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Optimization of Process Parameters in Abrasive Jet Drilling Of Hastelloy Using Taguchi Method

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Abstract: *Machining of nickel base Hastelloys is considered as moderate to difficult. During machining, these alloys work harden rapidly, generate high heat during cutting, weld to the cutting tool surface and offer high resistance to metal removal because of their high shear strengths. Abrasive jet machining (AJM) is a non-conventional machining process which is effective in machining hard and brittle materials. Hence to overcome the difficulties in machining of hastelloy by conventional machining process, Abrasive jet machining is employed. During AJM, the influence of process parameters on machining characteristics were studied using Taguchi method and the results were compared using ANOVA technique. The process parameters chosen were air pressure, standoff distance (SOD) and nozzle diameter. AJM performance was measured in terms of MRR and Kerf. In the Taguchi analysis it is observed that the air pressure has largest effect and nozzle diameter has the smallest effect on the material removal rate whereas the Standoff distance (SOD) has large effect and nozzle diameter has the least effect on Kerf. Similar kinds of results were observed when analyzed by ANOVA.*

Key Words: *Abrasive Jet Machining, MRR, Kerf, Hastelloy, Taguchi, ANOVA*

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I. Introduction

In abrasive jet machining, a stream of fine abrasive particles carried by compressed air (or) gas focused through a nozzle and strikes the target surface. The particles coming out of the nozzle with high velocities impinges on the work surface and removes the material from the surface by mechanical erosion. The air (or) gas stream carries both the abrasive particles and the fractured material away from the work area [1-2]. AJM is an effective process for machining hard and brittle metals, alloys, and non-metallic materials (e.g., germanium, silicon, glass, ceramics, and mica). The various operations performed on AJM are drilling, deburring, polishing, etching, and cleaning. In addition to its wide applications at the macro-scale, it has a significant role in micro-machining, especially micro-channels and micro-holes in the manufacture of micro-devices.

A number of experimental investigations have been carried out on AJM process to determine the effect of various input parameters on material removal rate, penetration rate, kerf and on surface finish [3-6]. The experimental research has also involved use of various optimizing techniques [7-11]. The work materials used by various researchers for AJM machining are Alumina Ceramics [11], Glass [12],[6],[4], Silicon Nitride [5] Zirconium dioxide [6], EDM die material [6], Quartz [14], PMMA [14], plaster-of-paris [10], stainless steel [15].

HASTELLOY C276 is a Nickel based super alloy with an addition of chromium, molybdenum and tungsten designed to have excellent corrosion resistance in a wide range of severe environments. The high nickel and molybdenum contents make the alloy resistant to pitting and crevice corrosion in reducing environments while chromium improves resistance to oxidizing media. This alloy is resistant to the formation of grain boundary precipitates in the weld heat-affected zone, thus making it suitable for most chemical process applications in as welded condition. Due to its high temperature strength, resistance to neutron radiation, and perfect anti-oxidation ability, it is widely used in the most severe environments such as chemical processing, pollution control, pulp and paper production, industrial and municipal waste treatment, and recovery of sour natural gas.

Machining of nickel base corrosion and temperature resistant alloys are considered as moderate to difficult. Machining of this alloy through notching is a prominent failure due to high mechanical properties of work piece which results in short tool life and low productivity. During machining these alloys work harden rapidly, generate high heat during cutting, weld to the cutting tool surface and offer high resistance to metal removal because of their high shear strengths.

A review of the literature shows that the great majority of published work is focused on AJM of different materials; however till date hastelloy was not included. Hence the usage of AJM to machine Hastelloy is being done to prevent the excessive heat production and wastage of the material which occur during the conventional methods of machining. The parameters like MRR and Kerf are mostly influenced by process parameters like SOD, ND and Pressure. Hence, AJM has been used for machining of Hastelloy and the MRR and Kerf are optimized by using Taguchi Techniques.

