INVESTIGATION OF THE INFLUENCE OF EDM PARAMETERS ON THE MACHINED SURFACE HARDNESS OF AISI D3 TOOL STEEL

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الملخص

لقد أثبتت طريقة التشغيل بالتفريغ الكهربي أنها الطريقة البديلة لتشغيل الأشكال الصعبة والمعقدة للمواد صعبة التشغيل مثل الصلب المقسّى. ويعتمد نجاح القطع التي تم تشغيلها بالتفريغ الكهربي على التفهم الكامل لآلية إزالة المادة وعلى العلاقة بين متغيرات القطع بالتفريغ الكهربي والخصائص السطحية للمادة المشغّلة.

تقدم هذه الورقة دراسة لمتغيرات التشغيل بالتفريغ الكهربي وتأثيرها على الخصائص السطحية لمادة صلب العدة المقسى AISI D3. تمثلت الاستجابة التشغيلية (المخرجات) في الصلادة السطحية للسطح المشغل (HRc) بينما كانت المتغيرات الداخلة (المدخلات) التيار النبضي وزمن النبضة الفعال وزمن النبضة غير الفعّال و فرق جهد الفجوة. ولقد شكلت النتائج المتحصل عليها على حصيلة قيمة لتأثير كل عنصر من المتغيرات الداخلة على الاستجابة التشغيلية.

ABSTRACT

Electric Discharge Machining (EDM) has been proven as an alternate process for machining complex and intricate shapes from difficult to machine materials such as hard steels. The success of electric discharge machined components in real applications relies on the understanding of material removal mechanisms and the relationship between the EDM parameters and the surface characteristics of the EDMed material. This paper presents an investigation of the influence of changes in EDM parameters on the surface hardness of electrical discharge machined AISI D3 tool steel. The machining response is the surface hardness of the machined surface (HR_c), while the input parameters are Pulse current (I_p), Pulse –on- time (T_{on}), Pulse –off- time (T_{off}), and the Gap voltage (V_g)**.** The results provide a valuable insight into the influence of each of the input parameters on the machining response.

KEYWORDS: EDM; Surface Hardness; Pulse Current; Pulse-on Time; Pulse-off Time; Gap Voltage

INTRODUCTION

In today technology there is a heavy demand of the advanced and difficult to machine materials, such as high strength thermal resistant alloys and hardened steels. In machining of these materials, conventional manufacturing processes are increasingly being replaced by more advanced techniques that can cope with these difficult to machine materials. Electrical discharge machining (EDM) is the pioneer of these techniques and has grown over the last few decades from a novelty to a mainstream manufacturing process. It is most widely and successfully applied for the machining of various workpiece materials in the advance industry. It is a thermal process with a complex metal removal mechanism, involving the formation of a plasma channel between the tool and work piece electrodes [1], the repetitive spark instigate melting and even evaporating the electrodes. The advantage of EDM process is its capability to machine difficult to machine materials with desired shape and size with a required dimensional accuracy and productivity. However, the efficiency of machining is low as compared to conventional machining. Though EDM process is very demanding but the mechanism of process is complex and far from completely understood. Therefore, it is troublesome to establish a model that can accurately predict the performance by correlating the process parameter. The optimum processing parameters are very much essential to be established to boost up the production rate to a large extent and shrink the machining time, since these materials and the process itself are costly.

The electrical discharge machined (EDMed) surface is essentially made up of three different layers consisting of recast layer (white layer), heat affected zone (HAZ) and unaffected parent metal [2,3]. A review on the metallurgy of EDMed surface was given by Lim et al. [4]. The level of thermal damage suffered by the electrode and the thickness of the white layer formed on the workpiece surface can be determined by analysing the growth of the plasma channel during sparking [5]. The white layer is the topmost layer exposed to the environment, so it exerts a great influence on the surface properties of the workpiece. Several authors discovered the presence of micro-cracks and high tensile residual stresses on the EDMed surface caused by the high temperature gradient [6]. The adverse effect of discharge energy also provided some insights on the fatigue strength of the workpiece, which propagates from the multiple surface imperfections within the recast layer [7]. In addition, the EDMed surface has a relatively high micro-hardness, which can be explained by the emigration of carbon from the oil dielectrics to the workpiece surface forming iron carbides in the white layer [1].

