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Determination of Influential Factors on EDMed Surface Properties Using Plackett-Burman Design

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Abstract: In many investigations, large number of process, or design parameters that are initially thought to affect the outcomes or outputs may not really have statistical significant influence on them. Screening experiments are used to identify the key parameters (factors) that significantly affect these outcomes. In this investigation, Plackett-Burman screening design was used to identify the factors that influence the surface properties of titanium alloy (Ti-6Al-4V) during electro-discharge machining (EDM) with Cu-TaC electrodes. These properties are the surface roughness and the surface micro-hardness. The experimental design has seven factors where each factor is set at two different levels. These factors include the TaC composition in the electrode and its compacting pressure. Others are urea concentration in the dielectric fluid, machining peak current, pulse duration, duty factor and the gap voltage. An 8-trial runs was used in conducting the investigation. The analysis of variance was used to analyze the results. The analysis has shown that all the factors except the urea concentration have statistical significant impact on the surface roughness of the EDMed material. On the other hand, the TaC composition and the gap voltage found to have no influence on the surface micro-hardness. The result would lead the way for further round of experimentation for in depth investigation of the factors and their interactions effects.

Key words: Plackett-Burman Design · Analysis of Variance · Micro-hardness · Surface Roughness

INTRODUCTION

In many manufacturing applications, engineers are faced with large number of process, or design variables which affect their final product quality, performance or quantity. It becomes appropriate for them to identify the vital ones so as that they can be focused upon. Screening designs offer effective and economic means to reduce such large number of parameters using minimum number of experimental trails to few. Subsequently higher level of investigation can be made with these fewer parameters. Typical screening experiment involves the use of fractional factorial design [1].

Plackett-Burman design (PBD) is the most frequently used screening design because if its ability to estimate all main effects with the same precision [2]. It is a fractional factorial design with the advantage of minimizing the experimental runs from large number of variables to smaller most significant factors [3-4]. Using this design, N factors can be screened with N + 1 experimental runs [5]. Being an orthogonal design, the main effects are independent, while the interactions are not of interest at this screening stage [2, 6].

Many researchers have used PBD in preliminary investigations to screen the influential factors on output variables [7-8]. Ali and Zulkuli [9] used geometric PBD to

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screen the mineral salt that would improve the citric acid fermentation from paddy straw using *Aspergillus niger*. They found NH_4NO_3 to be the most significant mineral. Salihu *et al*. [10] used non geometric PBD to identify the most significant medium components affecting lipase production by *penicillium citrinum* using 12 experimental trials. They were found to be Tween-80, peptone, yeast extract, malt extract and $NaNO_3$ at 5% significant level. Non geometric PBD are designs with multiples of 4 runs, but are not powers of 2. In such designs the standard methods of analyzing two-level fractional factorial are not found applicable due to partial aliasing among the effects [11]. Most of researches apply PDB in selecting influential factors and move further to optimize the responses with other powerful statistical tools. Kiran *et al*. [12] used Doehlert design to optimize the medium composition for producing endo-polygalacturonase after identifying the factors with PBD. The use of response surface methodology (RSM) as optimization tool after screening with PBD has also been reported by many literatures. Box Behken and central composite designs were among the frequently used ones [13-16].

In the present study, it is desired to modify the surface of titanium alloy (Ti-6Al-4V) using electrical discharge machining (EDM). The machining condition is made up of a number of variables ranging from electrode material, dielectric fluid to the machine settings. Earlier investigations on this material (alloy) through the EDM process have shown that some of these variables have not been considered. [17-19]. Therefore, the main objective of this research is to conduct a screening experiment on the variables that make up the machining condition using PBD to determine the significant ones.

Experimental Design and Methods

Plackett-Burman Design (PBD): A total of seven variables were identified from the electrode material, dielectric fluid and the machine setting.

Table 1: Factors and Levels

Factor	Label	Low Level(-)	High Level (+)
TaC composition (%)	A	40	60.00
Compact. Pressure (MPa)	B	20.67	34.45
Urea concentration (g/l)	C	5.00	15.00
Peak current (A)	D	3.50	6.50
Pulse duration (μsec)	E	3.30	5.30
Duty factor (%)	F	40.00	60.00
Gap voltage (V)	G	22.00	24.00

These are TaC composition in the electrode, compacting pressure, urea concentration, peak current, pulse duration, duty factor and the gap voltage. The selected levels of investigation are fixed at high (+1) and low (-1). The variables with their levels are presented in Table 1.

