OPTIMIZATION OF ABRASIVE WATER JET MACHINING PROCESS PARAMETERS USING TAGUCHI GREY RELATIONAL ANALYSIS (TGRA)

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Abstract- Abrasive Water Jet Machining (AWJM) is a versatile machining process primarily used to machine hard and difficult to machine materials. The objective of this paper is to optimize material removal rate and kerf width simultaneously using AWJM process on INCONEL 718. The process parameters are chosen as abrasive flow rate, pressure, and standoff distance. Taguchi Grey Relational Analysis is opted because of multi response optimization.

Keywords- AWJM, Grey Relational Analysis, Process Parameters, S/N Ratio, And Taguchi Method.

I. INTRODUCTION

Abrasive water jet (AWJ) cutting is a non-traditional cutting process that employs high-pressure water for producing high velocity stream, entrained with abrasive particles for a wide variety of materials ranging from soft to hard materials.

It is a versatile process that can be employed in many manufacturing applications such as cutting, milling, cleaning, and surface treatment and offers certain unique benefits like negligible heat affected zone in cutting process, high degree of maneuverability, and less machining force exertion.

II. PRINCIPLE

In this process a focused stream of abrasive particles carried by high pressure water or air at a velocity of about 150 - 300 (m/sec) are made to impinge on the work surface through a nozzle and the work material is removed by erosion by the high velocity abrasive particles. The abrasive particles should have irregular shape and consist of sharp edges. The abrasive particles are directed onto the work piece through a nozzle [4].

Table I Characteristics of different variables

Medium	Air, Water, CO_2, N_2
Abrasive	SiC, Al_2O_3 (of size 20µ to 50µ)
Flow rate of abrasive	1 to 4 lb/min
Velocity	150 to 300 m/min
Pressure	10 to 55 kpsi
Nozzle size	0.07 to 1 (mm)
Material of nozzle	Stainless steel, Sapphire
Nozzle life	12 to 300 hr
Standoff distance	0.25 to 15 mm (8mm generally)
Work material	Non Metals like glass, ceramics, and granites. Metals and alloys of hard materials like germanium, silicon, etc.
Part application	Drilling, cutting, de-burring, cleaning

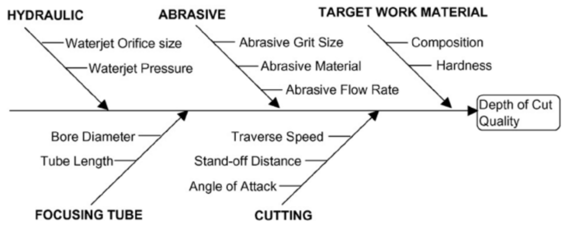

Fig.1 Parameters influencing the AWJM cutting process [6]

III. LITERATURE SURVEY

W. Koenig, CH. Wulf, P. Grass, H. WIllerscheid [5] found that the cut surface quality is dependent upon process parameters such as water jet pressure, feed rate, nozzle diameter, standoff distance and material thickness during WJM of FRPs.

P. J. Singh, W. L. Chen, J. Munoz [7] experimentally studied the effect of traverse speed, water jet pressure, abrasive flow rate and size, size of water orifice and mixing tube on AWJ cut, surface finish for different materials (aluminium, steel, glass and rubber). It was found that better surface finish is obtained at the top part of the cut surface of lower water jet pressure and by increasing abrasive flow rate decreasing traverse speed.

Ramulu and Arola [8] conducted an experimental investigation to study the effect of machining parameters on the surface roughness (R_a) and kerf taper in AWJM of graphite/epoxy laminates. Taguchi method (TM) and analysis of variance (ANOVA) indicated that grit size and standoff distance have the most significant influence on Ra. Abrasive flow rate and water jet pressures have the least influence on Ra at any machining depth.

M. A. Azmir, A.K. Ahsan, A. Rahmah, M.M. Noor, and A.A. Aziz [9] conducted an experiment on the optimization of AWJM on Kevlar with multiple performance characteristics using GRA. They conclude that the performance characteristics of the AWJM process namely hydraulic pressure, abrasive mass flow rate, standoff distance and traverse rate are improved together by using GRA.

M. A. Azmir1, A.K. Ahsan, A. Rahmah has performed experimental analysis on AWJM to assess the influence of surface roughness (R_a) and keft taper ratio (T_R) of aramid fiber reinforced composites using Taguchi's method and Analysis of Variance (ANOVA). They find traverse rate to have the most significant effect on surface roughness (R_a) and keft taper ratio (T_R).

