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Optimization of process parameters of abrasive water jet machining process for Dimension Deviation by Taguchi's parameter design approach

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Abstract: The emerging non-traditional technology, Abrasive water jet machining (AWJM) is used for tough materials that are exceptionally machine by conventional machining processes. In this paper, the cutting performance of AWJM is attained by a narrow high-speed stream, small-scale wearing away process.The optimal setting of process parameters has been achieved for minimum dimensional deviation while machining Mild steel on Abrasive Water-Jet machine. The effects of pressure, stand-off distance and orifice size on thedimensional deviation and their subsequent optimal settings have been consummated using Taguchi's parameter design approach. The outcomes indicate that the particular process parameters considerably affect the dimensional deviation of machined parts on abrasive water jet machine.The dimensional deviation is minimum at pressure level 3 (3309.6 bars) standoff distance level 1 (2.0 mm) nozzle level size 1(5.56 mm). The outcomes are also further tested by confirmation experiments.

Keywords: ANOVA, Abrasive particle size, Abrasive Water Jet Machining, dimensional deviation, Taguchi's Parameter Design Approach,nozzle size.

I. Introduction

Abrasive Water jet cutting is an innovative and relatively new technology.Micro erosion is the basic principle at work in waterjet cutting process. The mechanism of erosion of material depends upon the nature of the working material- ductile or brittle. For the ductile material, the material removed in volume but in the case of brittle material, cracking propagation around the striking point removed the material. For water jet machining process both phenomenaoccur but it depends upon which dominate for a particular material. 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 is travelling through a reduced cross sectional area of orifice. The particles present in water rapidly accelerate through small orifice thus producing an extremely thin, high-velocity jet of water. The pressure of the narrow stream of water impacting on a small area of workpiece cuts through any material placed in front of it. The advanced process, AWJM provides a high-quality material cutting with a great exterior finishing and therefore it is beneficial in the manufacturing of several components in aerospace, automotive, surgical equipment's and defence sector industries due to its performance characteristics.The AWJM process has several machining parameters, i.e., abrasive flow rate,striking water pressure, transverse speed,abrasive grit size, nozzle standoff distance, etc., which affect the output factors [i.e. material removal rate (MRR), kerf top width, taper angle (TA) and surface quality (SQ)].To obtain the optimum parameter setting for machining process is most important to attain desired quality. Few researchers have reported the effects of the process parameters on the performance characteristics of the Abrasive Water Jet Machining (AWJM) process.The used experimental set up of Abrasive Water Jet Machining (AWJM) is shown in figure 1.

Figure 1: OMAX 2626 Unit –AWJM Experimental Set up

Hashish (1984) studied machining of ductile material with high-velocity Jet. A data was set to establish relation of abrasive water jet parameters- water jet pressure, water jet diameter, abrasive material, abrasive flow rate,particle size, and traverse rate-on depth & quality of cuts produced. This is fundamental idea of off-line quality enhancement and Taguchi's method is one of the utmost wide-ranging and effective systems of off-line quality enhancement. Taguchi parameter design approach has been adopted to accomplish optimal settings and analyze effects of pressure, standoff distance and orifice size on surface quality (Byrne, 1987).

Taguchi has based upon W.E. Deming's perception that 85% of low quality is inferable from the manufacturing procedure and just 15% to the specialist (Roy, 1990). Consequently, his endeavour had been centered on to create powerful manufacturing frameworks that are insensitiveto regular varieties of the condition, wear of machine and so forth. Taguchi prescribes a three-stage procedure to accomplish desirable item quality by design/outline —system design, parameter outline and resilience outline. Framework configuration recognizes working levels of outline parameters; parameter configuration looks to decide parameter levels that give the best execution of product or process under examination; while resilience configuration additionally calibrates the after effects of parameter plan. The ideal condition is chosen with the goal that the impact of uncontrollable factors makes least variety tosystemperformance. Orthogonal arrays, ANOVA and signal-to-noise ratio investigation are basic statistical tools of Taguchi's parameter design (Ross, 1996). A number of researchers have been implemented Taguchi approach in different advanced manufacturing processes [Kundu J. and Singh H. (2016) and Aggarwal A., Singh H. (2005)]. The present article is an attempt to implement Taguchi approach for AWJM process.

