	% Improve-ment
SR(μm)	1.326	1.136	14.32881
KA(deg)	7.922	5.482	30.8003
Parameter settings	A_3 $B_2C_1D_3$	A_3 B_1 C_1D_3	

5. CONCLUSIONS

The study presents an analysis of abrasive waterjet machining of Al7075/Al_2O_3 composite. Grey incidence method was used to identify the optimal AWJM parameter setting for better values of surface finish and kerf angle. Taguchi's L9 orthogonal array was used for conducting the machining trials with two replications and following conclusions were drawn.

- The grey incidence method was used to find the optimal AWJM condition for Al7075/Al_2O_3composite as: waterjet pressure- 300MPa, traverse rate- 100 mm/min, stand-off- 1 mm and abrasive flow rate- 250 g/min.
- The quality index (GRG) values represent the quality characteristics (surface roughness and kerf angle) as a single entity. The near optimal setting of parameters was observed in trial number 8 (waterjet pressure-300MPa,traverse rate- 100 mm/min, stand-off- 2 mm and abrasive flow rate- 200 g/min), displaying a maximum value of GRG (0.80).
- Waterjet pressure was found out as the primary and most significant parameter affecting SR and KA with a total contribution of 67.45%, while the contribution of abrasive flowrate in affecting the responseswas 16.47%.
- Significant improvements in quality characteristics were observed (surface roughness-14.32% and kerf angle- 30.8%), hence validating the approach in the experimental domain.

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