I. Conner, M. Hasish, M. Ramulu investigated the AWJM of thin aerospace structural sheets of graphite/epoxy composites, INCOLEL, titanium and aluminium alloy. It was found that increasing the traverse rate for a fixed water jet pressure, garnet abrasive size, and abrasive flow rate increases Ra. Bottom kerf width decreases with an increase in traverse speed. However, the rate of decrease becomes less about increasing abrasive flow rate.

M. Ramulu,P. Posinasetti, M. Hasish critically reviewed and evaluated the AWJ drilling models through the Mathematical modelling. It was found that the water pressure, abrasive flow rate and drilling time significantly affected the dimensions and accuracy of the drilled holes.

Ersan Aslan, N. Camuscu, B. Birgoren have optimized cutting parameters (speed, feed, depth of cut) on two performance measures-flank wear and surface roughness in hard turning of steels with ceramic tools. This was achieved by using Taguchi techniques. The combined effects were then studied using ANOVA.

M.A. Azmir, A.K. Ahsan conducted experimental investigation to study for surface roughness and kerf width of Kevlar machined by AWJM. They found that the type of abrasive being used has the most significant on kerf width.

Khan and Haque studied the effect of different types of abrasive materials during AWJM. It was found that garnet abrasives produced the smallest kerf width followed by aluminium oxide and silicon carbide. Silicon carbide produced the maximum kerf width compared to aluminium oxide and garnet due to its higher hardness. It was also observed that the kerf width increases with the increase in water pressure and stand-off distance and decreases with the increase of feed rate. The kerf taper was found to be higher at a higher standoff distance and feed rate, but smaller at a higher pressure.

N. K. Jain, V. K. Jain, K. Deb carried out optimization of AWJM process parameters (water jet pressure, nozzle diameter, traverse speed, mass flow rate of water and abrasive flow rate) using genetic algorithm for material removal rate.

M.Joseph Davidson, K. Balasubramanian, G. R. N. Tagore have predicted surface roughness of flow-formed alloy by using design of experiments. The effects of the main parameters were studied and a mathematical model developed on this basis.

T. U. Siddiqui, M. Shukla used a hybrid Taguchi and response surface method approach for optimization of surface finish in AWJM of Kevlar composites. It was found that quality level and water jet pressure were the most significant factors affecting R_a in comparison to abrasive flow rate.

Siddiqui and Shukla presented simultaneous optimization of multiple performance characteristics namely surface roughness and kerf taper in AWJ cutting of aerospace grade Aramid composites using the Taguchi's quality loss function. A considerable improvement in performance characteristics is obtained at the optimized parameter settings as compared to the initial settings.

Yu Zhong presents a comprehensive study on the depth of cut in AWJ cutting when a controlled nozzle oscillation technique and a multipass cutting technique are jointly used with a view to increase the cutting performance. They find that multipass cutting operations can not only increase the total depth of cut, but also yield superior performance over the single pass cutting.

IV. TAGUCHI GREY RELATIONAL ANALYSIS (TGRA)

Taguchi's method is an efficient tool for the design of high a quality manufacturing system; it is employed when the number of parameters is high. Dr. Genichi Taguchi, a Japanese engineer has developed a method based on orthogonal arrays (OA). In this method quality is measured by the deviation of a characteristic from its target value.

A loss function is developed from this deviation. Uncontrollable factors which are also known as noise cause such deviation and result in loss. Taguchi method seeks to minimize the noise since the elimination of noise factor is impractical and so a parameter called signal to noise ratio (S/N) is defined.

To solve multiple performance characteristic problems, the Taguchi method is coupled with Grey Relational Analysis (GRA). In GRA experimental data are first normalized in the range of zero to one. Grey relational coefficients are calculated to represent the correlation between the ideal and the actual normalized data.

