Single Response optimization of abrasive waterjet machining process by Taguchi's parameter design approach

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Abstract: The emerging non-conventional technology,Abrasive WaterJet Machining (AWJM) isused for machining hard material parts that are extremely difficult to machine by conventional machining processes.The objective of the paper is to obtain an optimal setting of process parameters for thebest surface finish. The effects of pressure, stand-off distance and orifice size on surface roughness and their subsequent optimal settings have been accomplished using Taguchi's parameter design approach. The results indicate that the selected process parameters significantly affect the surface finish of machined parts on abrasive waterjet machine.Surface finish is well influenced by two process parameters — water jet pressure and nozzle diameter size of the AWJM.

Keywords: AWJM, Taguchi's Parameter Design Approach, optimization, nozzle size, abrasive particle size,SR, ANOVA.

I. Introduction

Abrasivewaterjet cutting is innovative and relatively new technology.Micro erosion is the basic principle at work in waterjet cutting process. A narrow stream of high-velocity water mixed with abrasive particles gives relatively inexpensive and environment friendly production with thereasonably high material removal rate. In a relatively short period of time, abrasive waterjet machining has become one of the leading manufacturing technologies.A high-pressure pump produces water at pressures up to 4000 bar.This high-pressure water is delivered to a cutting head.Then it is passed through a very small orifice which is placed in a nozzle.The constant volume of water travelling through a reduced cross-sectional area of orifice causes particles to rapidly accelerate thus producing an extremely thin, high-velocity jet of water.The pressure of thenarrow stream of water impacting on a small area of workpiece cuts through any material placed in front of it.AWJM finds its applications in aerospace industry, architecture,engineering, metal fabrication etc.The manufacturers have to acknowledge that considerable advantages can be obtained by controlling product quality at its design stage instead of at manufacturing stage in order to provide satisfaction to customers and deliver in a competitive international market. Figure 1 show theexperimentalsetup of abrasive waterjet machine-OMAX 2626 Unit used in the present study.

Figure 1: OMAX 2626 Unit-Experimental set up

Hashish (1984)studied cutting of ductile material with high-velocity Jet.A data was set to study effects of abrasive waterjet parameters- water jet pressure,water jet diameter,abrasivematerial,particlesize,abrasive flow rate,and traverse rate-on depth & quality of cuts produced.This is basic idea of off-line quality control and Taguchi's method is one of the most comprehensive and effective systems of off-line quality control.Taguchi parameter design approach has been adopted to accomplish optimal settings and analyze effects of pressure, standoff distance and orifice size on surface roughness(Byrne, 1987).

Taguchi has built upon W.E. Deming's observation that 85% of poor quality is attributable to themanufacturing process and only 15% to the worker(Roy, 1990). Thus his attempt had been focused on to develop robust manufacturing systems that are insensitive to daily and seasonal variations of environment, wear of machine etc. Taguchi recommends a three-stage process to achieve desired product quality by design—system design, parameter design and tolerance design. System design helps to identify working levels of design parameters; parameter design seeks to determine parameter levels that provide thebest performance of product or process under study; while tolerance design further fine-tunes the results of parameter design. The optimum condition is selected so that the influence of uncontrollable factors causes minimum variation to system performance. Orthogonal arrays, analysis of variance and signal to noise analysis are essential tools of Taguchi’s parameter design (Ross, 1996).