Marofana [8] argued that the EDMed workpiece hardness affects both metal removal rate and surface roughness and that the electrical discharge machining process is not only influenced by the thermal properties of the workpiece but also by its hardness.

Little research has been reported about EDM on AISI D3 steel yet for the modeling by surface response methodology. In this work, the effects of machining parameters on EDM machining characteristics were explored. Moreover, this work adopted an L9 orthogonal array based on Taguchi method to conduct a series of experiments, and statistically evaluated the experimental data by analysis of variance (ANOVA). The main machining parameters such as machining pulse current (Ip), pulse on time (T_{on}), Pulse off time (T_{off}), gap voltage (V) were chosen to determine the surface characteristics of the machined surface. This paper is assigned for the part of work dealing with the hardness of the machined surface.

EXPERIMENTAL WORK

Tool steel D3 was used as a test material. This material was selected because of its importance in the industry and tool making. The chemical composition in weight percent is shown in Table (1). The material was received in the form of blooms which in turn are sliced into sections of (45mm x 22mm x 15mm) by a sawing machine, then machined by milling machine for the purpose of finishing specimens to the required dimensions. Workpieces are then heat treated in order to increase hardness (from ~

HR_c48 to ~ HR_c55) through hardening at 980C° soaking for 43 minutes and then oil quenching, followed by tempering at 400Cº soaking for 60 minutes and then air cooling for the purpose of stress removal. The electrical discharge machining is done by an EDM die sink machine, model ONA CS/HS- 3 axis, shown in Figure (1). Brass electrode (Cu-61.8%, Zn-37.2% and impurities-1.0%) was selected to engrave the workpiece material to produce the shape shown in Figure (2). Commercial grade kerosene was used as the dielectric fluid and side injection of the dielectric fluid was opted.

Table 1: Chemical composition of tool steel D3 (wt. %)

C	Si	P	Mn	Ni	Cr	Mo	V	Cu	W	Fe
1.07	0.349	0.016	0.422	0.188	12.14	0.084	0.0195	0.057	0.565	Balance

Figure. 1: EDM die sinking – 3axis machine

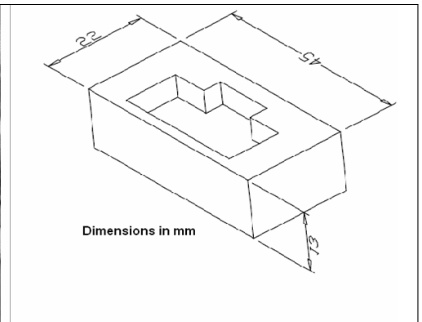

Figure. 2: Shape of the EDMed workpiece

DESIGN VARIABLES

The design variables are divided into two main groups: Input parameters (machining variables) and output measures (response characteristics).

The input parameters are: Pulse current I_p (A), Pulse–on–time T_{on} (µs), Pulse–off–time T_{off} (µs), and the Gap voltage Vg (V). The output measure being the surface hardness of the machined surface of work material (HR_c)

The controllable factors values were chosen based on literature review and capability of the commercial EDM machine used. Different settings of the four controllable factors were used in the experiments and have been divided into three different levels as shown in Table (2)

Table 2: Levels for Controllable Factors.

Symbol	EDM Machining Parameters	Level 1	Level 2	Level 3
I_p	Pulse current (A)	26	36	46
T_{on}	Pulse –on- time (µs)	50	200	800
T_{off}	Pulse –off- time (µs)	25	100	200
V_g	Gap voltage (V)	20	45	90

Analysis of machining variables

The present analysis includes Taguchi's method based on parametric optimization technique to quantitatively determine the effects of various machining parameters on the quality characteristics of EDM process and to find the optimum parametric condition for obtaining optimum machining criteria1 yield. In this analysis, the performed parametric design of experiment is based on the selection of an appropriate standard orthogonal array. The analysis of signal-to-noise (S/N) ratio and ANOVA were carried out to study the relative influence of the machining parameters on the hardness of EDMed surface of tool steel D3. Based on S/N ratio and ANOVA analysis, the optimal setting of the machining parameters for machined surface hardness were obtained and verified.

