

Investigation of the influence of EDM parameters on the overcut for AISI D3 tool steel

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Abstract: Electric discharge machining (EDM) has been proven as an alternative 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 formation of surface and subsurface damage. This paper presents a detailed investigation of the EDM machining characteristics of hardened AISI D3 tool steel. The machining response is the overcut of the process (OC), and 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 experimental results have provided the optimal combination of input parameters that gives the minimal overcut on the machined surface.

Keywords: overcut, pulse current, pulse-on time, pulse-off time, gap voltage

1 INTRODUCTION

In today's technology there is a heavy demand for the advanced and difficult-to-machine materials, such as high-strength thermally resistant alloys and hardened steels. In machining these materials, conventional manufacturing processes are increasingly being replaced by more advanced techniques that can cope with them. Electrical discharge machining (EDM) has grown over the last few decades from a novelty to a mainstream manufacturing process. It is widely and successfully applied for the machining of various workpiece materials in advanced industry [1]. It is a thermal process with a complex metal removal mechanism, involving the formation of a plasma channel between the tool and workpiece electrodes, with the repetitive spark instigating melting and even evaporating the electrodes. The advantage of the EDM process is its ability to machine difficult-to-machine materials to the desired shape and size with the required

dimensional accuracy and productivity. However, its machining efficiency is low, compared with conventional machining. The EDM process is very demanding, and its mechanism of operation is complex, and far from completely understood. Therefore it is difficult to establish a model that can accurately predict the performance by correlating the process parameters. Optimization of these parameters is essential to boost the production rate and reduce the machining time, since both the materials that are processed by EDM and the process itself are very costly [2].

Several research works have explained the material removal mechanism in terms of the migration of material elements between the workpiece and electrode. Sastangi and Chattophadhyay [3] showed an appreciable quantity of elements diffusing from the electrode to the workpiece and vice versa. These elements are transported in the solid, liquid, or gaseous state, and are alloyed with the contacting surface by undergoing a solid, molten, or gaseous-phase reaction.

Other research attempts have been made to model the EDM process and investigate the process performance to improve metal removal rate (MRR)

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and overcut (OC). Improving the MRR and surface quality are still challenging problems that restrict the expanded application of the technology. Semi-empirical models of MRR for various workpiece and tool electrode combinations have been presented by Wang and Tsai [4]. Luis *et al.* [5] studied the influence of pulse current, pulse time, duty cycle, open-circuit voltage, and dielectric flushing pressure on the MRR and other response variables in tungsten carbide. Josko and Junkar [6] studied the influence of surface area and the gap between electrode and workpiece in rough machining parameters, and concluded that in order to attain a high removal rate in EDM, a stable machining process is required, which is influenced partly by contamination of the gap between the workpiece (hardened steel 210CR12) and the electrode; it also depends on the size of the eroding surface for the given machining regime [6].

Diametral overcut also depends upon the finishing and roughing spark gap and crater size. Because of the presence of side sparks, overcuts are found to occur in the work material. The side spark gap is half the diametral difference between the electrode and eroded hole in the work material. The spark gap must be considered when selecting an electrode size to achieve a particular hole diameter. The frontal spark gap determines the ultimate depth of the blind hole. The variation between discharges in terms of their electrical characteristics and strike location within the gap is influenced by several factors [7–9]. It has been established that only spark pulses are responsible for metal erosion. Short-circuit, open circuits, and arcing pulses are collectively termed ‘ineffective pulses’ [10]. It has been experimentally shown that during EDM there is an appreciable amount of diffusion of metals from the tool electrode to the work material and vice versa [11].

Shankar *et al.* [12] concluded that the diametral overcut produced on En-31 tool steel is comparatively low when using copper and aluminium electrodes, which may be preferred for this material when low diametral overcut (higher dimensional accuracy) is the requirement. They also claimed that overcut increases with the increase of discharge current, but only up to a certain limit. Thus overcut depends upon the gap voltage and chip size, which vary with the amperage used.

Dhar *et al.* [13] conducted EDM experimental work on cast aluminium matrix composites, and

concluded that an increase in current increases the radial overcut, owing to an increase in MRR. An increase in pulse duration (keeping all other factors constant) also increases the radial overcut, owing to the prolonged presence of sparks, which produces an increase in energy per spark.

