International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249 – 8958, Volume-3, Issue-5, June2014

Taguchi Method Implementation in Abrasive Waterjet Machining Process Optimization

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Abstract-Abrasive waterjet machining (AWJM) is a non-conventional metal removal process as well as one of the best manufacturing processes suitable for machining on very hard material. The objective of this paper is to optimize the input parameters of AWJM, such as pressure within pumping system, abrasive material grain size, stand-off distance, nozzle speed and abrasive mass flow rate for machining SS304. The Taguchi design of experiment, the signal-to-noise ratio, and analysis of variance are employed to analyze the effect of the input parameters by adopting L_{27} Taguchi orthogonal array (OA). In order to achieve the minimum surface roughness (SR), five controllable factors, i.e. the parameters of each at three levels are applied for determining the optimal combination of factors and levels. The results reveal that the SR is greatly influence by the abrasive material grain size. Experimental results affirm the effectiveness of the solving the stated problem within minimum number of experiments as compared to that of full factorial design.

Keywords -Surface roughness, Taguchi method

I. INTRODUCTION

Non-conventional machining processes have been developed to overcome the shortcoming of conventional machining processes. Non-conventional machining processes have some advantages, such as accuracy, precision, quality, ability to cut high strength material, and the ability to perform complex cutting motion on workpiece having complex shape. However, the processes also have a weakness in terms of lower productivity in comparison to that of conventional machining processes [1]. Abrasive waterjet machining (AWJM) is the non-conventional machining process for material reduction which is accomplished by the virtue of erosion caused by the high pressure abrasive water jet. AWJM has become today's most popular non-conational production process [2, 3]. Abrasive waterjet cutting involves using an extremely fine jet of water travelling at high velocity, into which an abrasive material is mixed for cutting hard materials such as granite and titanium. This process makes a very fine cut into the material, known as a kerf [4]. The mechanism of jet-cutting is very complex. Material removal is done mechanically by erosion caused due to localized compressive failure which occurs when the local fluid pressure exceeds the ultimate compressive strength of the target material [5].

Manuscript Received on June 2014.

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II. LITERATURE REVIEW

Literature review says, the surface quality of the machined parts is one of the most important product quality characteristics and one of the most frequent customer requirements. In this study the Taguchi robust parameter design for modeling and optimization of surface roughness in dry single-point turning of cold rolled alloy steel 42CrMo4/AISI 4140 using TiN-coated tungsten carbide inserts was presented. Three cutting parameters, the cutting speed, the feed rate, and the depth of cut, were used in the experiment. Each of the other parameters was taken as constant. The average surface roughness (Ra) was chosen as a measure of surface quality. The data set from the experiment was employed for conducting the optimization procedures, according to the principles of the Taguchi method. The results of calculations were in good agreement with the experimental data. A certain discrepancy between the experimental results and calculations could be interpreted as the presence of measurement errors, many irregularities and deficiencies in the turning process, as well as environmental effects [6]. Literature review says, different types of abrasives are used in abrasive water-jet machining like garnet, aluminum oxide, olivine, silica sand, silicon carbide, etc. The present work gives a comparative analysis of the performance of garnet, aluminum oxide and silicon oxide during abrasive water-jet machining of glass. The study showed that width of cut increases as the stand-off distance of the nozzle from the work is increased which is due to divergence shape of the abrasive water-jet. However, the garnet abrasives produce the smallest width of cut followed by aluminum oxide and silicon carbide [7]. This research aims to examine the correlation between AWJM input parameter SR, and to optimize the application of Taguchi method in determining the input parameter values resulting in optimum SR. To achieve the aims, the research activities are focused on and narrowed down to the followings:

- The AWJM input parameter in the optimization considered are the pressure within the pumping system (PwPS), abrasive material grain size (AMGS), stand-off distance (SoD), nozzle speed (NS) and abrasive mass flow rate (AMFR).
- The machining process optimization response functions considered is SR.
- SS304 material was employed for the experiment.
- The workpiece is cut in vertical motion mode.

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III. The Experiment

The AWJM used in this research is KMT Waterjet Systems. The dimension of workpiece is 300 mm x 115 mm x 10 mm. The KMT Waterjet Systems uses CNC to control its motion axis. Simultaneous motion axis control enables the machine to perform a number of specific shapes. AWJM is a non-conventional machining process capable of cutting very hard and strong material. AWJM can be performed on conductive as well as non conductive materials. Schematically, AWJM working principal is shown in Figure 1. In AWJM the process, the workpiece is clamped on the worktable and cut using abrasive mixed with high pressure water jet [7].

