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A Case Study on the Use of Box-Behnken Design to Improve an Electrical Discharge Machining

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방전가공 개선을 위한 반응표면방법 적용에 관한 사례연구

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This study presents the usefulness of response surface methodology (RSM) in die-sinking electrical discharge machining (EDM) process improvement. Conventional research on this process has been focused on the single-electrode method, but the industry practitioners prefer adopting the two-electrode method, one for the roughing and the other for the finishing stages, using a single discharge step. We propose a multiple discharge step (MDS) method that uses three discharge currents at each stage. RSM is employed to optimize the discharge conditions. Experimentally, the MDS method combined with RSM improves electrode edge wear and surface roughness.

Keywords: Response Surface Methodology, Box-Behnken Design, Sinking Electrical Discharge Machining, Surface Roughness, Multiple Discharge Steps

1. Introduction

Making various attempts to improve existing methods through experiments is an essential activity for product development and process improvement. The problem is that these attempts do not always lead to good results. Statistically designed experiments play an important role in developing new products and improving manufacturing processes (Montgomery, 1999). The purpose of this study is to present a case study in which an electrical discharge machining improvement activity benefits from using statistical design of experiments.

Sinking electrical discharge machining (EDM) is commonly used to manufacture molds. EDM has been used not only in mold fabrication but also in aerospace and medical industries to machine hard materials precisely. The workpiece material is removed by an electrical discharge between the electrode and workpiece, which are separated by a dielectric fluid (<Figure 1>). Sinking EDM provides good geometrical accuracy when manufacturing high-aspect-ratio hardened tool steels. A great deal of research has been devoted to the effects of process conditions and gap filled with dielectric fluid on electrode wear, machining time, and surface roughness.

The electrical spark not only removes the target metal but also wears the electrode proportionally to the material removal volume. The edge wear of the electrode is much faster than the front wear, and very rapid at the beginning because the spark occurs more frequently at the edge, where the local electric intensity is higher than the flat surface. The edge geometry is affected by machining pa-

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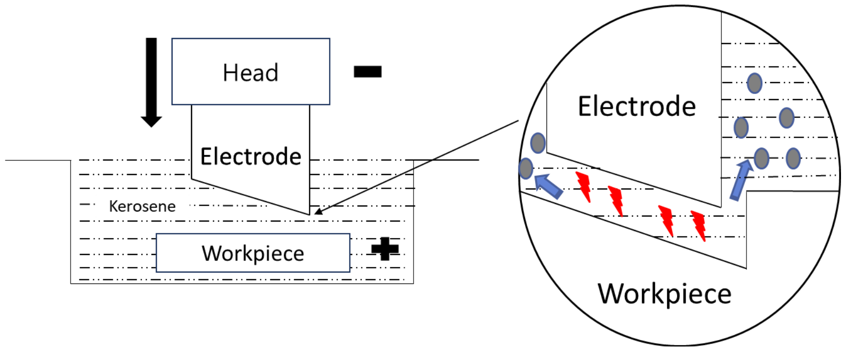


Figure 1. Die-sinking Electric Discharge Machining

rameters and dielectric flushing conditions (Ozgedik and Cogun, 2006). The electrode wear pattern is affected by the electrode geometry and electrode path in multi-axis EDM (Flaño et al., 2018).

A higher peak current increases the material removal rate, but also makes surface roughness worse, while a lower peak current requires a long machining time but ensures a good surface. The electric discharge occurs in a gap between the workpiece and the electrode immersed in a dielectric fluid. The gap distance is the clearance between the electrode and the workpiece, and it is controlled by servo voltage (Zhou et al., 2020).

EDM research has focused on the single-electrode method, but industry engineers have preferred using the two-electrode method; one for a roughing stage to reduce machining time and the other for a finishing stage to improve surface quality. Each stage involves only a single discharge step (SDS). In this paper, we are going to explore the effects of two-electrode roughing and finishing based on a multiple discharge step (MDS) approach for each stage. The MDS consists of three steps; the first uses a higher discharge current, the second medium current, and the third lower current to further improve both discharge efficiency and surface quality. We consider the common current difference between the first and the second, and between the second and the third, steps. The currents of the roughing and finishing stages are RSM-optimized to enhance EDM quality and productivity. The Box-Behnken design (BBD), one of the most popular response surface designs, is employed to estimate the linear, quadratic, and interaction effects. Empirical models are established for the three responses (surface roughness, edge wear, and machining time) and simultaneously optimized using the popular desirability function approach (Derringer and Suich, 1980).