II. Literature Review

Ramulu and Arola (1994) developed a mathematical model to calculate SR and KT in terms of machining parameters. The results revealed the effect of critical parameters on surface roughness. Chen and Siores (2003) investigated characterization of unlike materials cut faces by means of a SEM. The influence of grit particles scattering in the jet on pattern formation was studied. Akkurt et al. (2004) considered the influence of feed rate on SR in AWJC applications. The study was motivated on the surface quality of abrasive water jet cut surfaces. Lemma et al. (2005) optimized the AWJ cutting process by means of nozzle fluctuation practice. It was found that striation and roughness on work piece surface were the major problems that play role in the wider applications of technology in the industries. Valicek et al. (2007) made an experimental investigation of irregularities of upper metallic surfaces generated by AWJM. Surface roughness was quantitatively estimated by using contactless optical measurement. Based on RMS, roughness evaluation of poorest cut surface region, the dimensionless statistical parameter can be designed as elementary measurements for AWJ surface cut description. Orbanic and Junkar (2008) described the study of striation development mechanism in AWJC. The striation on surface cut with AWJ is a trademark marvel which is available when cutting with high navigate speeds for specific material type and material thickness. An alternate approach considering the fluctuating nearby impact anglein AWJ turning was displayed to estimate the last distance by Manu and Babu(2009). Shukla and Tambe (2010) studied analytical modelling of kerf widths and surface roughness in AWJM. The results demonstrated that the Neural Network model was able to successfully estimate the surface roughness matching with experimental results. The flow stress of workpiece material was resolved utilizing a trial including same grating and workpiece materials. The ampleness of this model was analyzed through AWJ turning tests under different process parameter mixes. The last distances across anticipated by the model are observed to be in great concurrence with the trial comes about.Selvam et al. (2012) studied aluminium material to estimate the influences of process parameters on SR in abrasive water jet cutting. Deris et al. (2017) concluded a hybridization model of support vector machine (SVM) and grey relational analysis in estimating surface roughness value. Iqbal et al. (2011) investigate effects of different parameters on the surface finish for AISI 4340 and aluminium 2219 by developing the full factorial design of experiments. Axinite and Kong (2009) developed an unified observing method to control water jet machining. It was able to detect process mal-functions viz. nozzle clogging,jet penetration etc. By regulating cutting conditions, enhanced quality and accuracy of machined surfaces were obtained. Korat et al. (2014) reported on abrasive water jet machining research involving to refining performance measures, observing and control of the process, improving the process variables. DerzijaBegic et al. (2015) investigated the surface roughness in AWJM. Two types of surface textures were used at the beginning of cut for a smooth surface and second texture at the bottom line of the cut for rough surface characteristics. Perec (2016) did work on abrasive suspension water jet cutting optimization using orthogonal array design. Kumar and Singh (2016) revealed the design of experiments method by Taguchi approach. The L-27 orthogonal array was chosen for the experimentation purpose.

The literature survey reveals that only a limited work has been done on performance measures of AWJM process. The main objective of the present study is to achieve optimal sets of AWJM process parameters—jet pressure, stand-off distance and nozzle diameter— to yield best dimensional accuracy while cutting mild steel. Taguchi's parameter design method was used to achieve this objective. Figure 2 shows various parameters influencing the process.