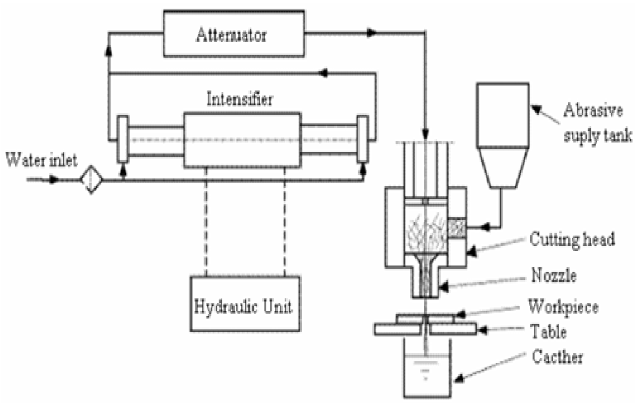

Figure 1: A Schematic Illustration of an Abrasive type Waterjet Cutting System

AWJM process is capable of producing a very smooth surface, regardless of the dimension of the workpiece. AWJM head be seen in Figure 2. In AWJM process cutting speed is very important that affect the workpiece geometry quality [8].

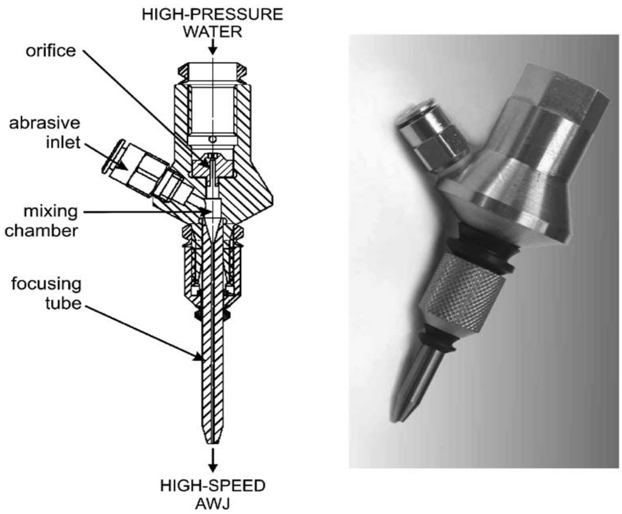

Figure 2: AWJM Head

A. The Components

The components of AWJM process are as follows.

- The nozzle
- The accumulator
- The control unit
- The mixing chamber
- The focusing tube
- The workpiece - The workpiece hardness is not a significance factor in AWJM process. AWJM can be performed on conductive as well as non conductive materials [7].
- Machining parameters- Machining parameters can affect SR. AWJM process parameters consist of
  - Pressure within the pumping system
  - Abrasive material grain size
  - Nozzle speed
  - Stand-off distance
  - Abrasive mass flow rate

B. The Workpiece Material

The material selected is SS304 having the composition of 0.08 C, 2.0 Mn, 1.0 Si, 18-20 Cr, 0.8-12 Ni, 0.045 P, 0.03 S in percent of weight. The shape of the workpiece is a plate of 300 mm x 115 mm x 10 mm in dimension.

IV. Design of Experiment

Taguchi method arranges a special design of orthogonal array (OA) to study the entire input parameter in much less experiments. Taguchi's philosophy which was originated by Dr. Taguchi [9] is an efficient tool for designing high quality manufacturing systems. The method is based on OA experiment of the experiments requiring much reduced combinatorial arrangement of the experiment; nevertheless it is capable of resulting in optimal setting of process control parameters. In addition, OA dictates fewer experimental runs and provides the Taguchi's signal-to-noise (*S/N*) ratios. In turns, Taguchi method has gained its recognition for undertaking engineering analysis. The method consists of hatching a plan of experiments which objective is to acquiring data in a controlled manner, *i.e.*, to obtain information regarding the behavior of a given process. The most pronounced benefits of the method are in reducing the reducing the experiments, and the cost of executing the experiments. Finally, Taguchi method is also capable of quickly concluding the significant factors determining the process [9]. The parameter design is a systematic approach to improve the product quality and to reduce the production cost by minimizing the sensitivity to noise factors. The mean and the variance of a response are the *S/N* ratio. Taguchi classifies parameter design problems into different categories depending on the goal of the researcher. The standard *S/N* ratios generally used are as follows:

- Nominal the best characteristic

$$S/N = 10 \log \frac{\bar{y}}{s_y^2} \quad \text{…… (1)}$$

- Larger the better characteristic

$$S/N = -10 \log \frac{1}{n}\left(\sum \frac{1}{y^2}\right) \quad \text{…… (2)}$$

- Smaller the better characteristic

$$S/N = -10 \log \frac{1}{n}\left(\sum y^2\right) \quad \text{…… (3)}$$

Where $\bar{y}$ is the average of observed data, y is the observed data, s_y^2 is the variance of data and n is number of observation.

