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Experimental Investigation of Surface Roughness and Kerf Width During Machining of Blanking Die Material on Wire Electric Discharge Machine

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ABSTRACT

Wire electric discharge machine (WEDM) is spark erosion in unconventional machining technique to cut hard and the conductive material with a wire as an electrode. The blanking die material SKD 11 is a high carbon and high chromium tool steel with high hardness and high wearing resistance property. This tool steel has broad application in press tools and dies making industries. In this research study the behavior of six process parameters includes Ton (pulse on time), Toff (pulse off time), IP (peak current), SV (servo voltage), WF (wire feed rate) and WT (wire tension) base on design of experiment method during WEDM of SKD 11 were experimentally studied. The 0.25 mm diameter of the brass wire has used as the electrode to cut the work piece. The surface roughness and kerf width are selected as performance measurement. Response Surface methodology (RSM) is utilized for process optimization as well as for formulating regression model for correlating process parameters with performance measurements.

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1. INTRODUCTION

WEDM process, also known as spark erosion process used to create very intricate and complicated shapes on electrically conductive work pieces through a wire. The sparks will be generated between an electrode (wire) and the work piece flushed by the dielectric fluid. The superior surface finishes and level of dimensional accuracy of workpiece obtainable after machining by WEDM mainly necessary for applications concerning the manufacture of dies and moulds, aerospace industries, medical and surgical industries, automobile industries, etc [1]. Due to inherent properties of WEDM, the complex and precision shape can be machined with this technique [2]. In the present research study, the WEDM of SKD 11 is modelled and optimized. The consequences can recover the manufacturing situation and excellence of the machined work piece extensively to meet the different manufacturing firm requirements [3].

Some research had been highlighted on modelling pulse duration to be altered in three different levels. Facts and optimizing the performance of the WEDM process. Mahapatra [4] developed quadratic mathematical models using Response surface methodology to depict the process behaviour of WDM operation. Experiments were performed by six input process variables like pulse frequency, wire speed, wire tension, discharge current, dielectric flow rateand related to the performance measure viz. SR ,and KW were measured for all of the experimental trials. Rao et al. [5] present optimization of process variables during cutting of Aluminum-24345 by WEDM using RSM. Multiple linear regression models has been developed relating the process parameters and machining performance. Rajesh and Anand [6] attempted to model the Material Removal Rate (MRR) and Surface Finish (Ra) in wire EDM process through response-surface methodology and Genetic Algorithm (GA). Working current, working voltage, oil pressure, spark gap Pulse on Time and Pulse off Time were selected as input parameters. Ghodsiyeh et al. [7] deliberate the

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performance of three input process variables during machining of titanium alloy on WEDM with 0.25 mm diameter of zinc coated brass wire by use of response surface methodology as a design of experiment as well as to perform ANOVA to find significant parameters affecting material removal rate. Sparking gap and surface roughness. Sharma et al. [2] investigated the effect of input controlled parameters on MRR for WEDM using high strength and low alloy as work-piece and brass wire as the electrode. The central composite response surface Methodology was utilized for creating design matrix for final experimentations as well as for formulating a mathematical model which correlates the independent process parameters with the desired surface roughness and material removal. Lusi et al. [8] proposed fuzzy logic and gray relation analysis combine with Taguchi techniques to forecast the optimal process variables such as open voltage, off time, servo voltage, arc on time and on time of WEDM process of SKD 61 tool steel as SR, Kerf and MMR multi-performance characteristics. Sudhakara and Prasanthi [9] explored the review of the research work carried out by various research workers with multiple methodologies and how the output parameters of the WEDM like surface finish, metal removal rate, dimensional accuracy and HAZ were affected by the input process parameters like on time, off time, voltage, wire tension, wire feed, dielectric pressure. Current, etc. Kumar et al. [10] studied the effect of machining parameters like peak current (Ip), pulse-on time (Ton), pulse-off time (Toff), and servo voltage (SV) for three response as cutting speed (CS), surface roughness (SR) and radial overcut (RoC) during machining of Nimonic-90 on wire electrical discharge machining (WEDM) by DoE as a Response surface methodology as well as utilizes desirability function for multi-objective optimization. Mohapatra et al. [11] discussed the effect of process parameters like wire feed rate, servo voltage, wire tension and pulse off timefor obtaining minimum SR and maximum MRR during machining of copper spur gear by desirability with grey Taguchi technique and Taguchi quality loss design techniques. Chakraborty and Bose [12] used entropy based grey relation analysis to identify the optimal cutting parameters: gap voltage, pulse on time, corner angle, servo feed setting, peak current and pulse off time for cutting velocity, SR, MRR and corner inaccuracy during WEDM process of Inconel 718 by Taguchi L27 OA design of experiments. Sivaraman et al. [13] analyzed the effect of various control parameters (pulse on time, pulse off time and wire tension) of WEDM of titanium on the response parameters to get higher metal removal rate and surface finish using Response Surface Methodology.

