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Optimization of Process Parameters of Abrasive Jet Machining on Hastelloy through Response Surface Methodology

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Abstract: The demand for micro products is rapidly increasing in chemical, marine and aerospace industries. The super alloys which have high strength and corrosion resistance properties play a major role. Hastelloy which is difficult to machine by the conventional processes can be machined by using AJM. Hastelloy C276 sheet of thickness 1mm has been drilled on the AJM test rig using variable process parameters. In this paper optimization of process parameters of Abrasive Jet Machining of Hastelloy C276 by RSM methodology is presented. The values obtained in RSM Analysis were compared with the Analysis of Variance (ANOVA). Various levels of experiments are conducted using L15 orthogonal array for both MRR and KERF.

Key words: AJM, Hastelloy C276, MRR, KERF, RSM

1. Introduction

Hastelloy C276 is a Nickel-chromium-molybdenum fashioned combination that is viewed as the most flexible consumption safe compound accessible. This amalgam is impervious to the arrangement of grain limit accelerates in the weld heat-influenced zone, in this way making it reasonable for most concoction procedure applications in an as welded condition. Combination C-276 likewise has superb imperviousness to setting, stress-erosion making and oxidizing environments laugh uncontrollably to 1900°F. AJM is a mechanical energy based unconventional machining process used to remove unwanted material from a given work piece. Material fracture occurs due to the impact of high velocity air/ gas stream of abrasive particles on the work piece [6]. Gas used is carbon dioxide or nitrogen or compressed air. The selection of abrasive particles depends on the hardness and Metal Removal Rate (MRR) of the work piece. Most commonly, aluminum oxide or silicon carbide particles are used [4]. Abrasive Jet Machining is used for drilling, deburring, etching, and cleaning of hard and brittle metals, alloys, and non-metallic materials [2]. There are no toxic wastes given off by abrasive water jets, and no oils are necessary in the process of machining [5]. The Major Process Parameters that affects the MRR & KERF in AJM are Gas Pressure, Nozzle diameter, Abrasive mass flow rate, Nozzle tip distance [3].

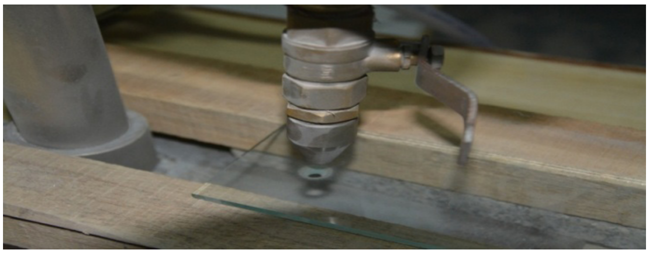


Fig.1: Hole generated by Abrasive jet machining process

Fig. 2: WC Nozzles of various sizes

The material removal rate (MRR) can be defined as the volume of material removed divided by the machining time. Another way to define MRR is to imagine an “instantaneous" material removal rate as the rate at which the cross-section area of material being removed moves through the work piece [1]. The formula used to calculate MRR is

$$MRR= \frac{\rho\pi d2t}{4z} \tag{1}$$

The cut or the hole generated in AJM with a width is called as KERF. The top kerf is wider than the bottom kerf. For maintaining proper KERF the optimal standoff distance is to be maintained.

The formula for kerf is

KERF = Diameter hole at the top-Diameter of the hole at bottom (2)

2. Methodology

Experimental design (DOE) is a useful complement to multivariate data analysis because it generates “structured" data tables, i.e. data tables that contain an important amount of structured variation. This underlying Structure will then be used as a basis for multivariate modeling, which will guarantee stable and robust models. The DOE technique helps to study many factors simultaneously and most economically.

Response surface methodology (RSM) is a combination and collection of mathematical and statistical techniques for empirical model building. By careful design of experiments, the objective is to optimize a response (output variable) which is influenced by several independent variables (input variables). An experiment is a series of tests, called runs, in which changes are made in the input variables in order to identify the reasons for changes in the output response. Two basis methods used in RSM are central composite and Box-Behnken methods. In the present optimization Box-Behnken design is used, which is a type of response surface design that does not contain an embedded factorial or fractional factorial design. For finding the response surface regressions and predictions MINI TAB software is used.