II. Experimentation

2.1 Experimental set up

The experimental work was carried on AJM test rig. The set up is shown in Figure 1**.** Atmospheric air was used as a medium of carrier gas and a compressor with a maximum pressure of 10 bar was used to achieve the desired range of pressure. The silicon carbide abrasives with an average grit size of 60 µm were mixed with an air stream and allowed to pass through the nozzle. The abrasive flow rate was kept constant throughout the machining process. Nozzles were made using Tungsten Carbide material with three different bore diameters of 2mm, 3mm, and 4mm and experiments were conducted at three levels of Pressure and SOD using all three nozzles. Hastelloy C 276 sheets were used as work material whose chemical composition is given in the Table1. The specimen after experimentation is shown in Figure 2.

Table 1. Chemical composition of Hastelloy

Element	Ni	Mo	Cr	Fe	W	Co	Mn	V	Si	P	S	C
%	57	15-17	14.5-6.5	4-7	3-4.5	2.5	1	0.35	0.08	0.025	0.01	0.01

Figure 1. AJM Test Rig

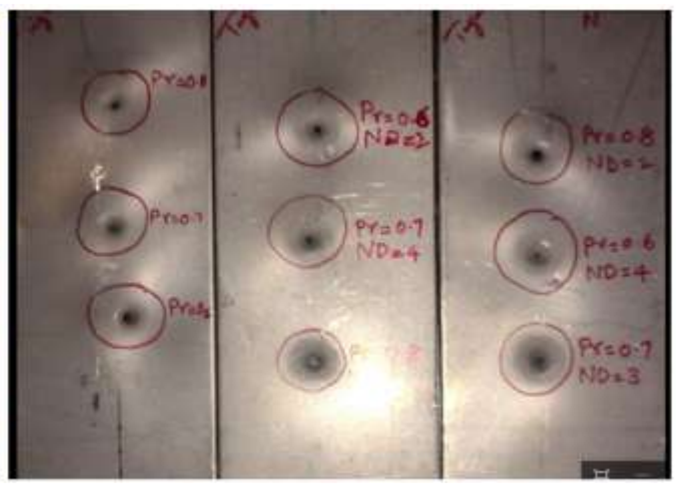

Figure 2. Taguchi Test Specimen (Hastelloy C-276)

2.2 Design of experiments

Design of experiments (DOE) using Taguchi method was used to conduct experiments. L9 orthogonal array was selected for this purpose. Three parameters namely air pressure, nozzle diameter and nozzle tip distance (stand off distance-SOD) at three different levels were considered to conduct a total of 9 experiments. These values are given in Table 2.

Table 2. Process parameters and their levels

S. No	Parameters	Levels		
		1	**2**	**3**
1	Pressure (kg/cm^2)	6	7	8
2	Stand of Distance (SOD) (mm)	7	8	9
3	Nozzle diameter (mm)	2	3	4

2.3 Response Variables

The performance of the process was measured in terms of material removal rate (MRR) and kerf. The initial and final weight of the work piece along with drilling time for each hole were noted for finding the Metal removal rate (MRR). Difference in diameters of top and bottom surface of the drill was measured to find the Kerf values.

III. Results And Analysis

3.1 Analysis of the S/N Ratio

Taguchi method stresses the importance of studying the response variation using the signal – to – noise (S/N) ratio. The term "signal" represents the desirable value and the “noise" represents the undesirable value. The formulae for signal-to-noise are designed in such a way that results in optimization of quality characteristic variation due to uncontrollable parameter. Therefore, the method of calculating the signal-to-noise ratio depends on whether the quality characteristic has smaller-the-best, larger the- better or nominal-the-better formulation [16].

The metal removal rate was considered as the quality characteristic with the concept of "the larger-the-better" and Kerf with the concept of "the smaller-the-better". The S/N ratios for “the larger the better” and "the smaller-the-better" are calculated as per equation (1) and equation (2) respectively [17].

S/N Ratio $\eta = -10 \text{ Log10 } (1/n \ \Sigma \ 1/Y_i^2)$ (1)

S/N Ratio $\eta = -10 \text{ Log10 } (1/n \ \Sigma \ Y_i^2)$ (2)

Where n = no of measurements in a Trail and Yi = Ith value in a run/row.