An outline of this paper is as follows. First, three EDM approaches (one-electrode SDS, two-electrode SDS, and two-electrode MDS) are explained and compared. Experimental design and analysis results are then presented to optimize the two-electrode MDS approach using RSM. In summary, the power of RSM is emphasized and future research direction is addressed.

2. Three EDM Approaches

2.1 One-electrode SDS Approach

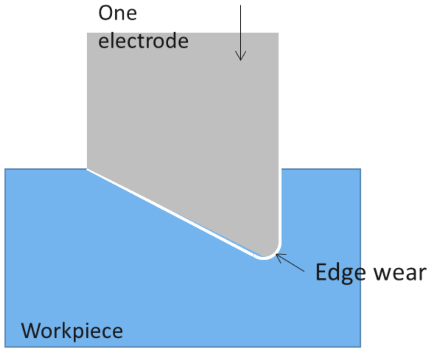
Conventional EDM research has focused on using a single electrode and a single discharge step (SDS), as shown in Figure 2(a). The use of one electrode for both roughing and finishing is more economical than the two-electrode approach. One-electrode SDS approach is appropriate if the removal volume is very small. However, this approach is inappropriate when machining large volumes; the use of a single electrode can increase the machining errors caused by severe electrode wear.

2.2 Two-electrode SDS Approach

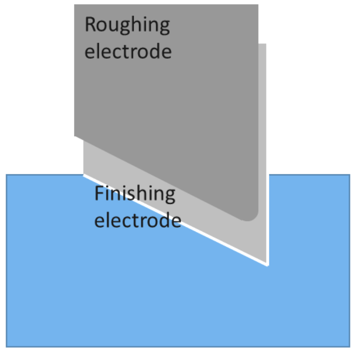
The sharp edge of the electrode becomes worn after extensive machining, causing errors in the concave edges of the workpiece. The industry has adopted two-electrode roughing and finishing stages to enhance both productivity and surface quality. In the roughing stage, a high discharge current is adopted to remove material rapidly with one electrode, and then a low discharge current is applied in the finishing stage with the other electrode. The approach is shown in <Figure 2(b)>.

2.3 Two-electrode MDS Approach

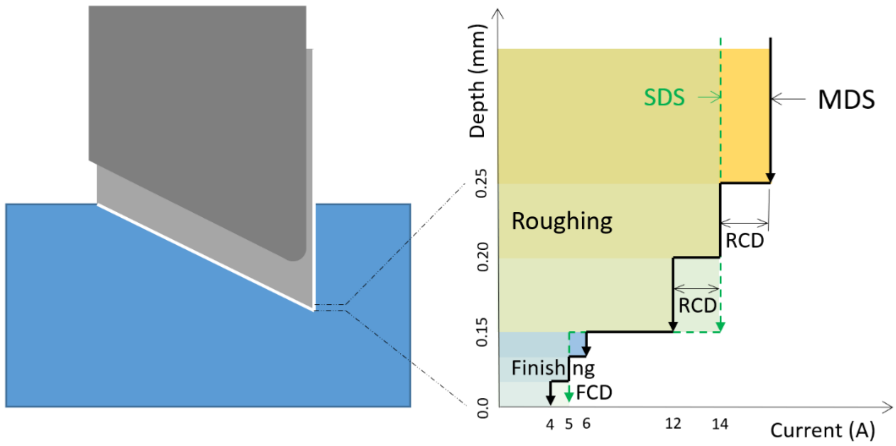
We try a new two-electrode approach based on multiple discharge steps (MDS) to improve productivity and surface quality. During both roughing and finishing, discharges are applied over three steps, to increase die-sinking EDM efficiency. The three steps are shown in <Figure 2(c)>. High discharge energy during roughing shortens the machining time but increases surface roughness. The discharge current is increased in the first step by an amount equivalent to the roughing current difference (RCD), fixed during the second step, and decreased during the third step by an amount equivalent to the RCD. The high discharge energy of the first step increases the material removal rate, and the low