A significant amount of investigation has been carried out on Wire EDM with a variety of conductive metals. In this study, the experiments were performed on WEDM taking SKD 11 as a workpiece. The material is attracting interest because of its high carbon and chromium as compared to other steel. Due to its high wear resistance, good corrosion resistance and high strength, this makes it favorable for tools and die manufacturing industries. Every WEDM is come along with insufficient operating data. This data is not sufficient for machining all material; there must be some performance analysis is required to find out the optimized set of parameters at which production, as well as quality, can be balanced. This present work highlights the development of mathematical models for correlating the inter-relationships of various WEDM machining parameters of SKD 11 such as; Ton, Toff, SV, IP, WT and WF on the surface roughness and kerf width. These works has been recognized based on the response surface methodology (RSM) approach. Mathematical, empirical models fitted to the experimental data will contribute towards the assortment of the most favorable process parameters settings.

2. EXPERIMENTAL PROCEDURE

A sequence of preliminary trials has been performed as per RSM. The experimental set up, work piece material and measuring apparatus, design of experiments and selection of input process variables and their range have been explained in the subsequent sections.

2. 1. Workpiece Material SKD 11 [14] required for experimentation was procured from M/s Bansidhar steel Corporation, Rakhiyal, Ahmedabad. Table 1 summarized chemical composition of SKD 11 material. During to perform all experiments, the height of the work piece material is 12 mm, and as tool electrode, 0.25 mm diameter of the brass wire is used.

2. 2. Experimental Setup and Performance Measuring Devices The experiments are performed on 4 axes Electronica Sprint cut-734 WEDM machine available at Jay Tech Industries, Odhav, Ahmedabad.

TABLE 1. Chemical composition of SKD 11

Element	Standard (Max Weight)	Actual (Max Weight)
C	1.40 – 1.60 %	1.55 %
Mn	0.60 % max	0.35 %
Si	0.60 % max	0.25 %
V	1.10 % max	0.9 %
Mo	0.7 -1.20 %	0.8 %
Cr	11.0 -13.0%	12.0 %
Fe	Balance	Balance

The different input control parameters are varied during the experimentation like Toff, Ton, WF, IP, WT and SV; to study their effects on surface roughness and kerf width. The wire is connected to -ve terminal while the work piece is connected with +ve terminal. The wire diameter is kept constant during the entire process. A fixture is used to grip the workpiece on the machine table to reduce any chance of misalignment. The electrode and work piece are separated from the deionized water. The centre line average (CLA) surface roughness parameter (Ra) is used to quantify surface roughness of the machined surface. Ra is measured using a contact type Mitutoyo Surftest SJ -410 roughness tester, having at least count of 0.001 µm. The cutoff length is 0.8 mm, and evaluation length is 4 mm. Ra is measured at three places upright in the direction of cut and mean of the three readings denotes average SR. The kerf width is measured using the profile projector as the sum of the wire diameter and twice wire– work piece gap. Figure 1 shows the set up for measurement of surface roughness.