The Plackett-Burman experimental design based on the first order model with no interaction effect has been represented by Equation 1[20].

$$Y = \beta_0 + \Sigma\, \beta_i\, X_i \qquad (1)$$

Where Y represents the response, β_0 is the model intercept, i represent the variable number, β_i the variable estimate and X_i corresponds to the independent variables (A, B,-G). The responses are the surface roughness (Ra) and the micro-hardness (Mh). An 8-trial geometric PBD consisting of the 7 factors at 2 levels was constructed and the experiments were replicated twice. The randomized design matrix with the responses is presented in Table 2. The main effect of each of the variable is given in Equation 2.

$$E_{(Xi)} = (\Sigma\, M_{i+} - \Sigma\, M_{i-}) / n \qquad (2)$$

Where $E_{(Xi)}$ is the response value effect of the variable, $\Sigma\, M_{i+}$ is the summation of the response value at high level, $\Sigma\, M_i$-is the summation of the response value at low level, n is the number of trials.

Table 2: The P-B Design Matrix in Coded Form with the Responses

								Ra (μm)		Mh (Hv)	
Run order	A	B	C	D	E	F	G	Ra_1	Ra_2	Mh_1	Mh_2
1	1	-1	-1	1	-1	1	1	6.35	6.38	105.6	152.0
2	-1	-1	-1	-1	-1	-1	-1	2.50	2.25	107.0	133.4
3	-1	-1	1	-1	1	1	1	10.34	8.60	257.4	316.8
4	1	-1	1	1	1	-1	-1	5.20	3.49	506.7	454.2
5	1	1	1	-1	-1	1	-1	2.56	1.61	284.1	208.2
6	-1	1	-1	1	1	1	-1	6.68	4.19	226.5	289.7
7	1	1	-1	-1	1	-1	1	4.55	3.24	357.6	440.9
8	-1	1	1	1	-1	-1	1	5.55	3.70	399.9	403.6

Procedures: The EDM experiment was conducted with all the conditions specified in Table 1. The compacted Cu-TaC electrode diameter is 13 mm and it was mounted on the machine through aluminum holder. The urea dielectric fluid was contained in a separate machining tank. The workpiece used is Ti-6Al-4V. After machining, the EDMed surfaces were subjected to both surface roughness and micro-hardness tests using SURFTEST and MVK-H2 Hardness testing machines respectively. The results are shown in Table 2. Both equations 1 and 2 were evaluated during analysis using Minitab 14 software. The data were analyzed through analysis of variance (ANOVA) at 5% significance level. The statistically significant factors are indicated by various plots presented in section 3.

RESULTS AND DISCUSSION

Table 3 and 4 presents the PBD statistical analysis for the Ra and the Mh respectively. Both the estimated effects and coefficients of the variables are presented alongside their ANOVAs. It can be seen that the blocking effect is statistically significant for the Ra, but not significant for the Mh. This implies that the blocking factor has an effect and was probably helpful in improving the precision the comparison of means. It also revealed that the main effects are highly statistically significant at ($p = 0.05$) and have F-value of 30.73 at ($P = 0.000$). Similarly, for the Mh, it has the F-value of 20.71 at ($P = 0.000$). Hence the main factors have large positive

Table 3: Plackett-Burman Design Analysis for Surface Roughness

Estimated Effects and Coefficients					
Variable / Term	Main Effect	Coefficient	SE Coefficient	T-value	P-value
Constant		4.8244	0.1505	32.06	0.000
A	-1.3037	-0.6519	0.1505	-4.33	0.003
B	-1.6287	-0.8144	0.1505	-5.41	0.001
C	0.6138	0.3069	0.1505	2.04	0.081
D	0.7363	0.3681	0.1505	2.45	0.044
E	1.9238	0.9619	0.1505	6.39	0.000
F	2.0288	1.0144	0.1505	6.74	0.000
G	2.5288	1.2644	0.1505	8.40	0.000

R-Sq = 97.09% R-Sq(adj) = 93.76%

Analysis of Variance

Source of Variation	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	1	6.592	6.592	6.5921	18.20	0.004
Main Effects	7	77.93	77.930	11.1329	30.73	0.000
Residual Error	7	2.536	2.536	0.3623		
Total	15	87.05				

Table 4: Plackett-Burman Design Analysis for Micro-Hardness

Estimated Effects and Coefficients					
Variable / Term	Main Effect	Coefficient	SE Coefficient	T-value	P-value
Constant		290.23	10.11	28.72	0.000
A	46.87	23.44	10.11	2.32	0.053
B	72.17	36.09	10.11	3.57	0.009
C	127.28	63.64	10.11	6.30	0.000
D	54.10	27.05	10.11	2.68	0.032
E	132.00	66.00	10.11	6.53	0.000
F	-120.38	-60.19	10.11	-5.96	0.001
G	28.00	14.00	10.11	1.39	0.208

R-Sq = 95.42% R-Sq(adj) = 90.19%

Analysis of Variance

Source of Variation	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	1	1482	1482	1482	0.91	0.373
Main Effects	7	236921	236921	33846	20.71	0.000
Residual Error	7	11439	11439	1634		
Total	15	249843				

SE-Standard Error; T-student's test; P-Corresponding level of Significance; DF-Degree of freedom; SS-Sum of Square; MS-Mean Sum of Square; F-Fisher's Function.