Little research has been reported so far about D3 tool steel for modelling by surface response methodology. In this work, the effects of machining parameters on the overcut of the ED-machined objects were explored. This work adopted an L9 orthogonal array based on the Taguchi method to conduct a series of experiments, and statistically evaluated the experimental data by analysis of variance (ANOVA). The main machining parameters, which are machining pulse current I_p , pulse-on time T_{on} , pulse-off time T_{off} , and gap voltage V_g , were investigated to determine their influence on the overcut of the machined surface.

2 EXPERIMENTAL WORK

D3 tool steel was used as the test material. This material was selected because of its importance in industry and in tool making. The chemical composition is shown in Table 1. The material was received in the form of blooms, which were sliced by a sawing machine into sections measuring 45 mm × 22 mm × 15 mm, and then machined by a milling machine to finish the specimens to the required dimensions. The workpieces were then heat-treated in order to increase their hardness, by heating them at 980°C for 43 min and then oil-quenching, followed by tempering at 400°C for 60 min and then air-cooling for the purpose of stress removal. The machining was done by a three-axis EDM die sink machine, model ONA CS/HS-3 axis. A commercial copper electrode (99.9 per cent Cu) was selected to engrave the workpiece material to produce the shape shown in Fig. 1. Commercial-grade kerosene was used as the dielectric fluid, and side suction of the dielectric fluid was chosen. The EDM machine used for this work is shown in Fig. 2.

3 DESIGN VARIABLES

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

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

C	Si	P	Mn	Ni	Cr	Mo	V	Cu	W	Fe
2.26	0.336	0.003	0.442	0.161	13.02	0.091	0.024	0.097	0.587	Balance



Fig. 1 The workpiece used in this work



Fig. 2 The EDM machine used in this work

The input parameters are pulse current I_p (A), pulse-on time T_{on} (μ s), pulse-off time T_{off} (μ s), and gap voltage V_g (V). The output measure is the overcut of the machined surface of the work material (OC).

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

3.1 Analysis of machining variables

The present analysis includes Taguchi's method based on a parametric optimization technique to determine quantitatively the effects of various machining parameters on the quality characteristics of the EDM process, and to find the parametric conditions that optimize the machining criteria yield. In this analysis, the parametric design of the experiment is based on selection of an appropriate standard orthogonal array. The signal-to-noise (S/N) ratio

Table 2 Levels for controllable factors

EDM machining parameter	Level 1	Level 2	Level 3
Pulse current, I_p (A)	26	36	46
Pulse-on time, T_{on} (μ s)	50	200	800
Pulse-off time, T_{off} (μ s)	25	100	200
Gap voltage, V_g (V)	20	45	90

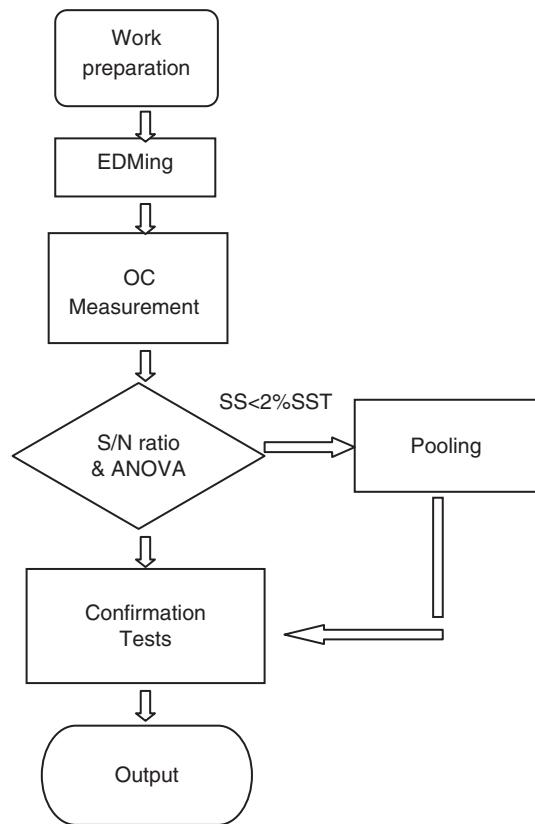


Fig. 3 Flow chart of the experimental and analytical work

and ANOVA were analysed to study the relative influence of the machining parameters on the overcut of the machined material. Based on the S/N ratio and ANOVA analysis, the optimal setting of the machining parameters for overcut were obtained and verified.

