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A TAGUCHI APPROACH FOR OPTIMIZATION OF PROCESS PARAMETERS IN WATERJET CLEANING PROCESS*

A. KHAJAVI, F. KOLAHAN** AND A. ESMAEELZADEH

Dept. of Mechanical Engineering, Ferdowsi University of Mashhad, P.O. Box 91775-1111, Mashhad, I. R. of Iran
Email: kolahan@um.ac.ir

Abstract– This paper addresses a Taguchi based method for optimization of process parameters in waterjet cleaning (WJCl). The experimental data was collected based on Taguchi L_{18} orthogonal array. The tests were conducted under varying waterjet pressure (*P*), nozzle traverse rate (*V*) and stand–off–distance (*D*). The effects of these input parameters are investigated on cleaning width (*W*), one of the most important characteristics in waterjet technique. In this regard, analysis of variance (ANOVA) and F–test have been used to evaluate the relative significance of process variables affecting cleaning width. Furthermore, using signal-to-noise (*S/N*) ratio, the optimal set of process parameters has been identified to maximize cleaning width. The optimization result is then verified against experimental data to evaluate the performance of Taguchi technique in determining the optimum levels of process parameters. This comparison clearly indicates that the Taguchi technique is quite effective in determining the best set of process parameters in waterjet cleaning.

Keywords– Optimization, taguchi method, waterjet cleaning, process parameters, ANOVA

1. INTRODUCTION

Over the past few decades, the application of the waterjet technology has rapidly expanded in industries such as automotive, aerospace, mining, construction and even in the fields of medicine and food processing [1]. Mechanism of material removal in WJCl involves erosion by discrete droplets, aimed at the workpiece surface through a high pressure – high speed jet of water. Most of its kinetic energy is converted into very high pressure and induces stress waves in the target material. This, in turn, can be used to remove material from the points of impacts. Advantages of this process include clean and sharp cut, dustless environment, no heat generation and thermal degradation of work material, no tool wear and less maintenance [2]. A schematic illustration of abrasive waterjet (AWJ) system is presented in Fig. 1.

The waterjet technology has a wide range of applications, including material cutting, deburring and surface cleaning [1]. Like any other machining processes, the performance of waterjet cleaning is significantly affected by its parameter settings. Important process parameters in waterjet cleaning are stand–off–distance (*D*), water jet pressure (*P*) and travel speed or feed rate (*V*). In turn, the values of these parameters, determine the process output characteristics, among which cleaning width is the most important one.

In recent years, various approaches such as artificial neural network (ANN) and Fuzzy Logic (FL) are considered in order to predict performance characteristics of WJ processes under different parameters settings. Along this line, Kovacevic and Fang [3] were among the first who attempted to develop FL and ANN models to establish the influence of cutting parameters of abrasive waterjet on the depth of cut for

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**Corresponding author

different materials. Lu *et al*. [4] developed an ANN model to predict the cutting speed to achieve the desired cutting surface quality in AWJ cutting.