3. Experimentation Work

The experimentation was carried out in St. Martin's engineering college on the AJM test rig. The experiment was done keeping constant pressure of 8kg/cm^2. This has been done as Hastelloy, which is very difficult to be machined at lower pressures. The experimental setup consists of the major components like Air compressor, Air filter, Pressure Regulator and Pressure gauge, Dehumidifier, Mixing Chamber, Nozzle and Arrangement to hold the work piece etc [9].

The variable levels that are considered based on the parameters are, for first variable Abrasive flow rate three levels are taken they are 3.5, 4.5, 5.5 and the units are (g/min), for variable standoff distance three levels are taken (8, 9,10 mm) and for variable Nozzle diameter the three levels taken are (2, 3,4 mm). Pressure of air, Size and Type of abrasive and are kept constant [8]. Experiments are carried out based on Response surface methodology is Box–Behnken design**.** The material used for experimentation is Hastelloy sheet and the Material Removal Rate (MRR) process parameter is the measure of performance. The abrasives used are Silicon Carbide of size 40 microns. The analysis was done using Minitab-17.

Table 1: Machining parameters and their levels

LEVELS	AFR (gm/min)	SOD (mm)	ND (mm)
1	3.5	7	2
2	4.5	8	3
3	5.5	9	4

3.1 Response Surface Regression for Metal Removal Rate

The metal removal rate is calculated based on the standard formulas and obtained the MRR values for 15 experiments based on random order priority. The run orders and the standard orders are established based on design of experiments. The Box-Behnken design matrix of three variables and a response (MRR) is shown in Table 2. The numbers of factors with base runs, total runs with the center points are mentioned below.

3.1.1 Box-Behnken Design for 15 runs

Factors: 3, Replicates: 1, Base runs: 15, Total runs: 15

Base blocks: 1, Total blocks: 1, Center points: 3

Table 2: The Box-Behnken design matrix of three variables and a response (MRR)

Sl.no	ND	SOD	AFR	MRR
1	2	8	3.5	0.019
2	4	7	4.5	0.017
3	3	8	4.5	0.042
4	3	8	4.5	0.042
5	3	9	5.5	0.07
6	2	7	4.5	0.018
7	3	7	3.5	0.052

8	4	8	5.5	0.036
9	3	8	4.5	0.042
10	2	8	5.5	0.02
11	3	7	5.5	0.063
12	4	8	3.5	0.036
13	3	9	3.5	0.042
14	2	9	4.5	0.01
15	4	9	4.5	0.029

3.1.2 Response Surface Regression: MRR (gm/s) vs. AFR, SOD, ND

Based on Box-Behnken design the response surface regression has been developed, and the influence of four variables on response (MRR) is discussed with F-values as shown in Table 3.

Table 3: Analysis of variance table of factors vs. MRR

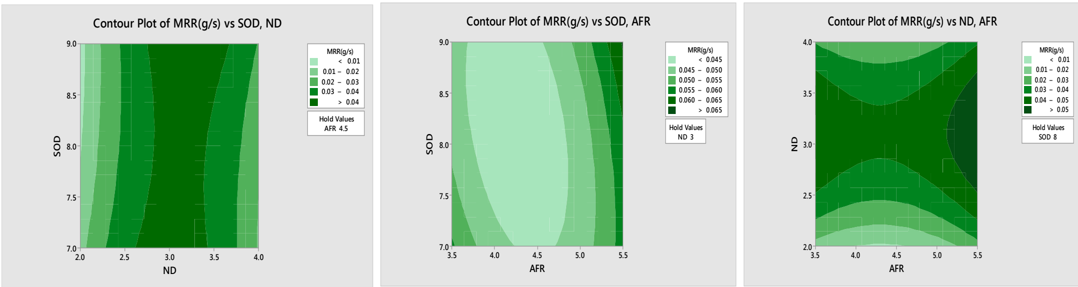
Source	DF	Adj SS	Adj MS	F Value	P Value
Model	9	0.004029	0.00045	10.29	0.01
Linear	3	0.00051	0.00017	3.91	0.088
ND	1	0.000315	0.00032	7.23	0.043
SOD	1	0	0	0	0.985
AFR	1	0.000196	0.0002	4.5	0.087
Square	3	0.003346	0.00112	25.63	0.002
ND*ND	1	0.002554	0.00255	58.68	0.001
SOD*SOD	1	0.000023	2.3E-05	0.52	0.501
AFR*AFR	1	0.000545	0.00055	12.53	0.017
2-Way Interaction	3	0.000173	5.8E-05	1.32	0.365
ND*SOD	1	0.000101	0.0001	2.31	0.189
ND*AFR	1	0	0	0	0.967
SOD*AFR	1	0.000072	7.2E-05	1.66	0.254
Error	5	0.000218	4.4E-05		
Lack-of-Fit	3	0.000218	7.3E-05	*	*
Pure Error	2	0	0		
Total	14	0.004247			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0065968	**94.88%**	85.65%	18.02%