The main effective plots of the S/N ratios for the output measures were obtained using Minitab 15 software. Plots with a steeper slope along with longer lines show that the factor has significant impact on the output variable. A flow chart illustrating the methodology of this work is shown in Fig. 3.

3.2 Analysis of signal-to-noise ratio

In the Taguchi method, the S/N ratio is used to measure how far the quality characteristics deviate from the desired value. The term 'signal' represents the desirable mean value of the output characteristics,

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

Exp. no. <i>j</i>	Design of experiments				Oercut (OC) (mm)			Average OC (mm) <i>y_{4j}</i>	S/N ratio
	<i>I_p</i> (A) A	<i>T_{on}</i> (μs) B	<i>T_{off}</i> (μs) C	<i>V_g</i> (V) D	<i>y_{1j}</i>	<i>y_{2j}</i>	<i>y_{3j}</i>		
1	26	50	25	20	0.095	0.070	0.070	0.078333	22.0239
2	26	200	100	45	0.095	0.080	0.100	0.091667	20.7186
3	26	800	200	90	0.115	0.125	0.150	0.130000	17.6658
4	36	50	100	90	0.105	0.120	0.115	0.113333	18.8997
5	36	200	200	20	0.135	0.125	0.125	0.128333	17.8274
6	36	800	25	45	0.210	0.215	0.195	0.206667	13.6873
7	46	50	200	45	0.110	0.110	0.090	0.103333	19.6792
8	46	200	25	90	0.175	0.130	0.105	0.136667	17.0959
9	46	800	100	20	0.290	0.260	0.275	0.275000	11.2047

Table 4 Average for S/N ratio and main effect of overcut

Level	<i>I_p</i>	<i>T_{on}</i>	<i>T_{off}</i>	<i>V_g</i>
1	20.14	20.20	17.06	17.02
2	16.80	18.55	16.94	18.03
3	15.99	14.19	18.39	17.89
Delta	4.14	6.01	1.45	1.01
Rank	2	1	3	4

and the term noise represents the undesirable value (i.e. standard deviation) of the output characteristics.

To obtain the optimal machining performance, the lower the overcut, the better the accuracy of machined surface. The S/N ratio for overcut for the *j*th experiment is defined as

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

where *m* is the number of replications, and *y_{ij}* is the value of the overcut of the *i*th replication test for the *j*th experimental condition.

Table 3 shows the experimental results for overcut and the corresponding S/N ratio using equation (1). The average S/N ratio for overcut for all the factors at different levels is determined as shown in Table 4.

The pulse-on time is the most significant factor affecting the overcut value, followed by the pulse current, with delta values of 6.01 and 4.14 respectively.

The S/N response graph for overcut is shown in Fig. 4. Greater average values of S/N ratio correspond to the minimum overcut. From the S/N response graph (Fig. 4), it is concluded that the optimum parametric combination is A₁, B₁, C₃, D₂ (i.e. pulse current 26 A, pulse-on time 50 μs, pulse-off time 200 μs, and gap voltage 45 V).

4 ANALYSIS OF VARIANCE

In this investigation, the analysis of variance (ANOVA) is performed to determine which machining parameter

significantly affects the quality characteristics of the EDM process, and also to find the relative contributions of the machining parameters in controlling the responses of the 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 the S/N ratio.

The total sum SST is decomposed into two sources: (1) the sum of squared deviations due to each machining parameter (SS_A, SS_B, SS_C, and SS_D); and (2) the sum of squared error (SS_E). To perform the *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 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 the squared error. The percentage contribution for each of the design parameters is a ratio of the value of the sum of squared of each design parameters to the total sum of squares of all the design parameters.

Table 5 shows the results of ANOVA for overcut. It is found that the pulse-on time has the most significant effect (63.1 per cent) on the overcut of the EDM process. The pulse current has a moderate effect (31.5 per cent), and the pulse-off time and gap voltage have very little effect. For a correct interpretation of the results, though, it is necessary to pool the factors having less influence: see Table 6. From the calculated value of *F*, it is concluded that at a 97.5 per cent confidence level the machining parameters A and B have a significant effect on the overcut, as the calculated value of *F* is greater than the value of *F*_{0.025(2,4)} = 10.65.