Table 3. Experimental Design Matrix and Results

SNo	Pressure (kg/cm^2)	SOD (mm)	Nozzle dia. (mm)	MRR (g/sec)	PSNRA1	Kerf (mm)	PSNRA2
1	6	7	2	0.018580	-32.9273	6	-14.2373
2	6	8	3	0.041790	-28.4974	3.5	-10.9980
3	6	9	4	0.073560	-23.4401	3	-10.7515
4	7	7	3	0.041890	-28.3307	5	-15.1884
5	7	8	4	0.055800	-23.3755	4	-10.7155
6	7	9	2	0.064600	-24.7142	2.5	-08.0755
7	8	7	4	0.077530	-23.1295	5	-14.0961
8	8	8	2	0.064585	-24.5703	2	-7.2296
9	8	9	3	0.081940	-20.0383	3	-8.2167

The results of MRR and Kerf values of the 9 experiments with S/N ratios are given in Table 3. The maximum material removal rate i.e.; MRR observed is 0.081940 gm/s which is at pressure 8 kg/cm^2, SOD 9 mm and 3 mm nozzle diameter. The lowest kerf value is 2 mm which is at pressure 8 kg/cm^2, SOD 8mm and 2 mm nozzle diameter.

Table 4 shows Taguchi Analysis Response Table for Signal to Noise Ratios for MRR (Larger is better). Here the pressure is most dominating factor i.e. has large effect on MRR. Nozzle diameter has the smallest effect on the material removal rate. Figure 3 shows the effect of parameters on Mean of S/N ratio (left side) & Mean of Means of MRR. The increase in pressure causes an increase in the MRR. This may happen because with an increase in the pressure there is an increase in the kinetic energy of the abrasive particles coming out of the nozzle. Similar kinds of results were reported by the earlier researchers. [18-20]

Table 4. Response table for signal to noise ratio for MRR (Larger is better)

Level	Pressure (kg/cm^2)	SOD (mm)	Nozzle dia. (mm)
1	-28.29	-28.13	-27.40
2	-25.47	-25.48	-25.62
3	-22.58	-22.73	-23.32
Delta	5.71	5.4	4.09
Rank	1	2	3

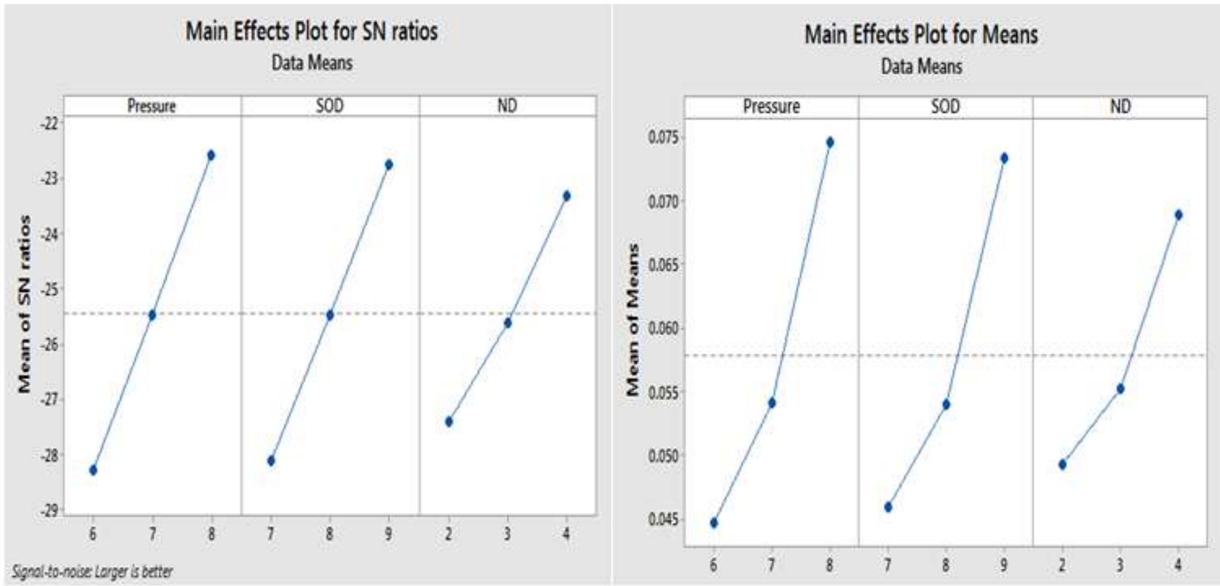

Figure 3: Effect of Parameters on Mean of S/N ratio (left side) & Mean of Means of MRR (right side)

Taguchi Analysis Response Table for Signal to Noise Ratios for Kerf (Smaller is better) is shown in Table 5. Here the Standoff distance (SOD) is most dominating factor i.e. has large effect and Nozzle diameter has the smallest effect on Kerf.