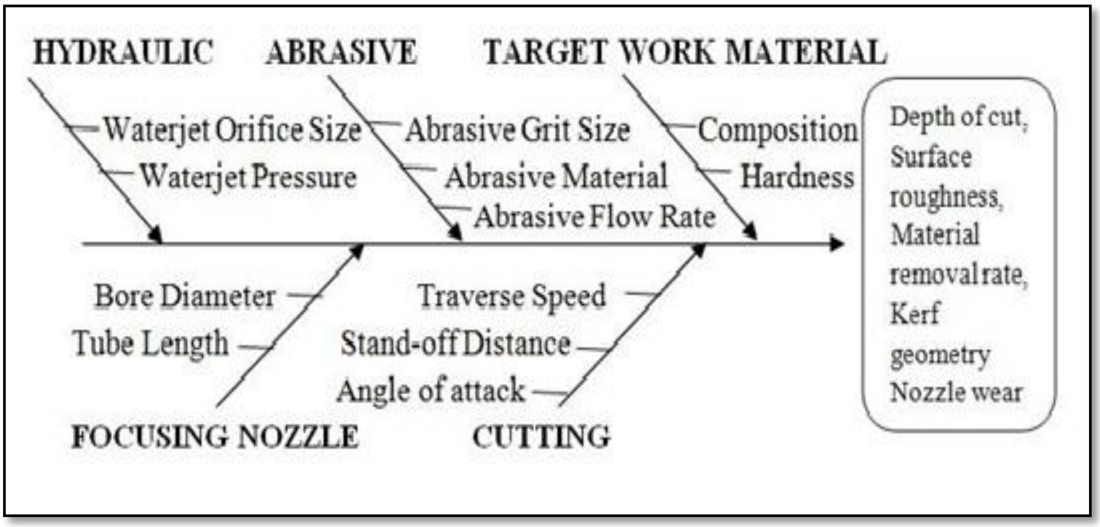

Figure 2: Process parameters influencing the AWJ cutting process

III. Materials and Methodology

A mild steel plate with dimensions 350mm×450mm×8mm was machined on abrasive water jet machine.Mild steel is low carbon steel having a lot of applications in thefabrication of vehicle and other advanced machine parts. Three abrasive water jet machining parameters—jet pressure, stand-off distance, and orifice size— were selected based on the review of theliterature and some trial experiments conducted by the authors. Anon-linear relationship among process parameters was developed. Thus each selected parameter was investigated at three levels. Table 1 reports the three levels of each selected process parameter to be used for revealing their effects on thedimensional deviation of machined parts.

TABLE 1: INPUT PROCESS PARAMETERS WITH THREE LEVELS

Parameters	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)

It is also decided to investigate the effects of two-factor relations in addition to the sound effects of the selected parameters. The total degrees of freedom (DOF) of the experiment is eighteen and the nearest possible OA satisfying the inequality constraint is L_{27}. This array specifies 27 experimental runs and has 13 columns. Using linear graphs and triangular tables as proposed by Taguchi, interrelating columns were recognized and then parameters and interactions were allocated to specific columns respectively as given in Table 2.

TABLE 2: L_{27} ORTHOGONAL ARRAY WITH PROCESS PARAMETERS AND INTERACTIONS ASSIGNED TO COLUMNS

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. Experimentation, Analysis and Discussion

A Mild Steel plate was machined on abrasive water jet machine. Each trial was simply repeated and thus 54 specimens were machined and their dimensional deviation values were measured with height gauge having the least count of 0.01 micron. The height gauge was prior calibrated.Experimental data for dimensional deviation is reported in Table 3. The dimensional deviation is a quality characteristic of "smaller the better" type, the S/N ratio for this response is calculated by using Eq. (1).

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

Where y_1, y_2,..........$y_n$are values of dimensional deviation for a trial condition repeated 'n' times. The S/N ratios calculated for each of 27experimental trials are reported in Table 4 beside with the raw data values for dimensional deviation.

The mean reaction alludes to the normal estimation of performance characteristics for every parameter at various levels. The normal estimations of dimensional deviation for every parameter at levels 1, 2 and 3 are computed and given in Table 4. The principle impacts of process parameters on the response characteristic when the procedure parameters change starting with one level then onto the next are additionally given in Table 4 and are plotted in Figure 3. The normal estimations of S/N proportions of the response characteristic for different parameters at various levels are reported in Table 5 and plotted in Figure 4.

TABLE 3: EXPERIMENTAL DATA FOR DIMENSIONAL DEVIATION

Trial No.	R_1 (mm)	R_2 (mm)	Average DD (mm)	S/N Ratio (dB)
1	0.030	0.050	0.040	27.695
2	0.050	0.070	0.060	24.318
3	0.080	0.100	0.090	20.862
4	0.040	0.060	0.050	25.850
5	0.070	0.070	0.070	23.098
6	0.070	0.090	0.080	21.871
7	0.030	0.070	0.050	25.376
8	0.060	0.080	0.070	23.010
9	0.100	0.100	0.100	20.000
10	0.030	0.030	0.030	30.457
11	0.050	0.070	0.060	24.318
12	0.070	0.070	0.070	23.098
13	0.050	0.030	0.040	27.695
14	0.060	0.100	0.080	21.675
15	0.100	0.100	0.100	20.000
16	0.050	0.030	0.040	27.695
17	0.100	0.060	0.080	21.675
18	0.100	0.100	0.100	20.000
19	0.030	0.030	0.030	30.457
20	0.040	0.060	0.050	25.850
21	0.030	0.050	0.040	27.695
22	0.050	0.030	0.040	27.695
23	0.040	0.040	0.040	27.959
24	0.060	0.080	0.070	23.010
25	0.030	0.030	0.030	30.457
26	0.040	0.060	0.050	25.850
27	0.050	0.070	0.060	24.318