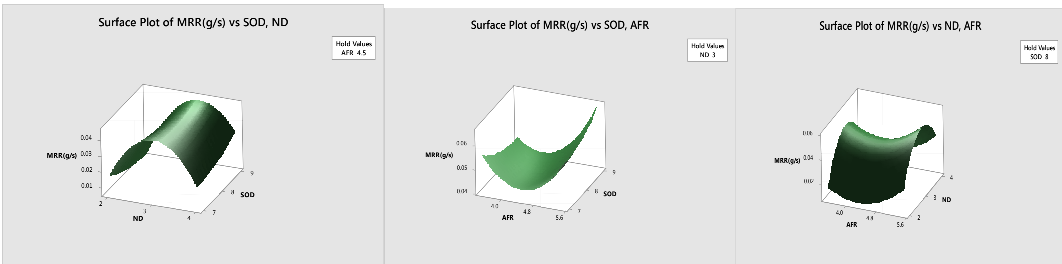
The regression model of response surface is generated based on linear, square and 2-way interactions. According to the model summary it is identified that the R-Square value is 94.88 % (any R-sq value more the 90% is considered as satisfactory regression model). The Regression equation is

$$MRR(g/s) = 0.440 + 0.1246\,ND - 0.0739\,SOD - 0.1380\,AFR - 0.02630\,ND*ND + 0.00249\,SOD*SOD + 0.01215\,AFR*AFR + 0.00501\,ND*SOD - 0.00014\,ND*AFR + 0.00425\,SOD*AFR$$



Graph 1: Contour plot of MRR VS SOD, ND &AFR

From Graph 1 contour plot of metal removal rate vs. AFR, SOD, ND are plotted. It is observed that MRR increases by increase in pressure but the pressure is kept constant for performing the response regression. The influence of AFR, SOD and ND are plotted ,the hold values of AFR (4.5 g/s) SOD (8mm) and ND (3 mm) are identified and the optimal values of parameters.



Graph 2: Representation of surface plot of MRR VS SOD, ND, AFR

The 3D surface plots shows the combined effect of a set of parameters on the response (MRR).The hold values of AFR, SOD, ND for the response are mentioned in Graph 2.

3.1.3 Response optimization: MRR (g/s)

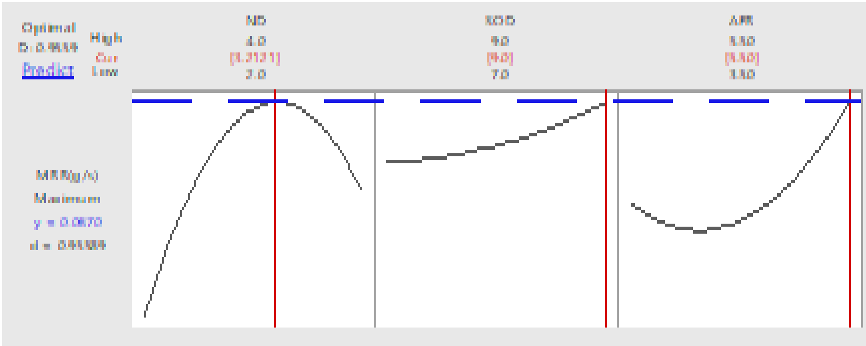
Table 4: Response and its levels

Response	Goal	Lower	Target	Upper	Weight	Importance
MRR(g/s)	Maximum	0.0096	0.0696	1	1	1

As shown in Table 4, the lower, upper and target values of MRR is selected. Multiple Response Prediction has been shown.