(a) One-electrode SDS



(b) Two-electrode SDS



(c) Two-electrode MDS

SDS: single discharge step, MDS: multiple discharge steps, RCD: roughing current difference, FCD: finishing current difference

Figure 2. Electrodes and Discharge Steps

energy of the third step reduces surface roughness. The low discharge guarantees a good surface finish but increases the finishing time. The finishing stage is also divided into three steps. At each step, the discharge current decreases by the amount of the finishing current difference (FCD). The high discharge energy of the first step reduces the finishing time, and the low energy of the third step improves the surface finish.

3. Comparative Experiments

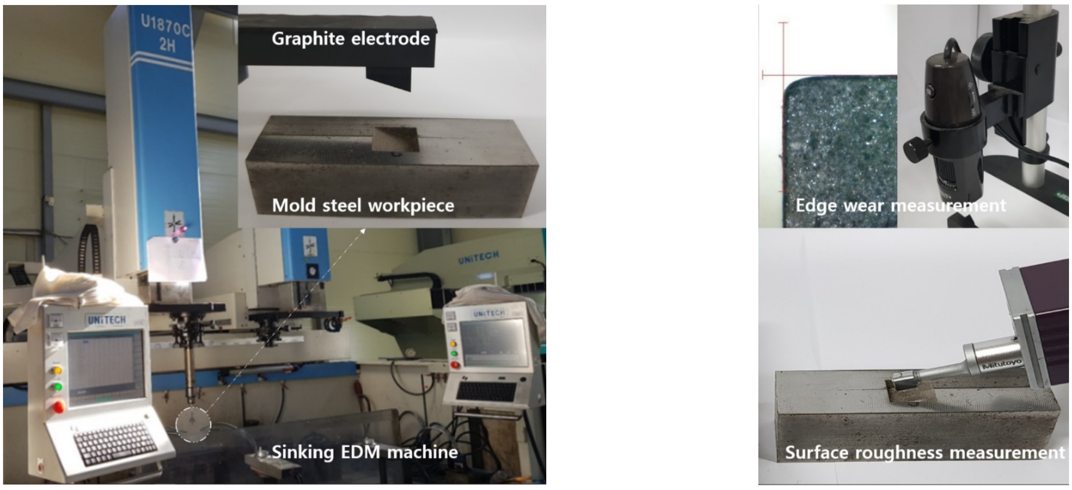
The three EDM approaches are compared in terms of surface roughness, edge wear, and machining time. The die-sinking EDM machine is used to fabricate wedges of mold steel, using graphite electrodes.

3.1 Material and Equipment

The composition of the workpieces to be machined is as follows: 0.50~0.55 C, 0.15~0.35 Si, 0.75~0.90 Mn, and a maximum of 0.50 Ni (all wt%). The workpieces are milled to create 20 × 20 × 50 mm “boxes” before EDM. The graphite electrodes are shaped into a convex wedge with a transverse area of 10mm × 10mm. The die-sinking EDM machine is used to fabricate concave wedge shapes on the mold steel using graphite electrodes, as shown in <Figure 3(a)>. The workpiece is placed on a magnetic table, and the graphite electrode is bonded to the head of the machine. The dielectric fluid jet is flushed in six directions to remove debris in the gap between the electrode and the workpiece. Electrode edge wear is measured using a digital microscope, and the roughness value of the inclined wedge surface is measured by a stylus roughness tester in <Figure 3(b)>.

3.2 Experimental Conditions

The discharge current in the roughing stage is set to 14 A based on the results of Kiyak and Cakır (2017), while the discharge current at the finishing stage is set to 5 A, according to Jeong et al. (2017). The other experimental parameters are determined based on the equipment maker’s recommendation.