The main effective plots of the S/N ratios for the output measures are obtained using Minitab 15 software. Plots with the steeper slope along with longer lines shows that the factor has significant impact on the output variable.

Analysis of Signal-to-Noise Ratio

In Taguchi method, S/N ratio is used to measure the quality characteristics deviating from the desired value. The term signal represents the desirable mean value of the output characteristics and the term noise represents the undesirable value (i.e., standard deviation) for the output characteristics. In order to obtain optimal machining performance, the higher the better quality characteristics for hardness are considered.
The S/N ratio for hardness, for j^{th} experiment is defined as

$$(S/N)_j = -10\,Log_{10}\left(\frac{1}{m}\sum_{i=1}^{m}\frac{1}{y_{ij}^2}\right) \qquad (1)$$

Where m is the number of replications and y_{ij} is the value of hardness of i^{th} replication test for j^{th} experimental condition.

Table (3) shows the experimental results for hardness and the corresponding S/N ratio using equation (1). Since the experimental design is orthogonal, it is possible to sort out the effect of each machining parameter at different levels. The mean S/N ratio for the pulse current (I_p) at levels 1, 2 and 3 can be calculated by averaging the S/N ratios for the experiments 1-3, 4-6 and 7-9, respectively.

Table 3: Design of experiments and experimental results for hardness and calculated S/N ratio

	Design of experiments								
Exp. No.	I_p (A)	T_{on} (μs)	T_{off} (μs)	V_g (V)	Hardness(HRc)			Average HRc	S/N ratio
J	A	B	C	D	y_{1j}	y_{2j}	y_{3j}	y_{4j}	
1	26	50	25	20	56.1	55.5	55.8	55.8000	34.9324
2	26	200	100	45	52.0	54.0	53.6	53.2000	34.5148
3	26	800	200	90	55.9	56.1	55.6	55.8667	34.9429
4	36	50	100	90	56.5	56.1	56.7	56.4333	35.0305
5	36	200	200	20	55.8	55.5	54.6	55.3000	34.8534
6	36	800	25	45	52.5	52.7	55.2	53.4667	34.5549
7	46	50	200	45	55.4	56.2	54.9	55.5000	34.8847
8	46	200	25	90	54.4	55.4	54.7	54.8333	34.7801
9	46	800	100	20	55.7	54.7	54.2	54.8667	34.7845

Average S/N ratio for every level of experiment is calculated based on the recorded value and is shown in Table (3). Different values of S/N ratio between maximum and minimum (main effect) are also shown in Table (4). The voltage gap and pulse –on – time are the two factors having the highest values 0.27 and 0.23, respectively. Referring to Taguchi prediction that the bigger different value of S/N ratio will impose the highest influence on hardness, or will be the most significant. So, it can be concluded that minor changes in the voltage gap and pulse – on – time will affect the hardness significantly.

Table 4: Ranking of input parameters as per influence on surface hardness

Level	I_P	T_{ON}	T_{OFF}	V_g
1	34.80	34.95	34.76	34.86
2	34.81	34.72	34.78	34.65
3	34.82	34.76	34.89	34.92
Delta	0.02	0.23	0.14	0.27
Rank	4	2	3	1

The average S/N ratio for all the levels of all machining parameters taking **HRc** as response is graphically exhibited in Figure (3). The highest average S/N ratio gives the maximum **HRc.** It is clear from the S/N ratio response graph (Figure. 3) that for achieving maximum **HRc** for the given controllable factors**,** the optimum condition of machining is A_3 B_1 C_3 D_3 i.e., pulse current of 46A, pulse-on-time 50µs, pulse-off-time 200µs and voltage gap 90V.