Table 5: Representation of parameters and their optimal levels

Solution	ND	SOD	AFR	Fit	Desirability
1	3.21212	9	5.5	0.067	0.955887



Graph 3: Optimization plot shows optimized values of parameters

From optimization plot Graph 3 the optimized parametric values and the ranges of optimization are AFR (5.5 g/min), SOD (9 mm), and ND (4 mm).

3.2 Response surface regression for KERF

The width of cut (KERF) is calculated based on the standard formulas and the difference between top surface diameter and bottom surface diameter. The obtained KERF values for 15 experiments are executed based on random order priority. The Box-Behnken design matrix of three variables and a response (KERF) is shown in Table 4.

3.2.1 Box-Behnken design with 3 factors and 15 runs

Factors: 3, Replicates: 1, Base runs: 15, Total runs: 15

Base blocks: 1, Total blocks: 1, Center points: 3

Table 6: The Box-Behnken design matrix of variables & response (KERF)

SL.NO	ND	SOD	AFR	KERF(mm)
1	4	8	3.5	4
2	2	8	3.5	5
3	4	9	4.5	5
4	2	9	4.5	6
5	4	8	5.5	5
6	3	8	4.5	4
7	2	7	4.5	3.8
8	3	9	5.5	6
9	3	8	4.5	3.8
10	3	9	3.5	5
11	2	8	5.5	4
12	3	7	3.5	6
13	3	7	5.5	6
14	3	8	4.5	4
15	4	7	4.5	6

3.2.2 Response surface regression: KERF (mm) Vs ND, SOD, AFR

Based on Box-Behnken design the response surface regression has been developed, and the influence of four variables on response (KERF) is discussed with F-values as shown in Table 5.

Table 7: Analysis of variance table of factors vs KERF

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	10.81	1.201	6.41	0.027
Linear	3	0.31	0.103	0.55	0.669
ND	1	0.18	0.18	0.96	0.372
SOD	1	0.005	0.005	0.03	0.877
AFR	1	0.125	0.125	0.67	0.451
Square	3	6.693	2.231	11.91	0.01
ND*ND	1	3.00E-04	3.00E-04	0	0.972
SOD*SOD	1	5.846	5.846	31.21	0.003
AFR*AFR	1	1.151	1.151	6.14	0.056
2-Way Interaction	3	3.81	1.27	6.78	0.033
ND*SOD	1	2.56	2.56	13.67	0.014
ND*AFR	1	1	1	5.34	0.069
SOD*AFR	1	0.25	0.25	1.33	0.3
Error	5	0.937	0.187		
Lack-of-Fit	3	0.91	0.303	22.75	0.042
Pure Error	2	0.027	0.013		
Total	14	11.75			

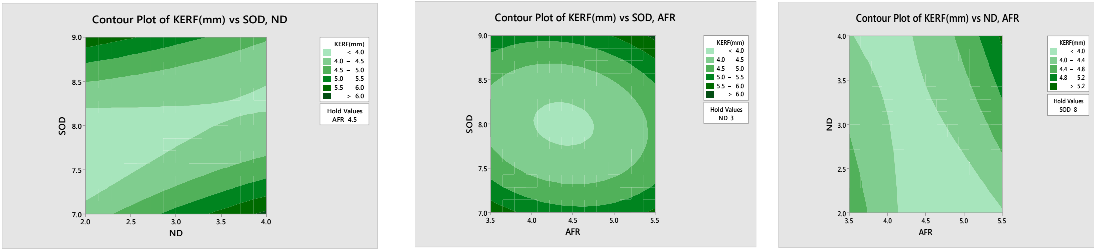
Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.432820	**92.03**%	87.68%	0.00%

The regression model of response surface is generated based on linear, square and 2-way interactions. According to the model summary it is identified that the R-Square value is 92.03 % (any R-sq value more the 90% is considered as satisfactory regression model). The regression equation is

*KERF (mm) = 91.2 + 4.25 ND - 18.83 SOD - 8.40 AFR + 0.008 ND*ND + 1.258 SOD*SOD + 0.558 AFR*AFR - 0.800 ND*SOD + 0.500 ND*AFR + 0.250 SOD*AFR*

From the contour plot of Graph 4 it is observed that the influence of AFR, SOD and ND on KERF. The hold values of AFR (4.5 gm/sec), SOD (8 mm) and ND (3 mm) which affects the width of cut are identified.