In addition to the *S/N* ration, statistical analysis of variance

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(ANOVA) can be employed to indicate the effect of input parameter on the response function. The steps in the Taguchi experimental design are:

- to select the output function response to be optimized,
- to identify the factors affecting output functions and to choose the levels of these factors,
- to select the appropriate OA,
- to assign factors and interactions to the columns or the array,
- to perform experiments,
- to analyze the result using *S/N* ratio analysis and ANOVA
- to determine the optimal input parameters, and
- to perform confirmatory experiments.

TABLE I INPUT PARAMETER AND THEIR LEVELS

Control Factors	Levels			unit
	1	**2**	**3**	
AMGS	60	80	100	mesh
SoD	1.5	2.5	3.5	mm
PwPS	150	225	300	MPa
NS	125	175	225	mm/min
AMFR	3	5	7	g/s

TABLE II EXPERIMENTAL OUTPUT AND S/N RATIO

Ex. No.	Control factors					SR Ra (μm)	*S/N* ratio
	AMGS	SoD	PwPS	NS	AMFR		
1	60	1.5	150	125	3	1.996	-6.00
2	60	1.5	150	125	5	1.973	-5.90
3	60	1.5	150	125	7	1.908	-5.61
4	60	2.5	225	175	3	1.97	-5.89
5	60	2.5	225	175	5	1.929	-5.71
6	60	2.5	225	175	7	1.921	-5.67
7	60	3.5	300	225	3	1.897	-5.56
8	60	3.5	300	225	5	1.924	-5.68
9	60	3.5	300	225	7	1.912	-5.63
10	80	1.5	225	225	3	1.546	-3.78
11	80	1.5	225	225	5	1.657	-4.39
12	80	1.5	225	225	7	1.415	-3.02
13	80	2.5	300	125	3	1.141	-1.15
14	80	2.5	300	125	5	1.328	-2.46
15	80	2.5	300	125	7	1.034	-0.29
16	80	3.5	150	175	3	1.765	-4.93
17	80	3.5	150	175	5	1.732	-4.77
18	80	3.5	150	175	7	1.651	-4.35
19	100	1.5	300	175	3	1.298	-2.27
20	100	1.5	300	175	5	1.354	-2.63
21	100	1.5	300	175	7	1.081	-0.68
22	100	2.5	150	225	3	1.538	-3.74
23	100	2.5	150	225	5	1.491	-3.47
24	100	2.5	150	225	7	1.087	-0.72
25	100	3.5	225	125	3	1.353	-2.63
26	100	3.5	225	125	5	1.241	-1.88
27	100	3.5	225	125	7	1.053	-0.45

The range of input parameter and the number of levels of the design are given in the Table I. The present experimental design adopts Taguchi's L27 of OA with each design parameter having three levels. The experimental arrangement of this study is shown in Table II.

V. EXPERIMENTAL RESULTS AND ANALYSIS

A. Optimal Combination of Input Parameters

The research aims to optimize SR. Therefore 'the smaller-the-better' is principle of the *S/N* ratio for the SR. The data measured in the research are AMGS, SoD, PwPS, NS, and AMFR.

B. Surface Texture Measuring Instrument Specification

SR is measured using surface texture measuring instrument [6] having following specification.

Description: Surface Texture measuring instrument

Type: SURFCOM 130A- Monochrome

Manufacturer: TOKYO SEIMITSU CO.LTD

Procedure: JIS B0651-1996, ISO 3274 and DIN4772

The result of experiment for SR is shown in Table II and the corresponding *S/N* ratio calculated according to Eqs. 3 as shown in Table II. The mean *S/N* ratio for each level of the input was calculated and the results are shown in Table II. The optimum setting is the parameter combination which has the highest *S/N* ratio. The *S/N* ratio for each parameter at different levels for SR is plotted in Graph 1. To obtain the smallest SR, the control factors are: AMGS = 100, SoD = 2.5, PwPS = 300, NS = 125 and AMFR = 7, as evident by examining Graph 3, which predict an SR of 1.034 μm. The effect of control factors were investigated through the analysis of variance (ANOVA). It is computational technique mainly to learn about the influence of various design factors and to observe the degree of sensitivity of the result to different factors affecting the quality characteristics. F-ratio value is a statistical analogue to Taguchi's signal to noise ratio for the control factor effect versus the experimental error. It uses the information based on sample variances to define the relationship between the power of the control factor effects and the power of the experimental error. Larger F-ratio value indicates that there is a big chance on the performance characteristic due to the variation of the process parameter [10].