(a) Workpiece, electrode, and sinking EDM machine (b) Microscope and roughness tester

Figure 3. Experimental Equipment and Measurement Instruments

Table 1. Comparative Experimental Conditions and Results of the Three EDM Approaches

EDM approaches	Electrodes	Current (A)	Roughness (μm)	Wear (mm)	Time (min)
One-electrode SDS	Rough & Finish	14	4.09	0.216	11.28
		5			
Two-electrode SDS	Rough	14	-	0.176	7.58
	Finish	5	4.27	0.065	3.07
Two-electrode MDS	Rough	16→14→12	-	0.156	7.54
	Finish	6→5→4	4.01	0.072	4.57

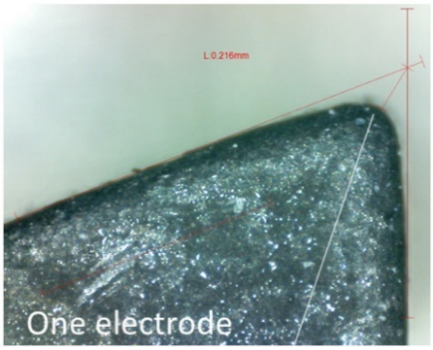
The experimental conditions and results of the three approaches are shown in <Table 1>. With the one-electrode SDS approach, roughing and finishing are performed by the same electrode. The two-electrode SDS approach uses one electrode for roughing and the other for finishing. The normal discharge current in the roughing stage is 14 A, to remove material quickly, and it changes to 5 A at the finishing stage for good surface quality. With the two-electrode MDS approach, the discharge currents in the roughing stage are 16 A for the first step, 14 A for the second step, and 12 A for the third step. The discharge currents in the finishing stage are 6 A for the first step, 5 A for the second step, and 4 A for the third step. All three approaches are repeated three times and the average values of the surface roughness, edge wear, and machining time are shown in <Table 1>.

3.3 Edge wear

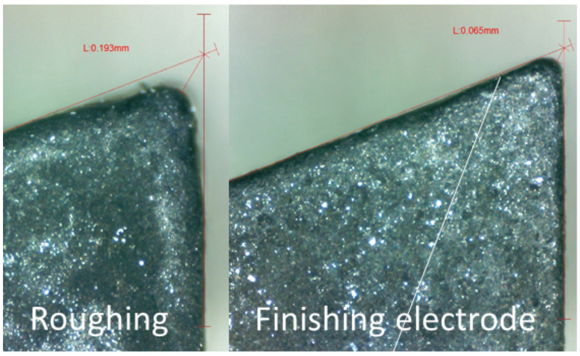
<Figure 4(a)> presents the edge wear of the one-electrode SDS approach. The substantial edge wear of 0.216 mm results from the fact that one electrode is used to remove the entire 4-mm-deep metal. <Figure 4(b)> shows the edge wear of the two-electrode SDS approach. The edge wear of the finishing electrode is reduced to 0.065 mm. <Figure 4(c)> shows the edge wear of the two-electrode MDS approach. The edge wear of the finishing electrode of the two-electrode MDS approach is 0.086 mm, which is a little larger than that of the two-electrode SDS approach.

3.4 Comparison of the Results among Different Approaches

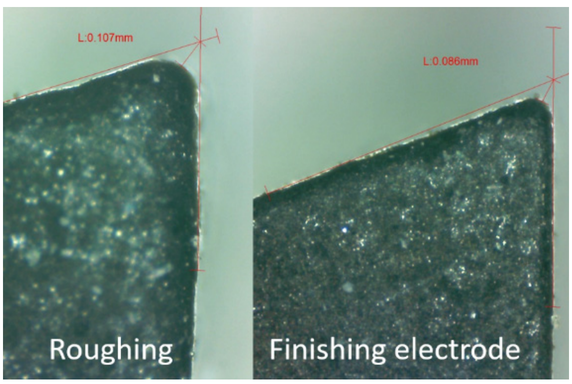
<Figure 5> compares the edge wear, surface roughness, and machining time among the three approaches. The edge wear of the two-electrode SDS approach is about 70% less than that of the one-electrode SDS approach. The edge wear result of the two-electrode MDS approach is inferior to that of the two-electrode SDS approach. The average surface roughness (Ra) values are similar among all three approaches. The two-electrode SDS approach is somewhat better than the other approaches in terms of machining time. A limitation of this comparison is that the current difference of the two-electrode MDS approach is fixed at 2 A in the roughing stage, and at 1 A in the finishing stages, while the gap distance is also fixed at 0.07 mm. To improve the