2. 3. Selection of Input Process Variables and Their Level In the current research work, the effect of different input process variables like Ton, Toff, SV, IP, WT and WF on performance measure i.e.surface roughness and kerf width have been investigated. The input process variables and their range have been chosen on the base of the screening experiment, machine capability, literature survey and manufacture's machine manual. The controlled input process variables and their levels in actual and coded values are listed in Table 2.

2. 4. Design of Experiments The response surface methodology approach was used to create the design of experiments and optimization process by Design expert 7.0. The RSM was used to develop second order regression equation relating response characteristics and process variables [15]. The experimentation beside with regression investigation facilitates the modelling of the preferred response to numerous input process variables. The experiment is planned to authorize evaluation of interaction and quadratic effects, also as a result, to provides an information regarding shape of response curve.

Figure 1. Set up for Surface roughness measurement

TABLE 2. Process variables and their ranges

Coded Factors	Real Factors	Parameters	Levels				
			-α	**-1**	**0**	**+1**	**+α**
A	Ton	Pulse on Time	110	112	115	118	120
B	Toff	Pulse off Time	50	52	54	56	58
C	IP	Peak Current	160	170	180	190	200
D	SV	Spark Gap Set Voltage	10	20	30	40	50
E	WF	Wire Feed Rate	4	6	7	8	10
F	WT	Wire Tension	4	6	7	8	10

Fifty-two experiments of tests have been led by CCD of RSM utilizing half replication for six input parameters with α=1.565 (α=k1/4) which known as practical α and it is beneficial when the number of input variables is more than five [16]. The present design of 52 experiments consists of 32 factorial points (experimental runs 1 to 32), 12 axial points to form a CCD with α=±1.565 for estimation of curvature (experimental runs 33 to 44), and eight center points (experimental runs 45 to 52) at zero level for replication to estimate pure error. The experimental trial runs are randomized to guarantee the end of human predispositions. Table 3 shows the experimental design matrix with a set of input variables and subsequent performance measure regarding output response. Figure 2 illustrates the shows the complete job after WEDM.

3. RESULT AND DISCUSSION

Experiments are conducted as per the design matrix and response characteristics are measured. The analysis of variance (ANOVA) was performed to check adequacy of fitted model and carry out graphical along with regression analysis.

Figure 2. Complete job after WEDM

3. 1. Analysis of Surface Roughness To evaluate for adequacy of the model, three various tests like model summary statistics, sequential model sum of squares and lack of fit test have been performed for Surface roughness. Table 3 represent ANOVA for the quadratic model at 95% confidence level. It shows that model F-value is 42.88 and the subsequent value of p is < 0.0001 which implies that the model is considerable. There is 0.01% possibility that a "Model F-Value" this outsized could occur due to noise. Moreover, the "Lack of Fit F-value" is 7.76 implies the Lack of Fit test is significant. There is only a 0.01% chance that a "Lack of Fit F-value" this large could occur due to noise. Thus, quadratic model is significant at 95% confidence level. The predicted R-Squared and adjusted R-squared have a close agreement with values 0.7804 and 0.8173 respectively, as a difference between these two is less than 0.03. Figure 3 highlight normal probability plot of residuals for surface roughness. It noticeably represents the errors is generally scattered as mainly of the residuals are clustered about a straight line.

The regression equation regarding real factor for the SR as a function of six input variables was developed using experimental information and is given underneath.

TABLE 3. ANOVA for Quadratic Model of surface roughness

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	16.19	11	1.47	42.88	< 0.0001	significant
A-TON	5.26	1	5.26	153.43	< 0.0001	significant
B-TOFF	0.13	1	0.13	4.02	0.0478	significant
C-IP	0.18	1	0.18	5.26	0.0241	significant
D-SV	2.95	1	2.95	86.16	< 0.0001	significant
E-WF	3.71	1	3.71	108.22	< 0.0001	significant
CE	0.18	1	0.18	5.28	0.0237	significant
DE	0.30	1	0.30	8.8938	0.0037	significant
B^2	0.12	1	0.12	3.5809	0.0616	
C^2	0.26	1	0.269	7.8511	0.0062	
E^2	0.35	1	0.35	10.3011	0.0018	significant
F^2	0.74	1	0.74	21.8502	< 0.0001	significant
Residual	3.15	92	0.03			
Lack of Fit	2.56	33	0.07	7.7646	< 0.0001	significant
Pure Error	0.59	59	0.01			
Cor Total	19.34	103				