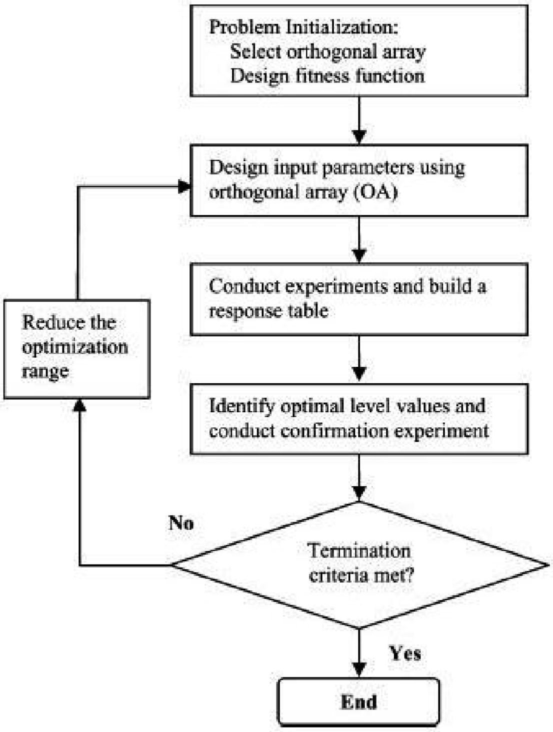

Fig.2 Flow chart of Taguchi's method [6]

V. CONTROLLABLE PARAMETERS

The possible controllable parameters of AWJM are water jet orifice size, water jet pressure, abrasive grit size, abrasive material, abrasive flow rate, traverse rate, standoff distance, angle of attack, composition of work piece.

From the above a full factorial experimental set consisting of abrasive flow rate, pressure and standoff distance as process parameters considering each at 3-levels with all possible combinations leading to a total of 27 experiments is chosen. The process parameters range is specified in Table II.

Table II Range of process parameters

Parameters	Symbol	Level 1	Level 2	Level 3
Abrasive flow rate (lb/min)	(A)	2.7	2.85	3
Pressure (k psi)	(B)	30	40	50
Standoff distance (mm)	(C)	3	4	5

Selection of the particular orthogonal array from the standard OA depends on the number of factors, levels of each factor.

Based on the above values and the required minimum number of experiments to be conducted (27), the nearest OA fulfilling this condition is L_{27} (3^{13}). It can accommodate a maximum three number of control factors, each at three levels with 27 experiments.

All 27 experiments are conducted at 90^0 jet impingement angle only. The specimen is weighed before and after the experimentation. The ratio of the volume difference to total cutting time gives the volumetric material removal rate.

a) Checking and preparing the AWJ machine ready for performing the machining operation.
b) Performing cutting operation on specimens to ensure a lower kerf width and higher MRR.
c) Calculating the weight of the specimen before and after machining, for the calculation of MRR.
d) Kerf width is calculated after experimental for every cut.

VI. EXPERIMENTATION

The equipment used for machining the samples is DWJ Flying Arm CNC abrasive water jet cutting machine equipped with KMT model of water jet pump with the designed pressure of 3800 bar (55000psi) and rated discharge of 2.3l/min. The machine is equipped with a gravity feed type of abrasive hopper, an abrasive feeder system, a pneumatically controlled valve and a work table with dimension of 1600mm×2100mm. For the nozzle assembly, it has an orifice of 0.25mm diameter of sapphire jewel. The abrasives were delivered using compressed air from a hopper to the mixing chamber and were regulated using a metering disc. All the cutting experiments were performed on INCONEL 718 material and are single pass experiments conducted by choosing standoff distance of 3mm and the jet impact angle of 90^0. Granite sand abrasives were used as abrasives.

Fig.3 Nozzle of AWJM

The kerf width was measured with the profile projector of magnification x10 and a least count of 0.02 mm. Kerf width of each cut was measured at three different places for accurate evaluation and the specimen is weighed before and after the experimentation.

Table III Response for the input parameters

S. No	A	B	C	MRR (mm^3/min)	Kerf width (mm)
1	2.7	30	3	779.14	2.04
2	2.7	30	4	810	2.14
3	2.7	30	5	825.42	2.18
4	2.7	40	3	993.6	1.8
5	2.7	40	4	939.6	1.7
6	2.7	40	5	880.2	1.6
7	2.7	50	3	1053.2	1.54
8	2.7	50	4	978.75	1.4
9	2.7	50	5	958.5	1.36
10	2.85	30	3	808.13	2.1
11	2.85	30	4	770.89	2.18
12	2.85	30	5	804.41	2.24
13	2.85	40	3	955.8	1.8
14	2.85	40	4	955.8	1.82
15	2.85	40	5	982.8	1.84
16	2.85	50	3	1012.5	1.6
17	2.85	50	4	985.5	1.58
18	2.85	50	5	985.5	1.52
19	3	30	3	763.44	2.1
20	3	30	4	782.06	2.05
21	3	30	5	782.06	2.06
22	3	40	3	912.6	1.62
23	3	40	4	977.4	1.8
24	3	40	5	972	1.82
25	3	50	3	924.75	1.42
26	3	50	4	951.75	1.46
27	3	50	5	924.75	1.4

From table IX it can be seen that the highest value of GRG is obtained in the 7th row, which is related to optimal process parameters. The optimal parameters are abrasive flow rate 2.7lb/min, pressure 50kpsi, and standoff distance 3mm. At these parameters we observe optimum outputs as MRR 1053.2 mm^3/min and kerf width 1.54mm.