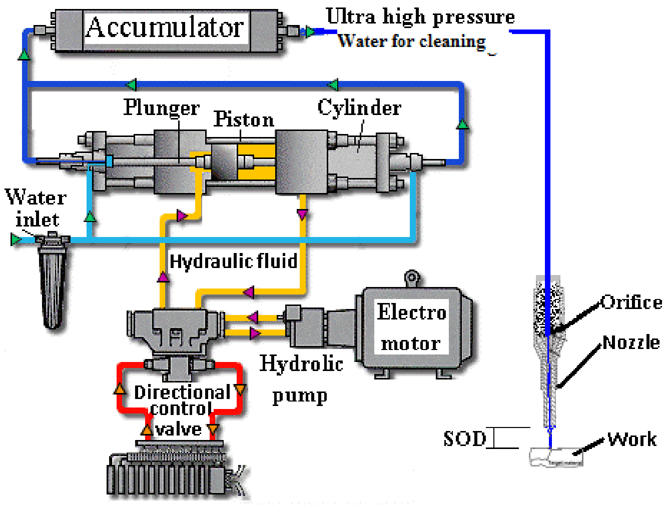

Fig. 1. Schematic illustration of a high pressure waterjet machining system

Studies addressing the waterjet cleaning and depainting applications are relatively rare. For depainting process, Babets *et al*. [5] used an ANN based predictive model combined with Zoutendijk's search to obtain the process parameters values for maximum cleaning rate. Later they employed FL technique to construct models to relate input variables (pressure, stand–off–distance, traverse rate) to the strip width in depainting process [6]. Leu *et al.* [7] carried out mathematical modeling and experimental verification of this process considering the water jet as stationary and striking at normal incidence angle. They developed an analytical expression for cleaning width as a function of stand-off distance, waterjet pressure, and nozzle radius. They also derived the equations for optimum and critical stand-off distance as well as maximum cleaning width. Meng *et al.* [8] developed a semi-empirical model for the WJCl process, taking into account the waterjet as moving and striking at normal incidence angle. Gao and Chen [9] compared adaptive-network-based fuzzy inference system (ANFIS) and FL approaches. They concluded that ANFIS is superior to Fuzzy logic for the prediction of high-pressure waterjet epoxy paint cleaning. Although all 48 test results of the full factorial design have been used, they could not achieve the average prediction errors of less than 10%. These researchers have also investigated the application of waterject technology in road surface cleaning using a combined fuzzy neural network method for calculating cleaning rate [10].

In recent years, Design of Experiments (DOE) approaches have increasingly been employed to establish the relationships between various process parameters and the process outputs in a variety of manufacturing industries. Taguchi method, one of the fractional factorial designs, uses a special design of orthogonal arrays to study the entire solution space with small number of experiments [11]. Literature reveals that very little effort is reported on the use of Taguchi method for optimization of WJCl process. Among few studies, Jegaraj and Babu [12] have used Taguchi approach and ANOVA technique to investigate the influence of parameters on cutting performance in abrasive waterjet machining. Orifice and focusing tube bore variations have been considered in developing their empirical models.

As mentioned earlier, cleaning width is the most important performance characteristic in WJCl which directly affects the cleaning time. Cleaning strip (width), in turn, is determined by the process parameters settings, such as waterjet pressure, nozzle traverse rate and stand–off–distance. To the best of our knowledge, there is no published work to investigate the effect of the process parameters and to determine their optimal levels for the waterjet cleaning. Most existing studies have limited practical applications. For instance, in the research reported by Gao and Chen [9] only the performance of two methods, namely ANFIS and Fuzzy Logic, have been compared to predict the cleaning width in waterjet process. Therefore, the main objectives of this study are: i) to establish the relationship between the process parameters and the WJCl cleaning width, and ii) to derive the optimal parameter levels for maximum cleaning width. These are made possible using Taguchi technique and statistical analysis performed on the experimental data. Finally, the article concludes with the verification of the proposed approach and a summary of the major findings.

2. ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

In this study the same set of experimental data is used as those provided by Gao and Chen [9] on high-pressure waterjet cleaning. The experiments have been conducted on a 200 mm diameter steel shaft coated with 0.2mm thick epoxy paint. The shaft was connected to a motor to provide its rotation around its centerline. The linear traverse rate of rotating shaft is expressed by:

$$V = \pi \times d \times n \tag{1}$$

Where d is the diameter and n is the rotational speed of the shaft. The ranges of the input process parameters used in the experiments are presented in Table 1.

Table 1. Process parameters and design levels used in the experiments [9]

No.	Symbols	Factors	Units	Level		
				1	2	3
1	P	Waterjet pressure	MPa	150	190	-
2	V	Nozzle traverse rate	mm/s	100	140	180
3	D	Stand-off-distance	mm	15	25	35

To evaluate the effects of machining parameters values on cleaning width and to identify the optimal settings, a designed experimental procedure is required. Taguchi approach in Design of Experiment (DOE) applications can dramatically reduce the number of trails required to gather necessary data [13]. Table 2 presents the experiment settings obtained by Taguchi L_{18} design matrix. The first three columns of this table show the input parameters settings for the experiments, while the last two columns respectively indicate the machining outputs and their corresponding Signal to Noise (S/N) ratios.

The data obtained above may be used to establish the relations between WJCl parameters and its response characteristic. In this paper, ANOVA technique is employed to establish the relative significance of the individual processing factors on the cleaning width.

The basic idea behind ANOVA is to breakdown total variability of the experimental results into components of variance, and then to assess their significance. The significance of the variation components associated with factor effects is assessed by comparing them with the residual. The optimum level of these significant parameters has been found by examining the level averages of the factors. In this regard, the F–test may be utilized for comparing variances [14].

In contrast to other optimal analytical methods, Taguchi's method may be employed to determine both the optimum result from finite analytical data and the dominant factors involved in the optimization for the process under investigation [15]. In the parameter design phase of this method, process variables can be grouped into control factors and noise factors. The design and indicative factors belong to the class of controllable variables that could be controlled both in the simulation experiment and in the real world.