Std. Dev.	0.19	R-Squared	0.8368
Mean	2.61	Adj R-Squared	0.8173
C.V. %	7.11	Pred R-Squared	0.7804
PRESS	4.25	Adeq Precision	25.764

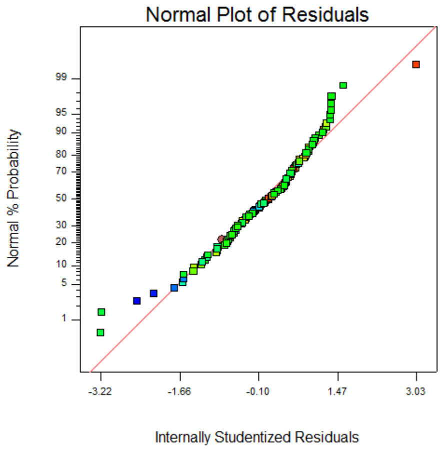


Figure 3. Normal probability plot for Surface roughness

Surface roughness = +78.61910 + 0.089044 * TON-1.78728*TOFF- .30636*IP+0.028325*SV-0.61146* WF - 2.24411* WT - 5.32500E-003 * IP * WF-6.90625E-003* SV * WF + 0.016349 * $TOFF^2$+9.68293E-004*IP^2+0.11091* WF^2+0.16154 *WT^2 (1)

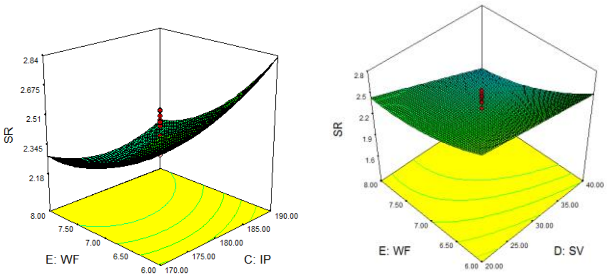
The quadratic functions of IP, WF, Toff and WT have considerable effects on surface roughness and are capable of to predict surface roughness inside the restrictions of control factors. The main effects of a TON, TOFF, IP, SV, and WF; interaction effects between WF and IP, WF and SV are found to be statistically important for this analysis.

The interaction plots consequent to these are represented in Figures 4 (a) and 4(b), respectively.

It is understandable from Figure 4 (b) that small values of IP (170–190 A) and higher the WF (6-8 m/min) gives minimum surface roughness. High Discharge energy due to a higher value of IP results in evaporation and overheating of molten metal. Because of these, high-pressure energy creates huge size craters on the machining surface. The deepness and diameter of the crater increase with the increase of IP, which increases the value of SR. Higher the value of WF further carries away the more heat from the cutting zone causing less material removal, along with it improves the surface finish. It is understandable from Figure 4(a) that high values of servo voltage (20–40) and higher values of wire feed rate (6 -8 m/min) give minimum surface roughness.

3. 2. Analysis of Kerf Width Table 4 represent ANOVA for the quadratic model at 95% confidence level. It shows that model F - value is 6.52 and the resulting value of p is < 0.0001, which implies that the model is considerable. There is just 0.01% probability that a "Model F-Value" this large could happen due to noise. In addition, the "Lack of Fit F-value" is 0.78 represents the lack of fit is not considerable relative to pure error. There is a 78.25% chance that a "lack of fit F-value" this large could take place due to noise. The predicted R2 of 0.2122 is in good agreement with the adjusted R2 of 0.3. Figure 5 highlights normal probability plot of residuals for kerf width. It apparently shows that errors are normally scattered as most of the residuals are clustered approximately along a straight line.