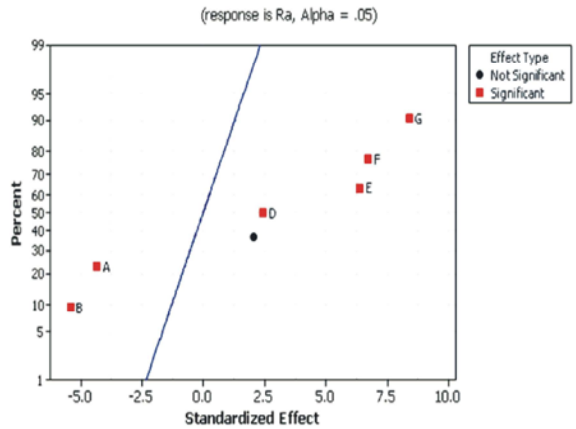

Fig. 1: Normal Probability Plot of Surface Roughness

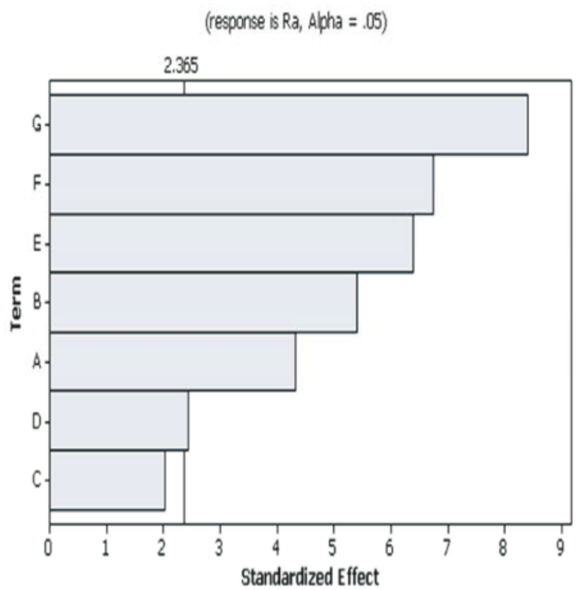

Fig. 2: The Pareto chart for surface roughness

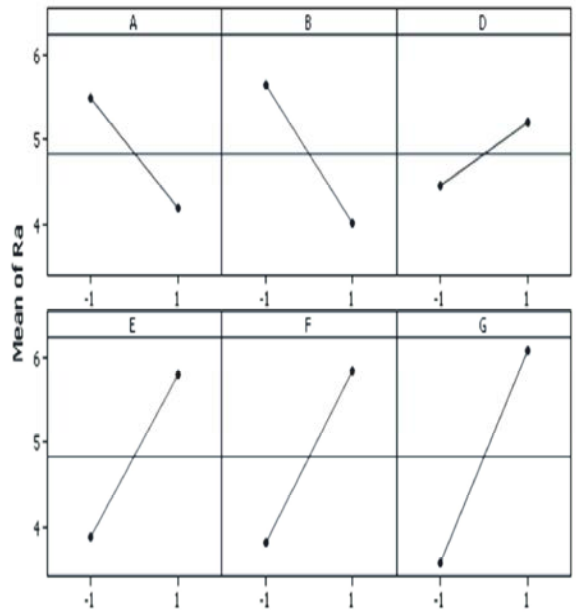

Fig. 3: Main effects plot (data means) for Surface Roughness

effects on the surface roughness and the micro-hardness respectively. The estimated effects (based on contrast effects) of the variables are presented in terms of Normal Probability plots of the residuals and Pareto charts for each of the outputs variables investigated. The main effects plots of the statistically significant factors were used to determine the minimum Ra and the maximum Mh that can be obtained.

In Figure 1, the effect factors A, B, D, E, F and G fall away from the straight line. This implies that they are statistically significant at 5% significant level.