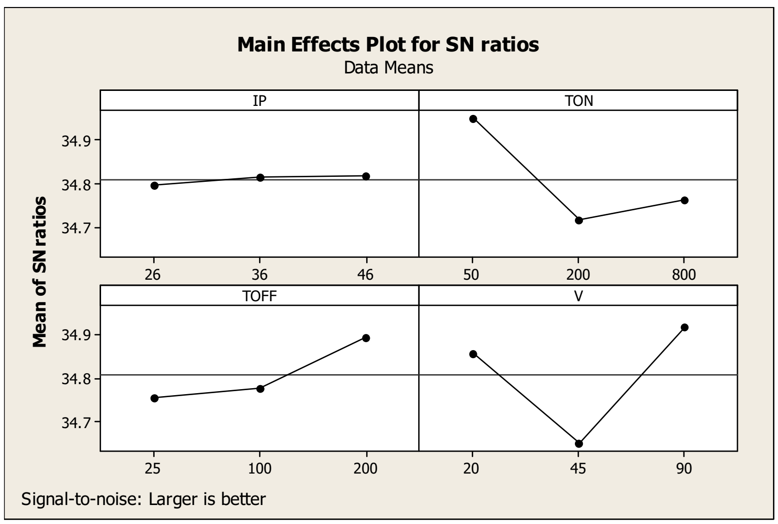

Figure 3: Signal-to-noise graph for hardness (HRc).

ANALYSIS OF VARIANCE (ANOVA)

In this investigation, the analysis of variance (ANOVA) is performed to determine which machining parameter significantly affects the quality characteristics of EDM process and also to find the relative contribution of machining parameters in controlling the responses of the EDM process. To accomplish ANOVA, the total sum of squared deviation (SS_T) from the total mean **S/N** ratio can be determined as:

$$SS_T = \sum_{j=1}^{N}((S/N)_j - (S/N)_m)^2 \quad (2)$$

Where N is the total number of experiments and $(S/N)_m$ is the grand mean of S/N ratio.

The total sum of SST is decomposed into two sources: (i) the sum of squared deviations due to each machining parameters (SS_A, SS_B, SS_C and SS_D) and (ii) the sum of squared error (SS_E). To perform F (variance ratio) test, the mean squared deviation due to each design parameter is calculated. The mean of squared deviation is equal to SS_T divided by the number of Degrees of freedom (DOFs) associated with the design parameters. The F-value for each design parameter is the ratio of the mean of the squared deviation to the mean of squared error. The percentage contribution by each of the design parameters is a ratio of the value of sum of squared of each design parameters to the total sum of squared for all the design parameters.

Pooling

Pooling is a method of estimating the error variance, which consists of pooling the sum of the squares of the control parameters that have a small contribution to the overall mean level. When the contribution of a parameter is small, the sum of squares for that parameter is combined with the error variance. This process of disregarding the contribution of a selected parameter and subsequently adjusting the contributions of the other parameter is known as pooling. If the sum of squares of parameter is less than (2%) of the total sum of squares, the parameter can' be pooled to obtain a larger Degree of Freedom (DOF) for the experimental error term (Peace, 1993). Taguchi's method advises that pooling should start with the smallest effect and successively include larger effects until the total of the error term DOF is equal to approximately half of the total table DOF.

When the DOF of the error variance is sufficiently large, error variance represents the experimental error. When the error DOF is small or zero, which is the case when all columns of the orthogonal array are occupied and trials are not repeated, smaller column effects are successively pooled to form a larger error term (this is known as a pooling-up strategy). The parameters that are now significant in comparison with the larger magnitude of the error term are now influential. Taguchi prefers this strategy, as it tends to avoid the mistake of ignoring helpful parameters. A larger error DOF naturally results when trial conditions are repeated and standard analysis is performed. When the error DOF is large, pooling may not be necessary. Therefore, one could repeat the experiment and avoid pooling. But to repeat all experiment conditions just for information on the error term may not be practical.