II. Literature Review

Ramuluand Arola(1994)developed a mathematical model to predict surface roughness and kerf taper in terms of cutting parameters.The resultsrevealed the influence of cutting parameters on surface roughness.Chen and Siores(2003) investigated characterization of different materials cut surfaces using a scanning electron microscope.The effect of abrasive particles distributed in the jet on striation formation was studied.Lemma et al.(2005)optimized the AWJ cutting process by using nozzle oscillation technique. It was found that striation and roughness on workpiece surface were the most persistent problems that stand in the way of wider applications of technology in theindustry. Akkurt et al.(2004)studied the effect of feed rate on surface roughness in AWJC applications. The study was focused on thesurface roughness of AWJ cut surfaces.Valicek et al.(2007)made anexperimental analysis of irregularities of metallic surfaces generated by abrasive waterjet.Surface roughness was quantitatively evaluated by using contactless optical measurement.Based on root mean square (RMS), roughness evaluation of worst cut surface zone, thedimensionless statistical parameter can be calculated as a basic quantity for AWJ surface cut characterization.Orbanicand Junkar(2008)described theanalysis of striation formation mechanism in AWJC.The striation on surface cut with AWJ is a characteristic phenomenon which is present when cutting with high traverse velocities for particular material type and thickness.Shukla and Tambe(2010)studied predictive modelling of surface roughness and kerf widths in abrasive water jet cutting.The results demonstrated that the Neural Network model was able to successfully model and predict the surface roughness matching with experimental results. A different approach considering thevarying local impact angle in AWJ turning was presented to predict the finaldiameter by Manu andBabu(2009).The flow stress of workpiece material was determined using an experiment involving same abrasive and workpiece materials.The adequacy of this model was examined through AWJ turning tests under various process parameter combinations.The final diameters predicted by the model are found to be in good agreement with the experimental results.Selvamet al. (2012)studiedthe effects of process parameters on surface roughness in abrasive waterjetcutting of aluminium.Deris et al.(2017)presented a hybridizationmodel of support vector machine (SVM) and grey relational analysis (GRA) in predicting surface roughness value. Other researchers e.g. Kundu J. et al. (2016) Kumar M. et al. (2016) used Taguchi approach with GRA for optimization for different manufacturing processes.They found that traverse speed was a most influential factor that affected surface roughness while standoffdistance was aleast influential factor that affected surface roughness.Iqbalet al.(2011)developed thefull factorial design of experiments in order to investigate effects of different parameters on thesurface finish for AISI 4340 (highstrength low alloy steel,hardened to 49 HRC) andaluminium 2219.Axinite and Kong (2009)developed an integrated monitoring method tosupervise waterjet machining. It was able to detect process mal-functionsviz. jet penetration, nozzle clogging etc. By adjusting cutting conditionsviz. feed, speed etc. improved accuracy and quality of machined surfaces wereobtained.Korat et al.(2014) reported on AWJM researchrelating to improving performance measures, monitoring and control of the process, optimizing the process variables.Perec(2016)did work on abrasive suspension water jet cutting optimization using orthogonal array design.Kumar and Singh(2016) revealedthe design of experiments method by taguchiapproach.L-27 orthogonal array was selected for the experimentation purpose.

The literature survey reveals that only a limited work has been done onperformance measures of AWJM process.The objective of the present study is to obtain optimal settings of AWJM process parameters— jet pressure, stand-off distance and nozzle diameter— to yield best surface finish while cutting mild steel. Taguchi's parameter design approach has been used to accomplish this objective.

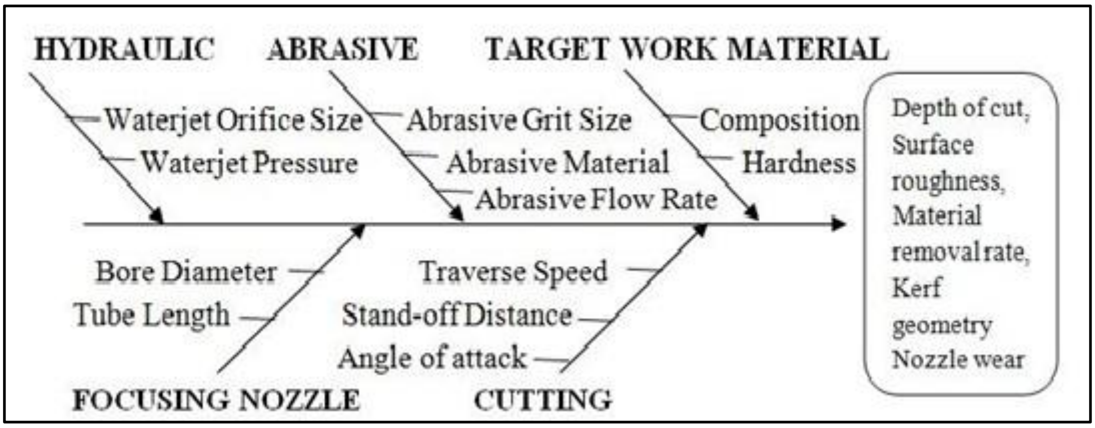


Figure 2: Process parameters influencing the AWJ cutting process

The Fishbone Diagram as given by Figure 2 shows various parameters influencing the process. The intensity and efficiency of the machining process depend on these several AWJ process parameters. They are hydraulic, work material, abrasive and cutting parameters.