(a) One-electrode edge wear of 0.216 mm



(b) Two-electrode edge wear of SDS 0.065 mm



(c) Two-electrode edge wear of MDS 0.086 mm

Figure 4. Edge Wears of Electrodes and the Machined Workpiece

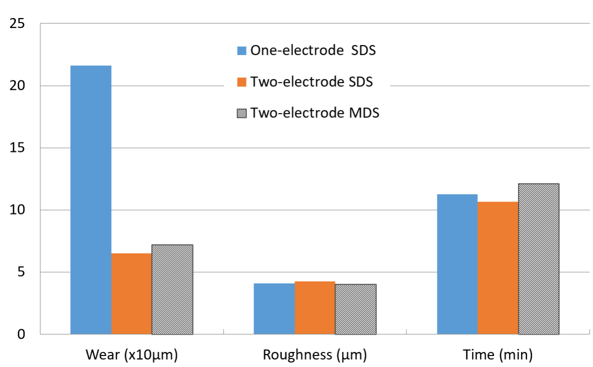


Figure 5. Comparison Graphs of Three Approaches

performance of the MDS approach, we use RSM to determine conditions minimizing edge wear, surface roughness, and machining time.

4. Response Surface Methodology for MDS

From the comparison of the three approaches, it is seen that the two-electrode EDM performs better in terms of edge wear than the one-electrode EDM. However, for the two-electrode cases, the MDS approach was no better than the SDS approach in terms of edge wear, surface roughness, or machining time. The Box-Behnken design is applied to optimize the roughing and finishing currents of the MDS and the gap distance.

4.1 Experimental Plan

The process variables and their respective levels are shown in <Table 2>. We consider three variables: the discharge current differences in the roughing and finishing stages, and the gap distance. In the MDS approach, a high discharge energy during the first step saves machining time, and a low discharge energy during the third step ensures a good surface finish. Therefore, in the roughing stage, the discharge current is increased in the first step by an amount equivalent to the RCD, fixed to 14 A during the second step, and decreased during the third step by an amount equivalent to the RCD. The RCD is set to 0, 2, or 4 A. The minimum RCD is 0 A (equivalent to that of the SCD approach), the intermediate RCD is 2 A (equivalent to the MDS approach before RSM optimization), and the maximum RCD is double the intermediate value. During finishing, the discharge current is increased, fixed, and then decreased in the first, second, and third steps, respectively. The FCD is set to 0, 1, or 2 A, using a method similar to that applied to derive the RCDs. The gap distance, which will be referred to as Gap, W is the clearance between the workpiece and the electrode. The Gap is set to 0.04, 0.07, or 0.10 mm. The intermediate level is the same as that of the SDS and MDS before RSM.

<Table 3> shows the BBD experimental matrix and measurement data, where the edge wear is the wear of the electrode after the finishing stage, and the machining time is the sum of the roughing and finishing times.

4.2 Analysis of Surface Roughness

Analysis of variance (ANOVA) is performed to draw a model with significant terms. Criteria for model fitting are the adjusted

Table 2. Parameters and Their Levels for the MDS Experiment

Parameters	Unit	Level 1	Level 2	Level 3
RCD	A	0 (14→14→14)	2 (16→14→12)	4 (18→14→10)
FCD	A	0 (5→5→5)	1 (6→5→4)	2 (7→5→3)
Gap	mm	0.04	0.07	0.10

Table 3. Box-Behnken Design Matrix and Data for MDS

Std order	Run order	RCD (A)	FCD (A)	Gap (mm)	Roughness (μm)	Wear (mm)	Time (min)
5	1	0	1	0.04	3.81	0.071	12.32
1	2	0	0	0.07	4.36	0.065	11.35
12	3	2	2	0.1	3.50	0.061	10.29
10	4	2	2	0.04	3.20	0.060	11.54
15	5	2	1	0.07	3.93	0.072	12.23
3	6	0	2	0.07	2.97	0.067	11.80
2	7	4	0	0.07	4.63	0.088	13.28
8	8	4	1	0.1	3.73	0.076	12.25
6	9	4	1	0.04	3.68	0.14	16.01
4	10	4	2	0.07	4.31	0.096	12.75
13	11	2	1	0.07	4.01	0.067	12.63
14	12	2	1	0.07	4.11	0.070	11.46
7	13	0	1	0.1	3.95	0.082	14.33
11	14	2	0	0.1	7.64	0.045	8.68
9	15	2	2	0.04	4.60	0.063	10.49