Table 2. Experimental results and S/N ratios for L_{18} orthogonal array

No.	P (MPa)	V (mm/s)	d (mm)	Cleaning width (mm)	S/N
1	1	1	1	3.4	10.6296
2	1	1	2	3.4	10.6296
3	1	1	3	4.0	12.0412
4	1	2	1	2.0	6.0206
5	1	2	2	3.0	9.5424
6	1	2	3	3.0	9.5424
7	1	3	1	2.0	6.0206
8	1	3	2	2.5	7.9588
9	1	3	3	2.5	7.9588
10	2	1	1	4.0	12.0412
11	2	1	2	4.5	13.0643
12	***2***	***1***	***3***	***5.2***	***14.3201***
13	2	2	1	3.5	10.8814
14	2	2	2	4.0	12.0412
15	2	2	3	4.0	12.0412
16	2	3	1	3.0	9.5424
17	2	3	2	3.5	10.8814
18	2	3	3	3.5	10.8814

Taguchi approach makes use of the signal–to–noise (*S/N*) ratios as performance measures to optimize the response variable or output quality characteristic against such variations in noise factors. In this method, a loss function is used to calculate the deviation between the experimental value and the desired value. This loss function is further transformed into *S/N* ratio. Based on the process under consideration, the *S/N* ratio calculation may be decided as "the higher the better, HB" or "the lower the better, LB" as are given in the following equations [16]:

$$\textbf{HB}:\ \eta = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{2}$$

$$\textbf{LB}:\ \eta = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{3}$$

where η denotes the *S/N* ratio calculated from the observed values, y_i represents the experimentally observed value of the i^{th} experiment, and n is the repeated number of each experiment.

Since the cleaning width is the measure of performance in WJCl process, the Higher the Better criterion is selected in this study. The *S/N* ratios determined from the experimentally observed values have been statistically evaluated by ANOVA technique. This is done in order to explore the effects of each WJCl parameter on the observed cleaning width values and to determine which machining parameters significantly affected the cleaning width. Based on the HB criterion, a greater η corresponds to a better performance and hence the optimal level of the machining parameters is the level with the greatest η value. By applying *F*–test procedure, the η value for each experiment of L_{18}Taguchi design matrix was calculated (Table 3).

Table 3. The η values based on the average S/N ratios

Cleaning parameters	Mean by factor level		
	Level 1	Level 2	Level 3
P	2.867	**3.911***	**-**
V	**4.083***	3.250	2.833
D	2.983	3.483	**3.700***
Optimum level *			

As illustrated in Table 3, the best waterjet pressure is 190 MPa (Level 2), traverse rate is 100 m/s (Level 1) and stand–off–distance is 35 mm (Level 3). The corresponding S/N ratio for these settings indicates that a maximum cleaning width of 5.0 mm may be achieved.

Figure 2 schematically shows the effects of different levels of machining parameters on the cleaning width. The same trend as discussed above may be seen in this figure.

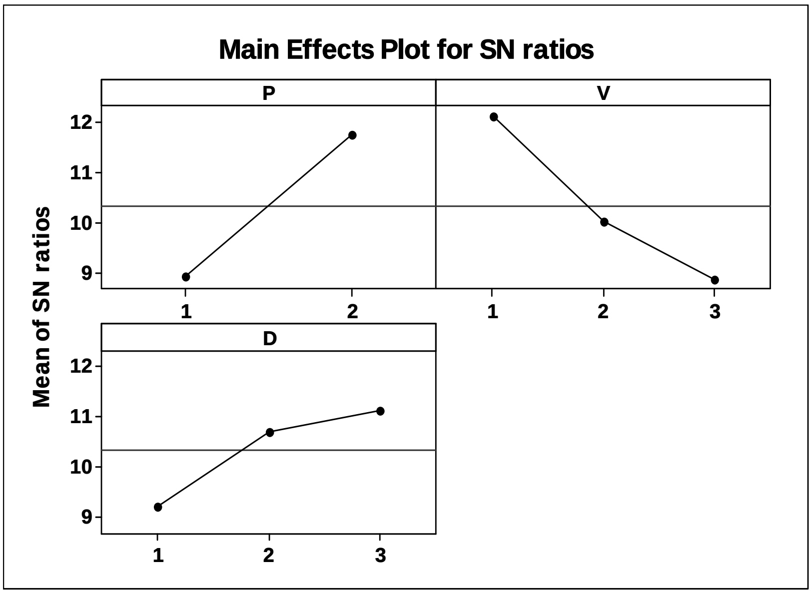

Fig. 2. Main effects plot of machining parameters for cleaning width

According to ANOVA procedure, large *F*–value indicates that the variation of the process parameter makes a big change on the performance characteristics [17]. In this study, a confidence level of 95% is selected to evaluate parameters significances. Therefore, *F*–values of machining parameters are compared with the appropriate values from confidence table, $F_{\alpha,v1,v2}$; where α is risk, v_1 and v_2 are degrees of freedom associated with numerator and denominator. As illustrated in Table 4, all factors are significant according to *F*–test analysis.