3.2 Validation for Optimization Using ANOVA

Though Taguchi Method is used in reducing the number of experiments, the effect of individual parameter on entire process is not effectively rated. By using ANONA the influence of individual parameters on process characteristics can be well determined [22]. Hence to determine the contribution of individual parameters on MRR and Kerf and to detect any differences in average performances of tested parameters, a general linear model of ANOVA was employed. The software used for executing the validation is Minitab 17. The optimized values produced in Taguchi are validated by using ANOVA. Table 6 shows the general linear model for MRR and Kerf versus parameters.

Table 5. Response table for signal to noise ratio for Kerf (Smaller is better)

Level	Pressure (kg/cm^2)	SOD (mm)	Nozzle dia. (mm)
1	-11.996	-14.507	-9.847
2	-11.326	-9.648	-11.468
3	-9.847	-9.015	-11.854
Delta	2.148	5.493	2.007
Rank	2	1	3

Table 6. General linear model: MRR and Kerf vs. Pressure, SOD, Nozzle Diameter

Factor	Type	Levels	Values
Pressure	Fixed	3	6,7,8
SOD	Fixed	3	7,8,9
ND	Fixed	3	2,3,4

Table 7. Analysis of variance for MRR using ADJSS for TESTS

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Pressure	2	0.001416	0.000708	9.51	0.095
SOD	2	0.001187	0.000593	7.97	0.111
ND	2	0.000613	0.000307	4.12	0.195
Error	2	0.000149	0.000074		
Total	8	0.003364			

S =0.0086257 R-sq=95.58%; R-sq(adj) =82.31%

Table 8. Analysis of variance for Kerf using ADJSS for TESTS

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Pressure	2	1.0556	0.5278	0.68	0.596
SOD	2	11.0556	5.5278	7.11	0.123
ND	2	0.3889	0.1944	0.25	0.800
Error	2	1.5556	0.7778		
Total	8	14.0556			

S =0.881917 R-sq=90.93% R-sq(adj) =55.73%

Table 7 shows Analysis of Variance for MRR. F Value (9.51) of the parameter indicates the Air Pressure is significantly contributing more towards cutting performance. F value (4.12) of parameter indicates the contribution of Nozzle diameter is less.

Table 8 shows Analysis of Variance for Kerf. F Value (7.11) of the parameter indicates that SOD is significantly contributing more towards cutting performance. F value (0.25) of parameter indicates the contribution of Nozzle diameter is less.

IV. Conclusions

This paper discussed the influence of process parameters on machining characteristics of hastelloy. Taguchi optimization and ANOVA techniques were employed for this purpose. The process parameters chosen were Nozzle pressure, SOD and Nozzle diameter and AJM performance was measured in terms of MRR and Kerf.

From the Taguchi technique the following conclusions were drawn:

- The pressure has largest effect and Nozzle diameter has the smallest effect on the material removal rate.
- The maximum material removal rate is occurred at pressure 8 kg/cm^2, SOD 9 mm and 3 mm nozzle diameter.
- The Standoff distance (SOD) has large effect and Nozzle diameter has the least effect on Kerf.
- The lowest kerf value is observed at pressure 8 kg/cm^2, SOD 8mm and 2 mm nozzle diameter.

  From ANOVA the following conclusions were drawn.
- The Air Pressure is significantly contributing more towards cutting performance and nozzle diameter has least contribution on MRR.
- SOD is significantly contributing more towards cutting performance and nozzle diameter has least contribution on Kerf.

From the above it is concluded that both Taguchi method and ANOVA techniques drew similar results.

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