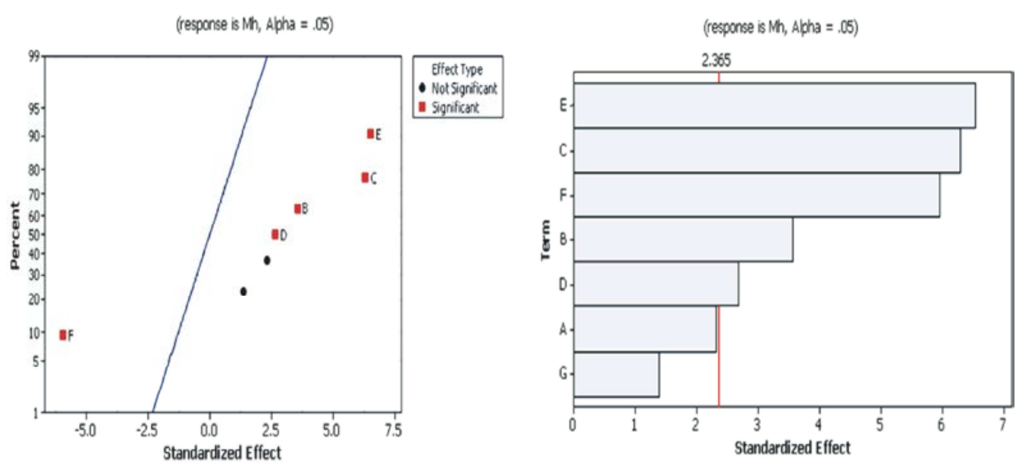

Fig. 4(a,b): (a) Normal probability plot for micro-hardness
(b) Pareto chart of the effects on micro-hardness

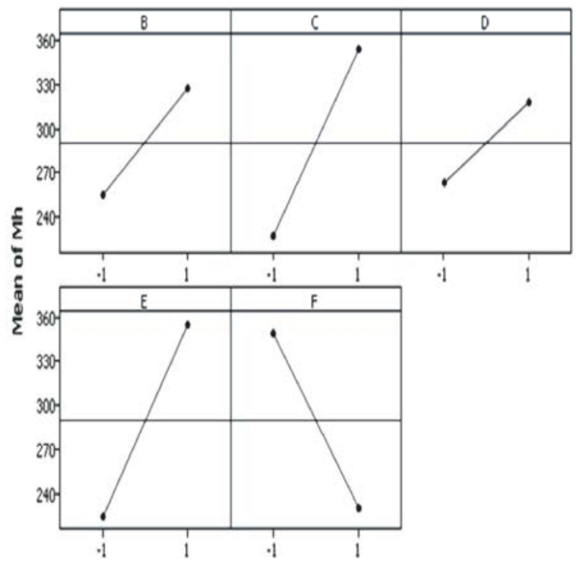

Fig. 5: Main effect plots of micro-hardness

They are important control factors that affect the mean surface roughness. The Pareto plot of Figure 2 also substantiates the findings in the Normal Probability plot. Factor G has the largest effect on the response (surface roughness), followed by F, E, B, A and D in that order. It is seen that the effect of factor C (urea concentration) is that it is not statistically significant. Therefore, urea concentration does not have any significant impact on the degree of surface roughness attained by the EDMed material. Figure 3 is plotted based on the estimated effects. These results suggested that the surface roughness would be at minimum when factor A (TaC composition) and B (compacting pressure) are set at high levels and other significant factors (peak current, pulse duration, duty factor and gap voltage) are set at lows.

In Figure 4a, the effects of factors D, B, F, C and E are found statistically significant at 5% significant level. The Pareto plot (Fig. 4b) shows that factors E (pulse duration), C (urea concentration) and F (duty factor) has tha largest effect on the micro-hardness. The TaC composition and the gap voltage have no statistically significant influence on the surface micro-hardness. From Figure 5, the maximum micro-hardness can be obtained with high levels of B, C, D and E, then low level of F. The identified parameters which influence both the surface roughness and micro-hardness can further be explored with more advanced methods such as response surface methodology (RSM). With this, the strength of each of the factors and their interactions effects could be ascertained.

CONCLUSIONS

Plackett-Burman design has been used to screen the significant factors that influence the surface roughness and micro-hardness of Ti-6Al-4V alloy during EDM with Cu-TaC electrodes. TaC composition, compacting pressure, peak current, pulse duration, duty factor and gap voltage were found to be statistically significant for the surface roughness attained during machining. The surface roughness can be minimized by setting TaC composition and compacting pressure at high levels, while other significant factors (peak current, pulse duration, duty factor and gap voltage) are set at low levels.

For the case of micro-hardness, TaC composition and gap voltage are not statistically significant. However, pulse duration, urea concentration, peak current, compacting pressure and duty factor have significant influence on the micro-hardness. The micro-hardness can be maximized by setting compacting pressure, urea concentration, peak current and pulse duration at high levels while maintaining the duty factor at low level.

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