III. Materials and Methods

In the present work, mild steel is machined on AWJM. A mild steel plate with dimensions 8*350*450mm was used to themachine on abrasive waterjet machine.Mild steel has a lot of applications in themanufacturing of automobile and machine parts.Three abrasive waterjet machining parameters—jet pressure, stand-off distance, and orifice size— were selected based on the review of theliterature. The non-linear relationship among process parameters can be revealed only if more than two levels of the parameters are considered. Thus each selected parameter was analyzed at three levels.MINITAB-17software was used for the design and analysis purpose in this study. Table 1 reports the three levels of each selected process parameter to be used for revealing their effects on thesurface finish of machined parts.

Table 1: Process parameters with their values at 3 levels

Parameters designation	Process Parameters	Level 1	Level 2	Level 3
A	Pressure (bar)	1861.6	2620.1	3309.6
B	Stand-off Distance (mm)	2.0	3.5	5.0
C	Orifice size (mm)	5.56	6.35	7.14

SELECTION OF ORTHOGONAL ARRAY (OA)

The degree of freedom (DOF) is the number ofindependent components which are free to vary. For aparameter, it is calculated as the number of levelsminus one. There are three input parameters in thisstudy each with 3 levels. So each parameter has 2DOF. It was also decided to investigate the effects of three two-factor interactions in addition to the main effects of the selected parameters. Each interaction has 2*2=4 DOF. The total degrees of freedom of the experiment thus become18. Now we have to select anorthogonal array which is a 3 level design and has more than 18. So, Taguchi's L27 orthogonalarray with six input variables and 3 interactions was selected. Using linear graphs and triangular tables as proposed by Taguchi, interacting columns were identified and then parameters and interactions were assigned to specific columns accordingly as given in Table 2.

Table 2: L-27orthogonal array with process parameters and interactions

Run	1	2	3	4	5	6	7	8	9	10	11	12	13
	A	B	A*B	A*B	C	A*C	A*C	B*C	D	E	B*C	F	-
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

IV. Analysis and Discussion of Results

Each trial was simply repeated two times and thus 54 specimens were prepared and their surface roughness values were measured with surface roughness tester having a least count of 0.01 micron. The surface tester was prior calibrated.The experimental data for surface roughness is reported in table 3.

Table 3: Experimental data for surface roughness

Trial No.	R_1 (μm)	R_2 (μm)	Average DD (μm)	S/N Ratio (dB)
1	3.66	3.80	3.73	-11.44
2	3.32	3.44	3.38	-10.58
3	3.16	3.24	3.20	-10.10
4	3.67	3.81	3.74	-11.46
5	3.70	3.78	3.74	-11.46
6	3.63	3.81	3.72	-11.41
7	3.85	3.93	3.89	-11.80
8	3.34	3.74	3.54	-11.00
9	3.40	3.68	3.54	-10.98
10	4.80	5.16	4.98	-13.95
11	4.05	4.25	4.15	-12.36
12	4.13	4.21	4.17	-12.40
13	4.37	4.57	4.47	-13.01
14	4.17	4.43	4.30	-13.01
15	3.46	4.06	3.76	-11.53
16	3.95	4.19	4.07	-12.19

17	3.93	4.15	4.04	-12.13
18	4.10	4.18	4.14	-12.34
19	4.87	5.01	4.94	-13.87
20	4.80	4.94	4.87	-13.75
21	4.14	4.30	4.22	-12.51
22	4.55	4.77	4.66	-12.51
23	4.55	4.69	4.62	-13.30
24	4.25	4.33	4.29	-12.65
25	4.93	5.05	4.99	-13.96
26	4.27	4.41	4.34	-12.75
27	4.40	4.58	4.49	-13.05

The surface roughness is a quality characteristic of “smaller the better” type, the S/N ratio for this response is calculated by using Eq. (1).

$$\text{S/N ratio} = -10 \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \qquad (1)$$

The S/N ratios computed for each of twenty-seven trials are reported in Table 3 along with the raw data values for surface roughness.