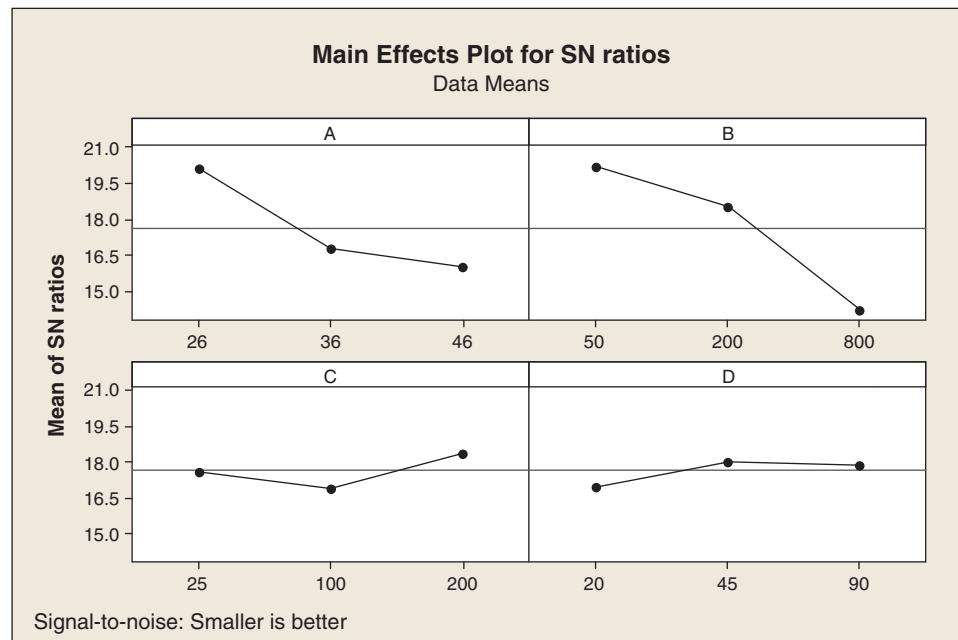


Fig. 4 Signal-to-noise graph for overcut

Table 5 Results of ANOVA for overcut

Symbol	Machining parameter	DF	SS	MS	F	Contribution (%)
A	Pulse current	2	28.9190	14.4595	—	31.5
B	Pulse-on time	2	57.9361	28.9680	—	63.1
C	Pulse-off time	2	3.1608	1.5804	—	3.45
D	Voltage gap	2	1.7937	0.8969	—	1.95
Error		0	—	—	—	—
Total		8	91.8096	—	—	100.00

Table 6 Pooled ANOVA for overcut

Symbol	Machining parameter	DF	SS	MS	F	Contribution (%)
A	Pulse current	2	28.9190	14.4595	11.67	28.8
B	Pulse-on time	2	57.9361	28.9680	23.38	60.5
C	Pulse-off time	(2)	Pooled	Pooled	—	—
D	Voltage gap	(2)	Pooled	Pooled	—	—
Error		4	(4.9545)	(1.2386)	1	10.7
Total		8	91.8096	—	—	100.00

5 CONFIRMATION OF TESTS

By selecting the optimal level of the design parameters, the final step is to verify and confirm the obtained (predicted) parameters with those found through experimental work to assess the quality characteristics of the EDM process. The predicted optimum value of the S/N ratio, $(\bar{S}/N)_p$, can be determined as

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

where $(S/N)_m$ is the grand mean of the 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 affect the quality characteristics.

Table 7 shows a comparison of the predicted overcut with the actual overcut using the optimal machining parameters. Good agreement between the predicted and the actual overcut can be seen.

This also agrees with research works [7–12] and [14], in that low pulse current and low pulse-on time are always considered to give low values of overcut, which, hereby, is also applicable to D3 tool steel.

Table 7 Results of overcut confirmation experiments

	Optimal machining parameters			
	Predicted	Experimental	A ₁	B ₁
Level	A ₁ B ₁ C ₃ D ₂	A ₁ B ₁ C ₁ D ₁		
Overcut (OC)	0.064	0.078		
S/N ratio	23.822	22.121		

The obtained results are believed to give low values of duty factor, which may cause machining instability and give low MRR. However, the predicted machining parameters are the ideal, and are expected to give the highest-accuracy machining (expressed by low overcut), but with a poor productivity rate owing to the very low MRR.

6 CONCLUSIONS

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

1. Pulse-on time and pulse current are the two influential parameters, in order of importance, that significantly affect the overcut. The pulse-off time and gap voltage are less influential.
2. To achieve minimum overcut, the optimum levels of the parameters are pulse current 26 A, pulse-on time 50 μ s, pulse-off time 200 μ s, and gap voltage 45 V.

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