Overall mean of dimensional deviation, T_{DD} = 0.060 mm

TABLE 4: Average Values and Main Effects of Dimensional Deviation

Parameters designation	Average Values of dimensional deviation (mm)			Main Effects (mm)	
	L_1	L_2	L_3	L_2-L_1	L_3-L_2
A	0.068	0.063	**0.046**	-0.005	-0.017
B	**0.052**	0.063	0.064	0.011	0.001
C	**0.039**	0.062	0.079	0.023	0.017

Figure 3: Effect of input process parameters on dimensional deviation (raw data)

Table 5: S/N mean values and main effects

Process Parameters	S/N average values			Main Effects	
	L_1	L_2	L_3	L_2-L_1	L_3-L_2
A	23.72	24.20	27.15	0.48	2.95
B	26.19	24.44	24.44	-1.75	0
C	28.36	24.33	22.38	-4.03	-1.95

It is marked from Figure 3 that dimensional deviation is lowest at thethird level of jet pressure (A), thefirst level of stand-off distance(B)and thefirst level of nozzle diameter(C). The interaction effects of parameters are not significant and the plots of the same are thus not included.

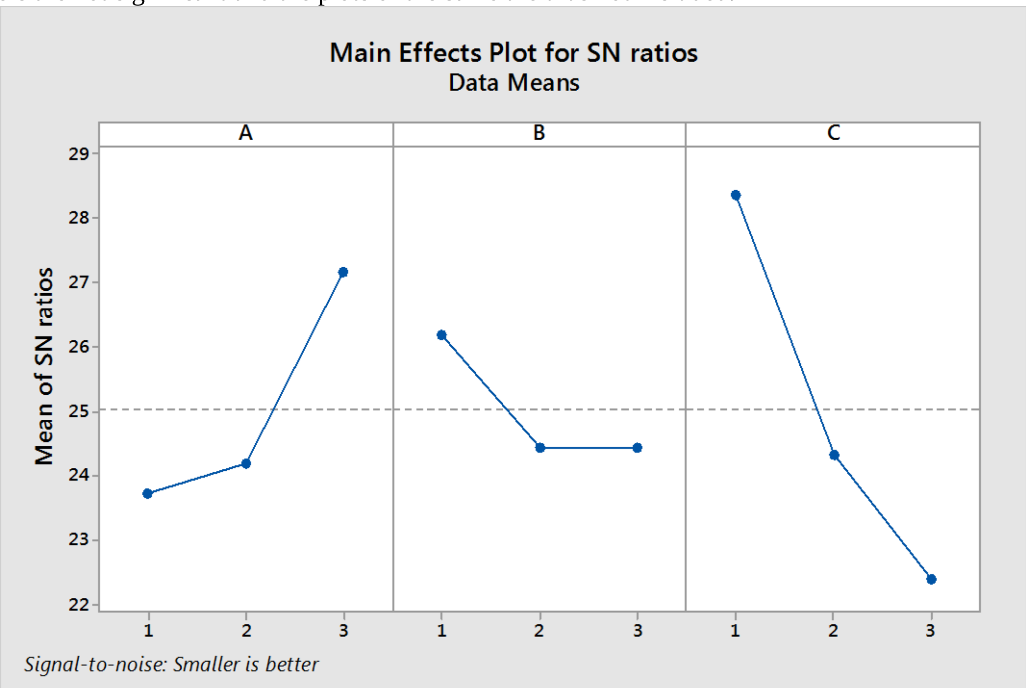

Figure 4: Effect of Process parameters on dimensional deviation (S/N ratio)

The signal to noise ratio plots in Figure 4 reveal that the highest points correspond to the best settings of the process parameters for minimum dimensional deviation and these are the same as depicted in Figure 3.Thus the S/N data and raw data plots envisage the same optimal settings of the significant factors.

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. Tables 6 and 7 report ANOVAs for raw data and S/N data respectively. The analysis reveals that all three factors jet pressure (A), Stand-off distance (B) and orifice size (C) are significant at 95% confidence level in both the ANOVAs since their ‘p’ value is less than 0.05. Thus, all these factors significantly affect the average value and the variancenearby the mean value.