Figure 3 and 4 show the main effects plot and interaction plot for data means respectively.

Figure 3: Main effects plot for data means

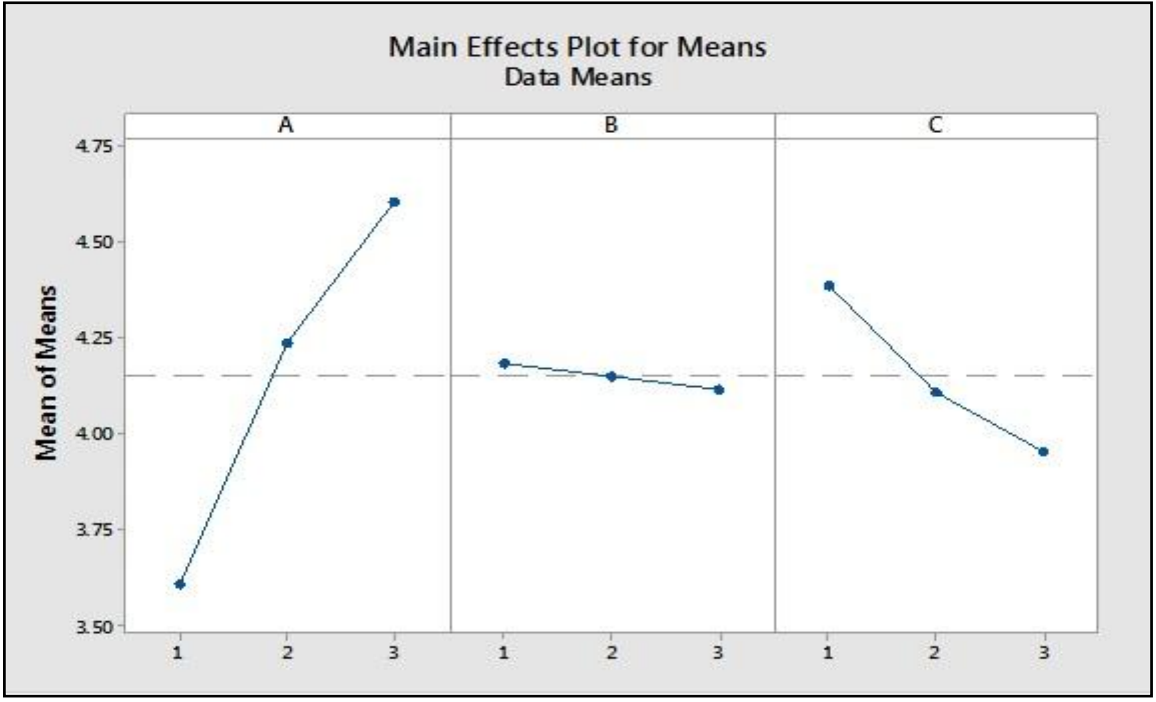
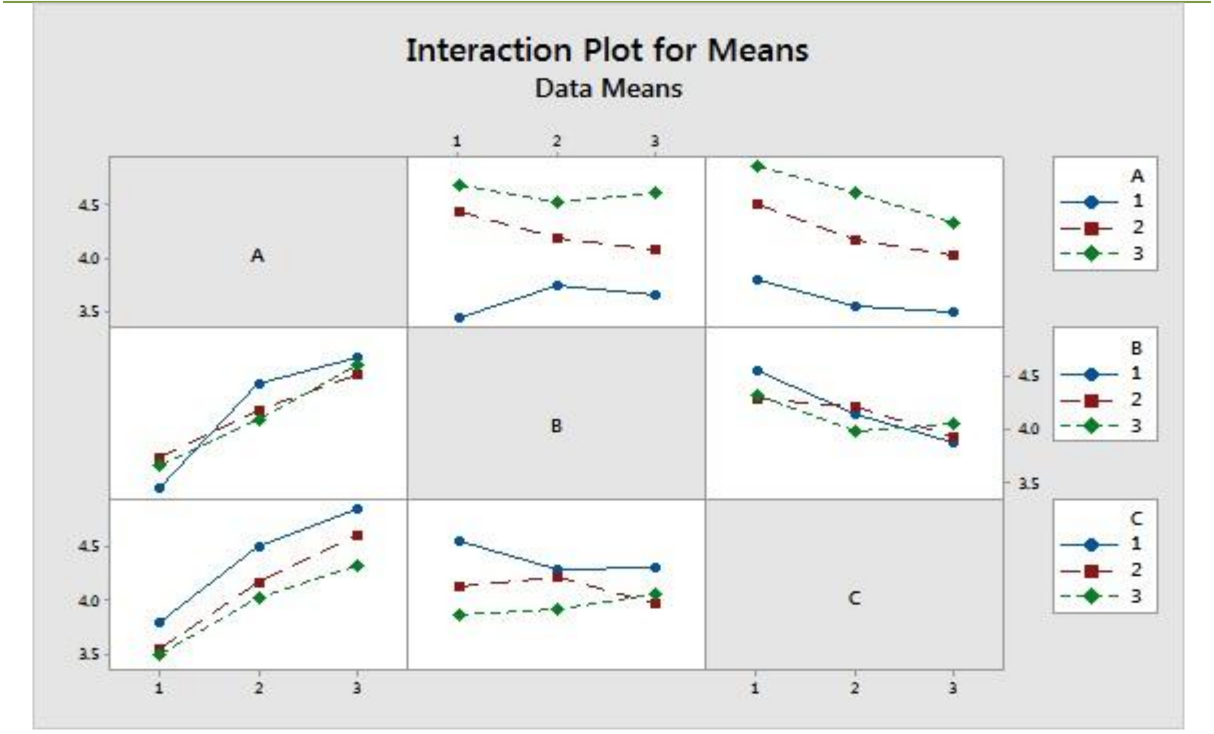