The regression equation regarding real factor for the kerf width as a function of six input process parameters was created using experimental information and is given underneath.



(a) (b)

Figure 4. (a) Iteration effect of servo voltage and wire feed (b) Iteration effect of the wire feed

TABLE 4. ANOVA for Response Surface Reduced Quadratic Model of Kerf width

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	10639.91	8	1329.98	6.51	< 0.0001	Significant
B-TOFF	143.27	1	143.27	0.70	0.40	
C-IP	290.03	1	290.03	1.42	0.23	
D-SV	3216.06	1	3216.06	15.76	0.00	Significant
E-WF	845.40	1	845.40	4.14	0.04	Significant
F-WT	693.95	1	693.95	3.40	0.06	
BC	1097.26	1	1097.26	5.37	0.02	Significant
CE	1181.64	1	1181.64	5.79	0.01	Significant
D^2	3172.27	1	3172.27	15.54	0.00	Significant
Residual	19386.05	95	204.06			
Lack of Fit	6267.30	36	174.09	0.78	0.7825	Not Significant
Pure Error	13118.75	59	222.35			
Cor Total	30025.96	103				

Std. Dev.	14.29	R-Squared	0.3544
Mean	297.98	Adj R-Squared	0.3000
C.V. %	4.79	Pred R-Squared	0.2122
PRESS	23654.92	Adeq Precision	10.024

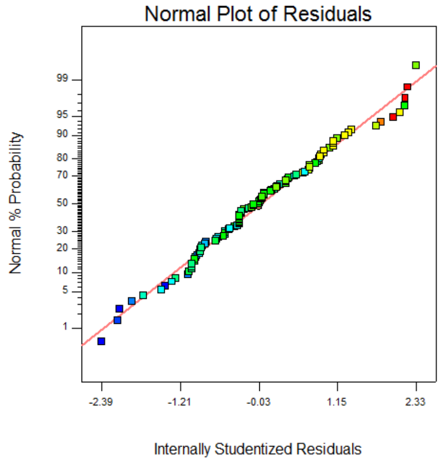
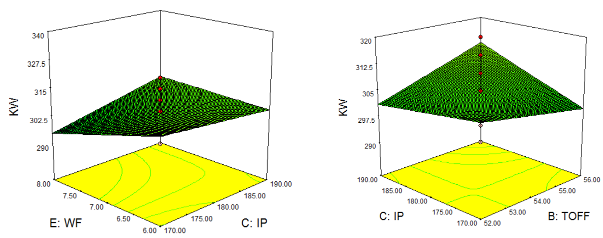


Figure 5. Normal probability plot for kerf width

$$\text{Kerf Width} = +2725.55707-36.56896*TOFF-13.98925*IP+6.32135*SV-80.72837*WF-3.06650*WT+0.20703*TOFF*IP+0.42969*IP*WF-0.094353*SV^2 \quad (2)$$

The quadratic functions of the pulse of time have considerable effects on kerf width and can predict kerf width within the limits of input parameters. In this case main effect of servo voltage, wire feed rate, iteration effect of a pulse of time and peak current, peak current and wire feed rate and quadratic effect of servo voltage are significant model terms. It depicts that Equation (2) is adequate to represent the actual relationship between process parameters and responses. Figure 6 (a) shows the considerable effect of a pulse of time and peak current on kerf width. Kerf width is decreased by increasing the pulse off time from 52 mu to 56 mu, with a parallel decrease of peak current from 170 A to 190A. On increasing the pulse off time, the machining status becomes stable, and the probability of uncontrolled sparking is reduced. Also, the sparking frequency is reduced. All these effects contribute to the reduction in the kerf width. It is evident from the Figure 6 (b) that higher the value of wire feed rate combines with the lower value of peak current recommended smaller the kerf value.