TABLE 6: Analysis of Variance (ANOVA) for Means

Source	DF	Seq.SS	Adj.SS	Adj.MS	F	P
A	2	0.002822	0.002822	0.001411	19.54	0.001
B	2	0.000822	0.000822	0.000411	5.69	0.029
C	2	0.007267	0.007267	0.003633	50.31	0.000
A*B	4	0.000289	0.000289	0.000072	1.00	0.461
A*C	4	0.000844	0.000844	0.000211	2.92	0.092
B*C	4	0.000178	0.000178	0.000044	0.62	0.664
Residual Error	8	0.000578	0.000578	0.000072		
Total	26	0.012800				

TABLE 7: Analysis of Variance (ANOVA) for S/N Data

Source	DF	Seq.SS	Adj.SS	Adj.MS	F	P
A	2	62.174	62.174	31.0872	18.94	0.001
B	2	18.469	18.469	9.2347	5.63	0.030
C	2	167.372	167.372	83.6859	50.99	0.000
A*B	4	4.074	4.074	1.0186	0.62	0.661
A*C	4	12.140	12.140	3.0350	1.85	0.213
B*C	4	3.905	3.905	0.9762	0.59	0.677
Residual Error	8	13.130	13.130	1.6412		
Total	26	281.264				

Table 8: Process Parameters and their levels for minimum Dimensional Deviation

Parameters	Process Parameters	Optimal Levels
A	Pressure	3 (3309.6 bar)
B	Standoff distance	1 (2.0 mm)
C	Nozzle Size	1 (5.56 mm)

Prediction of Optimal Value:

Table 8 reports the optimal settings of the significant factors—jet pressure, stand-off distance and orifice size. The average values of dimensional deviation corresponding to theoptimal settings of the process parameters are taken from Table 4. The predicted optimal dimensional deviation is calculated by using Eq. (2). The value of $\acute{T}$ is taken from Table 3 as the overall mean of dimensional deviation.

$\mu_{DD} = \acute{T} + (\acute{A}_3 - \acute{T}) + (\acute{B}_1 - \acute{T}) + (\acute{C}_1 - \acute{T})$ ...*(2)*

$= \acute{A}_3 + \acute{B}_1 + \acute{C}_1 - 2\acute{T}$

= 0.046 + 0.052 + 0.039 – 2(0.060)

= 0.017mm

The above-predicted value of dimensional deviation is only a point estimate. There is 50% chance of true average of dimensional deviationbeing 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).

μ_{DD}: optimum predicted value of dimensional deviation.

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

Where f_e(error DoF) = 8

$F_{0.05}(1, 8) = 5.3177$ (Tabulated value at 95% confidence level)

$V_{e=}$ Error variance = 0.000072

$n_{eff} = \frac{N}{1+Total\ DoF\ used\ in\ estimation\ of\ mean}$

N= total number of experiments = 27

R = sample size = 3

CI_{CE}= 0.0159mm

After putting all values in equation (3), the 95% confidence interval for µDD is 0.0011mm < μ_{DD}< 0.0329mm.

The final step i.e. confirmation experiment inauthenticating the conclusions drawn based on Taguchi's parameter design method. The optimum conditions are setting of levels for significant factors andthree experiments are conducted under constant specified conditions. The mean of the results of confirmation experiment is matched with the anticipated meanbased on different levels of parameter tested. In present experimental study average value of dimensional deviation (DD) is 0.026mm which is in between the predicted range of DD.

V. Conclusions

The following conclusions can be carried out from theexperimental study:

1. The effects of jet pressure, stand-off distance and orifice size on thedimensional deviation and their subsequent optimal settings were accomplished by Taguchi’s parameter design method.
2. During AWJM of mild steel material, all three process parameters jet pressure, stand-off distance, orifice size are found significant and all the three interactions are found to be insignificant to the response dimensional deviation.
3. Optimal settings of several process parameters to estimate optimal dimensional deviationarejet pressure=3309.6 bars; stand-off distance=2.0mm, nozzle size=5.56mm.
4. The expected range of dimensional deviation brings out to be 0.009mm< µDD< 0.041mm and predicted value of dimensional deviation is 0.025mm.
5. Two experiments for dimension deviation are performed and their average is taken. The average comes out to be 0.026mm and it is well contained within the confidence intervals. Hence the predicted optimal setting may be implemented.

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