VII. MINITAB

MINITAB is a powerful statistical software package used in the areas of mathematics, statistics, economics, sports and engineering. It is highly interactive software which makes entering data, conducting regression analysis, ANOVA analysis, designing experiments using DOE, performing Taguchi analysis, drawing control charts for processes, performing reliability/survival tests, multivariate tests, plotting time series plots, etc. very easy and time saving. It is the best tool for data driven quality improvement programs. In this project, MINITAB (version 17) has been used for ANOVA analysis and for plotting various graphs.

Table IV Analysis of Variance (ANOVA) for S/N ratios

Source	DOF	Adj SS	Adj MS	F-Value	P-Value
Abrasive flow rate	2	0.012329	0.006165	6.78	0.006
Pressure	2	0.645868	0.322934	355.33	0.000
Nozzle tip distance	2	0.001699	0.000850	0.93	0.409
Error	20	0.018176	0.000909		
Total	26	0.678073			

Table V Response values for S/N ratios

Levels	Abrasive Flow Rate(lb/min)	Pressure(kpsi)	Standoff distance(mm)
1	-5.079	-8.812	-5.323
2	-5.735	-4.942	-5.598
3	-5.565	-2.625	-5.458
Delta	0.656	6.186	0.275
Rank	2	1	3

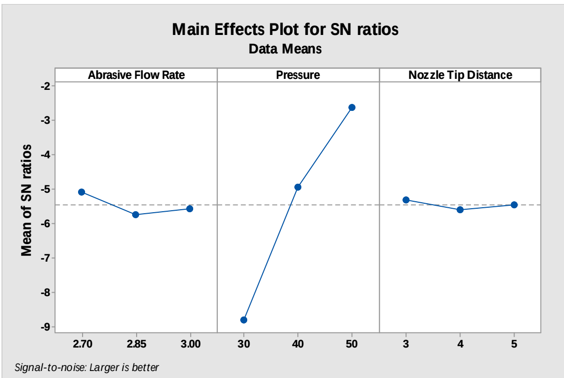

Fig.3 Main Effects Plot for S/N ratios

Table VI Comparison of S/N ratio values

$\eta_{predicted}$ (dB)	-1.298
$\eta_{conformation}$ (dB)	-1.362

A main effect plot is a plot of the mean response values at each level of a design parameter or process variable, this plot can be used to compare the relative strength of the effects of the various factors. The sign and magnitude of a main effect plot would give information on the following:

- The sign of a main effect gives the direction of the effects starting average response value increases or decreases.
- The magnitude gives the strength of the effect.

From the above graphs, it can be seen that optimal conditions obtained from the graph are abrasive flow rate 2.7lb/min, pressure 50kpsi and standoff distance 3mm.

Referring to table VII the S/N ratios for three levels can be calculated using Grey Relational Grade based on below formula.

$$\eta = -10 \log_{10}\left[(1/n)\sum_{i=1}^{n} y_i^{-2}\right]$$

Table VII Summary of S/N ratios

Factor	Level 1 (Db)	Level 2 (Db)	Level 3 (Db)
Abrasive flow rate (A)	-5.079	-5.735	-5.565
Pressure (B)	-8.812	-4.942	-2.625
Standoff distance (C)	-5.323	-5.597	-5.459

The individual optimum conditions are: abrasive flow rate level 1 (2.7lb/mm), pressure level 3 (50kpsi), and standoff distance level 1 (3mm). Thus the overall optimum conditions are A1-B3-C1 combination.

Table VIII Optimum set of control factors

Factors/Levels	Abrasive Flow Rate(A) (lb/min)	Pressure(B) (kpsi)	Standoff Distance(C) (mm)
Optimum value	2.7	50	3

VIII. VERIFICATION

The predicted value for S/N ratio is obtained using the below formula.

From table VIII the following calculations are done:

$$\eta_{predicted} = Y + (\overline{A1} - Y) + (\overline{B3} - Y) + (\overline{C1} - Y)$$
$$= \overline{A1} + \overline{B3} + \overline{C1} - 2Y$$
$$= [(-5.079) + (-2.625) + (-5.323)] - [2 \times (-5.865)]$$
$$\eta_{predicted} = -1.298 \text{ dB}$$

Therefore, the predicted average for optimum condition is -1.298 dB.