(a) (b)

Figure 6. (a) Combine effect of Pulse off time and peak current on kerf width (b) Combine effect of wire feed rate and Peak current on kerf width

4. MULTI-OBJECTIVE OPTIMIZATION USING DESIRABILITY APPROACH

Derringer and Suich (1980) describe multiple response methods called desirability. It is an attractive method for an industry for optimization of multiple quality characteristic problems. The technique makes use of an objective function, D(X), called the desirability function. The simultaneous objective function is a geometric mean of all transformed responses [17]:

$$D = (D_1 \times D_2 \times D_3 \times .... \times D_n)^{1/n} = \left(\prod_{i=1}^{n} D_i \right)^{1/n} \quad (3)$$

Desirability is an objective function that ranges from zero exteriors of the limits to one of the goal. The statistical optimization finds a point that maximizes the desirability function. In the current research work, the optimization module in the Design- Expert has been utilized to find out the combination of input process parameters, i.e., wire feed rate, pulse off time, peak current, pulse on time, servo voltage and wire tension which satisfy the requirements imposed on each of the responses and process parameters. The optimization process searches the best possible values of kerf width and surface roughness by minimizing kerf width and surface roughness. The constraints for each response and input parameters are given in Table 5.

The most favorable working conditions for process variables and the following performance measure have been computed with the help of design expert and are recorded in Table 6. To authenticate the optimum results, confirmatory experimental runs have been conducted. It has been shown that the values of response parameters obtained through experimental conditions (Table 6) are in close agreement with the predicted values.

TABLE 5. Range of Input process variables and Responses for Desirability

Variables	Goal	Lower Bound	Upper Bound	Importance
TON	is in range	112	118	3
TOFF	is in range	52	56	3
IP	is in range	170	190	3
SV	is in range	20	40	3
WF	is in range	6	8	3
WT	is in range	6	8	3
SR	minimize	1.431	3.606	5
KW	minimize	260	340	5

TABLE 6. Optimum Process parameters for Multi-objective optimizations and confirmation experiment results

Optimum Process Parameters						Response Predicted		Response Experimental		Desirability
Ton	Toff	IP	SV	WF	WT	SR	KW	SR	KW	
112.20	55.41	170	40	8	7	1.78	289.4	1.80	290.3	0.729

5. CONCLUSIONS

In this paper influence of process parameters on surface roughness and kerf width is investigated. The parameters and their combinations affecting the process were obtained using ANOVA.

1. The empirical models for surface roughness and kerf width of SKD 11 machined by the wire electrical discharge machining process have been proposed by RSM. The models created are considered steady representatives of the experimental outcome with prediction errors, which is less than ±5 %.
2. The servo voltage is the mainly influencing factor for kerf width and surface roughness of SKD 11.
   The multi response optimization by providing same importance to both the responses achieved the lowest surface roughness as 1.78 μm and lowest kerf width 289.4 μm.

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Kerf Width

چکیده

دستگاه تخلیه الکتریکی سیم (WEDM)، فرسایش جرقه در روش ماشینکاری غیر متعارف است تا مواد سختی و رسانایی را با یک سیم به عنوان یک الکترود برش دهد. مواد خام SKD 11 فولاد ابزار کربن بالا و کروم بالا با سختی و مقاومت بالا مقاومت در برابر سایش را دارد. این فولاد ابزار کاربرد گسترده ای در ابزارهای پرس و صنایع رنگرزی دارد. در این تحقیق، رفتار شش پارامتر فرآیند شامل Ton (پالس در زمان)، Toff (زمان خاموش شدن پالس)، IP (جریان پیک)، SV (ولتاژ سروو)، WF (نرخ انتقال سیم) و WT (پایه سیم) در طراحی روش آزمایش در طول WEDM SKD 11 مورد آزمایش قرار گرفت. قطر ۰٫۲۵ میلیمتر سیم برنج به عنوان الکترود برای برش قطعه کار استفاده می شود. زبری سطح و عرض کربه به عنوان اندازه گیری عملکرد انتخاب می شوند. روش پاسخ سطحی (RSM) برای بهینه سازی فرایند و همچنین برای فرموله کردن مدل رگرسیون برای همبستگی پارامترهای فرایند با اندازه گیری های عملکرد استفاده می شود.

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