Table 4. ANOVA results of waterjet parameters for cleaning width

Cleaning parameters	Degree of freedom (Dof)	Sum of square (SS_j)	Variance (F_j)	F-Value
P	1	4.909	4.909	107.76*
V	2	4.861	2.4306	53.35*
D	2	1.621	0.8106	17.79*
Error	12	0.547	0.0456	-
Total	17	11.938	-	-

***Significant**
$F_{0.05,1,12}$ = **6.55** **&** $F_{0.05,2,12}$ = **5.10**

Percent of contribution indicates the relative importance of a factor on the process output characteristic. The contributions of the machining parameters on the cleaning width are shown in Fig. 3. According to Fig. 3, waterjet pressure is the major factor affecting the cleaning width (*W*) with 41% contribution, whereas traverse rate and stand–off–distance have smaller effects on W with 37% and 13% contributions, respectively. The remaining (9%) effects are due to noise factors or uncontrollable parameters.

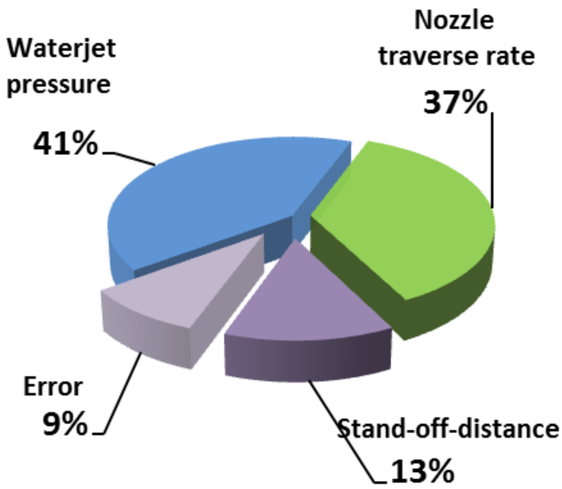

Fig. 3. The effects of waterjet process parameters on the cleaning width

3. VALIDATION OF OPTIMIZATION RESULTS

To further investigate the performance of the proposed approach and the adequacy of our statistical analysis, the predicted cleaning width, based on the optimal settings given by S/N ratios, is compared with that of actual test. As shown in Table 4, the S/N ratios indicate that waterjet pressure, traverse rate and stand–off–distance should be set at levels 2, 1 and 3 respectively. Based on their corresponding S/N ratio, these settings should result in a maximum cleaning width of 5.0. For the same parameters setting, the actual experimental value of cleaning width is 5.2 mm (experiment #12 in Table 2). Table 5 presents the comparison between the experimental and predicted cleaning widths based on the optimal process parameters. As illustrated, the difference between predicted and actual cleaning widths is only 3.85% which is quite acceptable. This demonstrates that the experimental results are strongly correlated with the estimated values given by statistical analysis.

Table 5. Validation of optimization results for maximum cleaning width

	Optimal condition			
	Prediction	**Experiment**	**Difference**	**Error (%)**
Level	$P_2\ V_1\ D_3$	$P_2\ V_1\ D_3$	-	-
Cleaning width (W)	5.0	5.2	0.2	3.85
S/N Ratio for W	13.8393	14.3201	-	-

It should be noted that this procedure may also be used to determine the process parameters settings for any desired cleaning width values within feasible ranges.

4. CONCLUSION

In this study the Taguchi method has been applied to optimize the process parameters for the waterjet cleaning process. In addition, the relative significance of each of the main process parameters has been determined using Signal to Noise analysis. To acquire the required data, part of the experimental results provided by Gao and Chen [9] have been used. It is shown that Taguchi experimental design can effectively reduce the sample size required for analyzing the waterjet cleaning process. ANOVA results reveal that all three cleaning factors are significant in determining cleaning width. Furthermore, the optimum set of process parameters for the maximum cleaning width has been obtained based on *S/N* ratios. The optimal levels were found to be P_2, V_1 and D_3, corresponding to waterjet pressure of 190 mm, nozzle traverse rate of 100 mm/s and Stand–off–distance of 35 mm respectively. By using these settings it is possible to increase cleaning width considerably. Moreover, the comparison between predicted and experimental results, for maximum cleaning width, reveals that the proposed approach is both accurate and effective in predicting the output response characteristics of WJCl process. In the present study, the interactions of the process parameters have not been considered. Investigation of the interactions between Waterjet process parameters could be an interesting topic for future researches.

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