Figure 4: Interaction plot for data means



The analysis of variance (ANOVA) is an important statistical tool to ascertain the significance of the selected process parameters in affecting the selected response. A parameter is declared significant at a stated level of significance which is complementary to the confidence level.

Here, 95% confidence level or 5% level of significance has been taken which caters to the requirements of most of the engineering products. Table 4 and Table 5 report ANOVA results for raw data and S/N data respectively.

Table 4: Analysis of Variance (ANOVA) for Means

Source	DF	Seq.SS	Adj.SS	Adj.MS	F	P
A	2	4.54344	4.54334	2.27107	49.08	0.000
B	2	0.02001	0.02001	0.01000	0.22	0.810
C	2	0.86267	0.86267	0.43134	9.32	0.009
A*B	4	0.34984	0.34984	0.08746	1.89	0.206
A*C	4	0.05870	0.05870	0.01468	0.32	0.859
B*C	4	0.25357	0.25357	0.06339	1.37	0.326
Residual Error	8	0.37025	0.37025	0.04628		
Total	26	6.45839				

Table 5: Analysis of Variance (ANOVA) for S/N Data

Source	DF	Seq.SS	Adj.SS	Adj.MS	F	P
A	2	20.7004	20.7004	10.3502	55.90	0.000
B	2	0.0436	0.0436	0.0218	0.12	0.890
C	2	3.6259	3.6259	1.8130	9.79	0.007
A*B	4	1.6812	1.6812	0.4203	2.27	0.150
A*C	4	0.1257	0.1257	0.0314	0.17	0.948
B*C	4	1.0831	1.0831	0.2708	1.46	0.299
Residual Error	8	1.4811	1.4811	0.1851		
Total	26	28.7409				

The analysis reveals that the jet pressure and orifice size are significant at 95% confidence level in both the ANOVAs since their 'P' value is less than 0.05. Thus, both these factors significantly affect the mean value and the variance around the mean of the surface roughness. The third factor, stand-off distance, is insignificant in affecting the response and can be kept at some economical setting.