Graph 4: Contour plot of KERF VS SOD, ND, and AFR

3.3.3 Response optimization: KERF (mm)

Table 8: Response and its levels

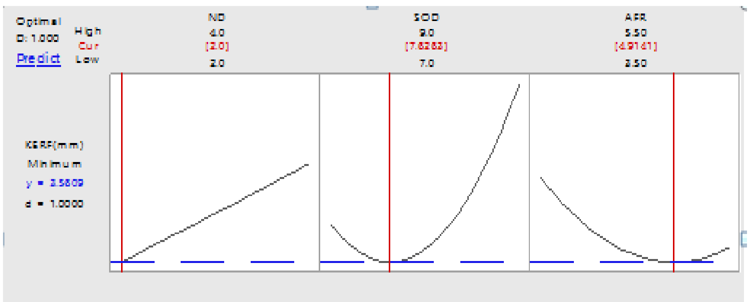
Response	Goal	Lower	Target	Upper	Weight	Importance
KERF(mm)	Maximum	2.6	3.8	6	1	1

As shown in Table 8, the lower, upper and target values of KERF is selected. The Multiple Response Prediction has been shown.

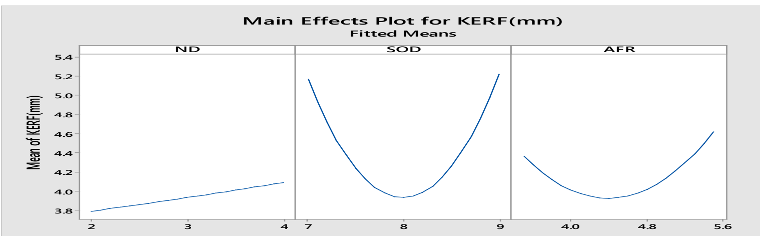
Table 9: Representation of parameters and their optimal levels

Solution	ND	SOD	AFR	Fit	Desirability
1	2	7.62626	4.9141	3.5608	1

The representation of predicted optimal values of parameters, i.e. ND, SOD and AFR with the response (KERF) is shown in Graph 5. Main effect plot of KERF is indicated in Graph 6. Fig 3 shows the hastelloy plates of different thicknesses machined by AJM process.



Graph 5: Plot representation of predicted optimal values of parameters



Graph 6: Representation of main effect plot of KERF

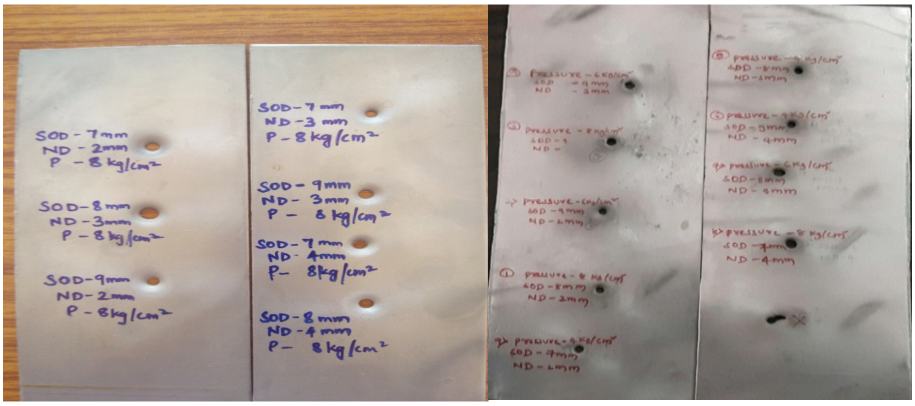


Fig. 3: Hastelloy plates of different thicknesses machined by AJM

4. Conclusion

Response surface methods are implemented on machining of glass, ceramics, composites, Hastelloy by selecting pressure, AFR, SOD,ND as factors and metal removal rate and KERF as objectives. According to the design of experiments 15 experiments are conducted for glass and Hastelloy and 27 experiments are conducted for ceramics and composites. Plots are developed for showing the influence of variables on objectives. Regression equations for both MRR & KERF are developed. The response variable values suitable for machining are also identified. The design and the experiment have been validated as the R-square value should range between (90-100) percent.

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