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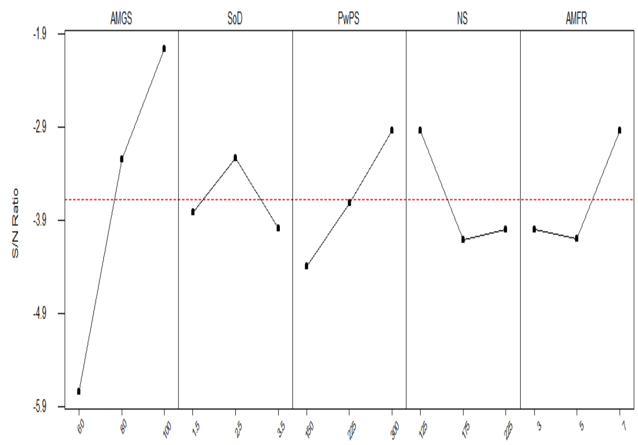

Graph 1: Mean *S/N* Ratio Graph for SR

TABLE III ANALYSIS OF VARIANCE FOR SR

Control factors	DOF	Sum of squares	Mean square	F	P	Factor effect (%)
AMGS	2	2.062	1.031	60.48	0	35.24
SoD	2	0.070	0.035	11.63	0.03	6.78
PwPS	2	0.262	0.131	52.36	0	30.5
NS	2	0.183	0.091	15.06	0	8.77
AMFR	2	0.169	0.084	32.09	0	18.71
Error	16	0.128	0.008			
Total	26	2.874				

Applying ANOVA, the effect of each input on SR can be determined. Table III illustrate the ANOVA correspond to the SR of the machining SS304. Based on the calculation resumed in Table III it is clear that AMGS is the most significantly affect SR at 35.24% of factor effect, followed by PwPS, AMFR, NS and then SoD at 30.5 %, 18.71%, 8.77 % and 6.78 % factor effect respectively. The optimum condition represents the combination of control levels that is expected to produce best performance. The average *S/N* ratio for each factor level indicates the relative effect of the various factors on quality characteristics of Ra during machining of SS304. Taguchi Analysis observed the higher value of mean *S/N* ratio as better quality characteristic [11, 12]. Therefore, based on the average *S/N* ratio for each factor level as illustrated in based on Graph 1, the optimum machining performance for Ra was obtained at level 3rd for abrasive material grain size (mesh 100), level 2nd for Stand of distance (2.5 mm), level 3rd for pressure inside the pumping system (300 MPa), level 1st for nozzle speed (125 mm/min) and level 3rd for abrasive mass flow rate (7 g/s).

C. Confirmation Experiments

Validation of the machining process optimization is produced by carrying out confirmation experiments implement the assigned input parameters. The confirmation experiment results show Ra of 1.097 µm, which is very close to the predicted result.

VI. Conclusion

The result inquires the optimum AWJM process employing Taguchi method. The application of Taguchi method in the analysis of experimental result yields the following conclusion.

- The surface roughness decreases with the increase of abrasive material grain size.
- The surface roughness increase with the increase of stand of distance.
- The surface roughness decreases with the increase of pressure inside the pumping system.
- The surface roughness increase with the increase of nozzle Speed.
- The surface roughness decreases with the increase of abrasive mass flow rate.
- Taguchi's robust Orthogonal Array design method is suitable to analyze the surface roughness problem as described in this paper.
- It is found that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for the optimization of the cutting parameter.
- To obtain the smaller SR, the following parameter are recommended AMGS = 100, SoD = 2.5, PwPS = 300, NS = 125 and AMFR = 7.
- With a factor effect value of 35.24 %, AMGS parameter proves to be most significant for SR. The parameter behaviors are not linear due to the interactions with input parameters, which must be analyzed in further study.

VII. Future Scope

Future study could consider more factors in the research to see how the factors would affect surface roughness. Also further study could consider the outcome of Taguchi parameter design when it is implemented as a part of management decision making system.

VIII. Acknowledgment

The author would like to thanks Mr. Vijay Lagad, Managing Director allowing permission for carry out experiments and to utilize his valuable resources at a Supernova Waterjet Cutting Systems, Nashik.

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