It is evident from figure3 that surface roughness is minimum at first level of jet pressure (A) and third level of nozzle diameter (C). The effect of stand-off distance (B) is not significant. The interaction effects of parameters are also not significant and the plots of the same are thus not included.

Figure 4 reveals that the highest points correspond to the best settings of the process parameters for minimum surface roughness are the first level of jet pressure and third level of orifice size. Thus the raw data, as well as S/N data plots, envisage the same optimal settings of the significant factors.

Figure 5: Main effects plot for S/N ratios

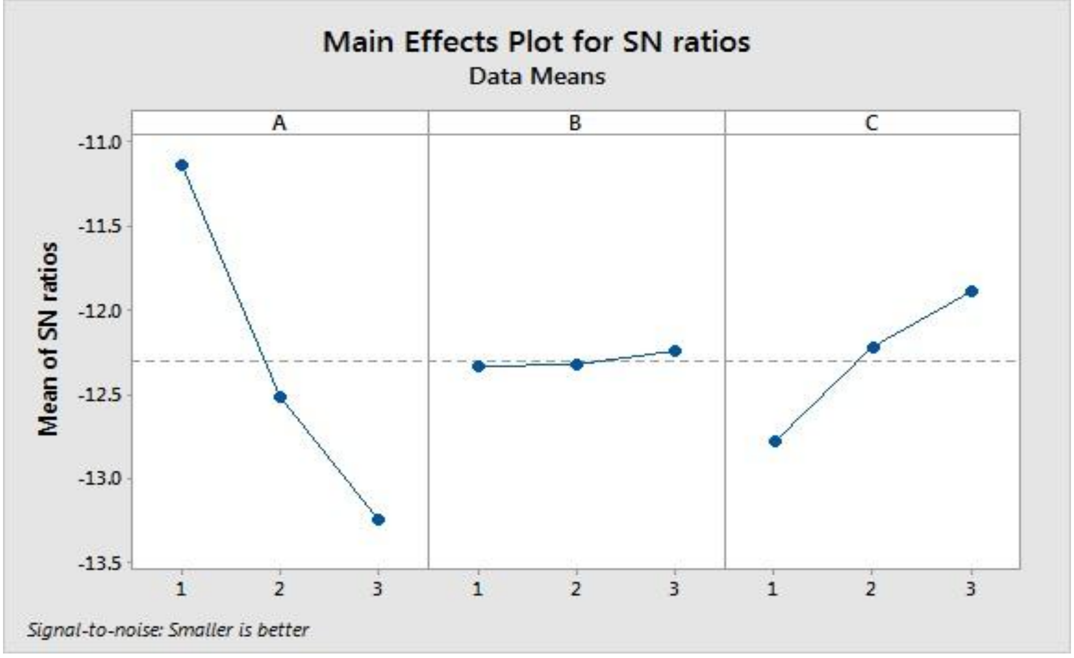
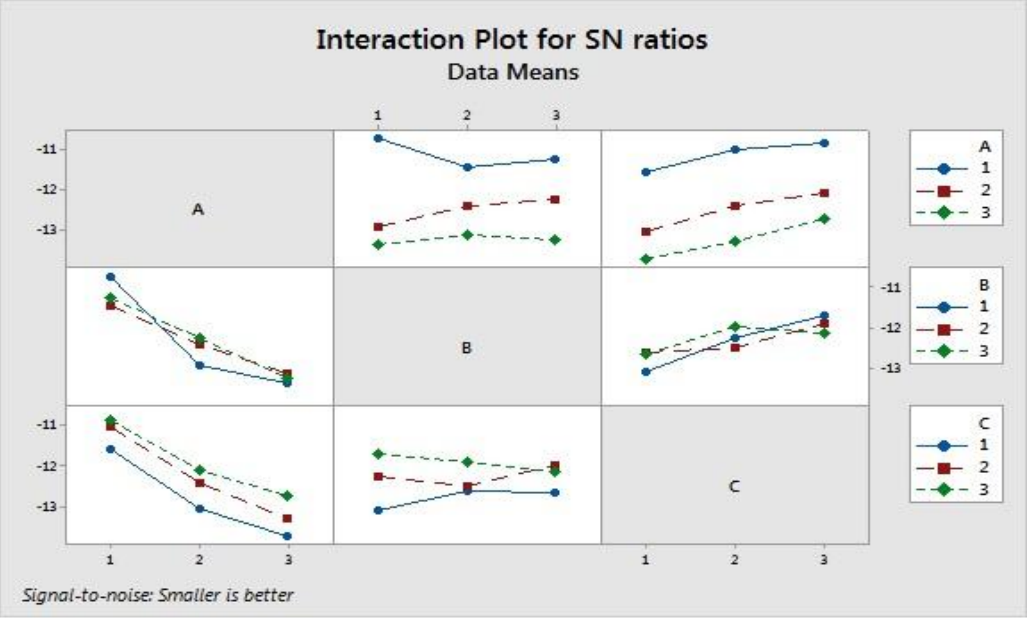