A confirmation test is performed with the obtained optimum cutting parameters (Abrasive flow rate 2.7lb/min, pressure 50kpsi, Standoff distance 3mm). The values are taken for a single trial and the S/N ratio is calculated for this condition. The GRG = 0.855 and S/N = -1.362.

From table VI predicted S/N ratio is nearest to the confirmation test S/N ratio; this explains that the obtained parameters are optimal.

CONCLUSION

The following conclusions can be drawn from the results of the present work:

- The optimal parameter values are abrasive flow rate at 20.41 gm/sec, pressure at 344.7Mpa and standoff distance at 3mm. At these parameters the values of MRR and kerf width are 1053.2 mm^3/min and 1.54mm respectively.

- It is shown that the performance characteristics of the AWJM process, namely water jet pressure, abrasive flow rate and standoff distance are improved together by using Taguchi Grey Relational Analysis.

- From ANOVA it is found that water jet pressure has more significant effect on kerf width and MRR rather than abrasive flow rate and standoff distance.

- The predicted S/N ratio is nearest to the conformation test S/N ratio; this explains that the TGRA process adopted for optimization of parameters is accurate.

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Table IX Grey relational coefficient (GRC) and relational grade (GRG) for each experiment

X_i^* -Normalized value

S. No	MRR	KW	MRR X_i^*	KW X_i^*	MRR Δ	KW Δ	MRR GRC	KW GRC	GRG	S/N Ratio
1	798.2	2.04	0.121	0.227	0.879	0.773	0.363	0.391	0.378	-8.457
2	810	2.14	0.161	0.114	0.839	0.886	0.373	0.361	0.367	-8.707
3	825.2	2.18	0.214	0.068	0.786	0.932	0.389	0.349	0.369	-8.66
4	993.6	1.8	0.79	0.5	0.206	0.5	0.709	0.5	0.604	-4.375
5	939.6	1.7	0.608	0.614	0.392	0.386	0.561	0.564	0.562	-5.001
6	880.2	1.6	0.403	0.727	0.597	0.273	0.456	0.647	0.551	-5.170
7	1053.2	1.54	1	0.795	0	0.205	1	0.71	0.855	-1.362
8	978.75	1.4	0.743	0.955	0.257	0.045	0.661	0.917	0.789	-2.063
9	958.5	1.36	0.673	1	0.327	0	0.605	1	0.802	-1.913
10	808.13	2.1	0.154	0.160	0.846	0.841	0.372	0.373	0.372	-8.584
11	770.89	2.18	0.026	0.068	0.974	0.932	0.340	0.349	0.345	-9.264
12	804.41	2.24	0.141	0	0.859	1	0.368	0.333	0.351	-9.102
13	955.8	1.8	0.664	0.5	0.336	0.5	0.598	0.5	0.549	-5.209
14	955.8	1.82	0.664	0.477	0.336	0.523	0.598	0.489	0.543	-5.297
15	982.8	1.84	0.757	0.455	0.243	0.545	0.673	0.478	0.576	-4.797
16	1012.5	1.6	0.860	0.727	0.140	0.273	0.781	0.647	0.714	-2.928
17	985.5	1.58	0.766	0.75	0.234	0.25	0.682	0.667	0.674	-3.426
18	985.5	1.52	0.766	0.818	0.234	0.182	0.682	0.733	0.707	-3.006
19	763.44	2.1	0	0.159	1	0.841	0.333	0.373	0.353	-9.042
20	782.06	2.08	0.064	0.182	0.936	0.818	0.348	0.379	0.364	-8.783
21	782.06	2.06	0.064	0.205	0.936	0.795	0.348	0.386	0.367	-8.704
22	912.6	1.62	0.515	0.705	0.485	0.295	0.507	0.629	0.568	-4.913
23	977.4	1.8	0.738	0.5	0.262	0.5	0.657	0.5	0.578	-4.756
24	972	1.82	0.720	0.477	0.280	0.523	0.641	0.489	0.565	-4.962
25	924.75	1.42	0.557	0.932	0.443	0.068	0.530	0.88	0.705	-3.036
26	951.75	1.46	0.650	0.886	0.350	0.114	0.588	0.815	0.701	-3.079
27	924.75	1.4	0.557	0.955	0.443	0.045	0.530	0.917	0.723	-2.813

★★★