The results of ANOVA for Hardness is shown in Table (5) The calculated value of F in ANOVA table is used to measure relative factor effects. The larger the value of F, the more important that factor becomes for controlling the responses of EDM process. So F-value can be used to rank order the contribution of factors. From the results of ANOVA, it is reflected that the gap voltage is the most influencing factor for controlling HRc. The pulse -on- time has moderate effect, pulse-off-time little effect on HRc. The pulse current has very little effect on HRc of EDM process. Since ANOVA has resulted in zero degree of freedom for error term, it is necessary to pool the factor having less influence for correct interpretation of results. It is observed that the pooled error is less than 10%, indicating that important factors are not omitted from the experiments see (Table 6).

According to F test, the change in the design parameter has a significant effect on the quality characteristics if the calculated value of F is greater than the value of F_a (n_1, n_2), where (1-a) is the confidence level and n1-and n2 are the DOFs of design parameter and error, respectively. Within 95 per cent confidence limits for n_l =2, and n_2 =2, the value of $F_{.025}$ (2, 2) is 39. The calculated value of F for each design parameter is greater than 39. Hence at 97.5 per cent confidence level, the change in each design parameter has a significant effect on hardness.

Table 5: Results of ANOVA

Symbol	Machining parameter	DOF	Sum of squares	Variance	F	Contribution %
A	Pulse current	2	0.000666	0.000333	---	0.28
B	Pulse-on-time	2	0.091826	0.045913	---	37.87
C	Pulse-off-time	2	0.033126	0.016563	---	13.66
D	Gap voltage	2	0.116847	0.058423	---	48.19
Error		0	---	---	---	
Total		8	0.242465			100.00

Table 6: Pooled ANOVA for Hardness.

Symbol	Machining Parameter	DOF	Sum of squares	Variance	F	Contribution %
A	Pulse current	(2)	Pooled	Pooled	---	---
B	Pulse-on-time	2	0.091826	0.045913	137.87	37.60
C	Pulse-off-time	2	0.033126	0.016563	49.74	13.38
D	Gap voltage	2	0.116847	0.058423	175.4	47.90
Error		(2)	(0.000666)	(0.000333)	---	1.12
Total		8	0.242465	---	---	100.00

CONFIRMATION TESTS

After the selection of the optimal level of design parameters, the final step is to predict and verify the improvement in the quality characteristics of the EDM process. The predicted optimum value of S/N ratio $(\bar{S/N})_p$ can be determined as

$$(\bar{S/N})_p = (S/N)_m + \sum_{j=1}^{p}((\bar{S/N})_j - (S/N)_m) \quad (3)$$

Where $(S/N)_m$ is the grand mean of S/N ratio, $(\bar{S/N})_j$ is the mean S/N ratio at the optimum level, and p is the number of main design parameters that affects the quality characteristics.

Table (7) shows a comparison of the predicted hardness (HRc) with the actual HRc using the optimal machining parameter and good agreement between the predicted and the actual HRc is observed (see exp. N^o. 4 in Table 3).

Table 7: Results of confirmation experiment for hardness (HRc)

	Optimal machining parameters	
	Predicted	Experimental
Level	$A_3 B_1 C_3 D_3$	$A_2 B_1 C_2 D_3$
Hardness (HRc)	57.22	56.43
S/N ratio	35.151	35.031

CONCLUSIONS

The Taguchi method of parametric optimization is applied for the optimization of the machining parameters of EDM process-for AISI D3 tool steel with respect to machined surface hardness.

From the experimental results, S/N ratio and ANOVA analysis and predicted optimum machining parameters, the following conclusions are drawn:

(a) The gap voltage, pulse –on- time and pulse – off - time are the three influential parameters (in rank order based on percentage contribution) which significantly affect the hardness. The pulse current has very little effect on machined surface hardness by the EDM process.

(d) For achieving maximum hardness (HRc), the optimal level of parametric conditions according to the proposed controllable variables are A_3 B_1 C_3 D_3 ; i.e., pulse current of 46A, pulse-on-time 50µs, pulse-off-time 200µs and voltage gap 90V.

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