Figure 5 and 6 represent the main effects plot and interaction plot for S/N ratios respectively.

Figure 6: Interaction plot for S/N ratios



ESTIMATION OF PREDICTED OPTIMAL VALUE

The predicted optimal surface roughness is calculated by using Eq. (2). $\acute{T}$isoverall mean of the population and it comes out to be 4.162 µm.

So, $\mu SR = \acute{T} + (\acute{A}_1 - \acute{T}) + (\acute{C}_3 - \acute{T})$ *(2)*

$= \acute{A}_1 + \acute{C}_3 - \acute{T} = 3.400$ µm

The above-predicted value of surface roughness is only a point estimate. There is 50% chance of true average of surface roughness being either smaller than this or larger than this. So, the estimate is expressed in terms of a range through confidence interval. The 95% confidence interval for the confirmation experiments is calculated by using Eq. (3).

$$CI_{CE} = \sqrt{F_a(1, f_e).V_e\left\{\frac{1}{n_{eff}} + \frac{1}{R}\right\}} \tag{3}$$

Here f_e(error degree of freedom)= 8

$F_{0.05}(1, 8) = 5.32$ (Tabulated value at 95% confidence level)

V_e(error variance)= 0.04628

$n_{eff} = \frac{N}{1 + Total degrees of freedom involved in estimation of mean}$

N= total number of experiments = 54

Hence, $n_{eff} = 54/5$

R = sample size = 2

Putting all values in equation 4

$CI_{CE} = 0.382$

The 95% confidence interval for µSR is 3.018 µm < µSR<3.782 µm

The confirmation experiment is the final step in verifying the conclusions drawn based on Taguchi's parameter design approach. The optimum conditions are set for significant factors, the insignificant factors are set at economic levels, and a selected number of tests are run under constant specified conditions. The average of the results of confirmation experiment is compared with the anticipated average based on parameters and levels tested. The confirmation experiment is a crucial step and is highly recommended by Taguchi to verify the experimental conclusions.Table 6 shows the confirmatory experimental results. The mean value of SR has been found to be within confidence intervals.

Table 6: Confirmatory Experimental results

Response (units)	Predicted Value	CI_{CE}	Experimental Value
SR (µm)	3.400	3.018 < µSR < 3.782	3.242

V. Conclusions

The following results have been carried out from the experimental study:

1. The input process parameters jet pressure and nozzle diameter are found to be significant factors in both the ANOVAs, hence these mainly affect mean and variance of surface roughness.
2. During Abrasive Water Jet Machining of material mild steel, standoff distance and all the three interactions are found to be insignificant to the response SR.
3. The optimum value of surface roughness was obtained at jet pressure=1861.6 bars; stand-off distance=5.0mm and nozzle diameter=7.14mm.
4. The optimal predicted value comes out to be µSR=3.400 µm and the confidence interval is 3.018 µm < µSR <3.782 µm.
5. The confirmation experiments are performed at the optimal levels of parameters. Two experiments are performed and their average is taken. The average comes out to be 3.242 µm and it is well contained within the confidence intervals. Hence the predicted optimal setting may be implemented.

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