R^2 and the smallest S(root mean square error). A model with the largest adjusted R^2 and smallest S(root mean square error) is persued. Equation (1) is the regression model for the average surface roughness (Ra) with respect to the FCD ΔI_f and Gap W in the uncoded units estimated from the experimental data:

$$Ra = 2.43 - 0.7\ \Delta I_f + 37.7\ W - 22.9\ \Delta I_f \cdot W \qquad (1)$$

As the roughing stage is followed by the finishing stage, the Ra should be unaffected by the RCD. ANOVA shows that the coefficient of determination R^2 of the fitted model is 62.51%, the adjusted R^2 is 52.28%, and S is 0.7413 . Thus, 62.51% of the surface roughness variation is attributable to the linear effects of the FCD, the Gap, and their interaction. Model adequacy checking with studentized residuals reveals that the roughness value of 7.64 at run number 14 is an outlier, which is outside of 6 standard deviation of the studentized residuals. The existence of the outlier leads to the small R2 value, which reflects the possibility of tough surface roughness resulting from imperfect discharging and errors when measuring inclined surfaces. <Figure 6> is the contour plot of the estimated Ra, with respect to FCD ΔI_f and Gap W when RCD is fixed at 2 A. The FCD has a greater influence on Ra. When the FCD is increased, Ra tends to decrease to a minimum. <Figure 6> also shows that the Gap has less effect on Ra when the FCD is increased by up to 2 A. <Figure 7> is the photographed surfaces when FCD is 0 A and 2 A, respectively, when the Gap is fixed to 0.07mm.

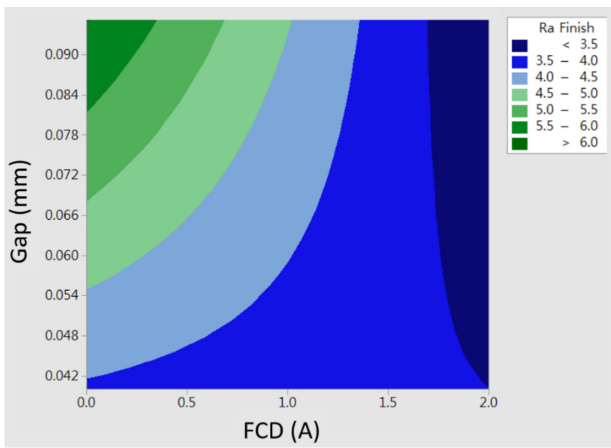
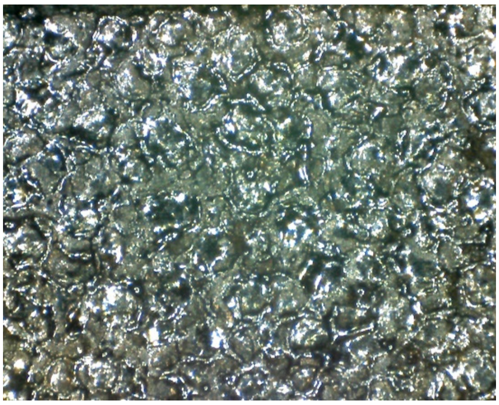
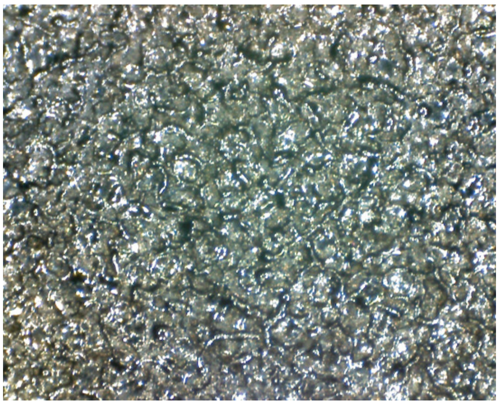


Figure 6. Estimated Response Surface of Roughness vs. FCD and Gap



(a) Ra = 4.6 μm, FCD 0 A



(b) Ra = 3.2 μm, FCD 2 A

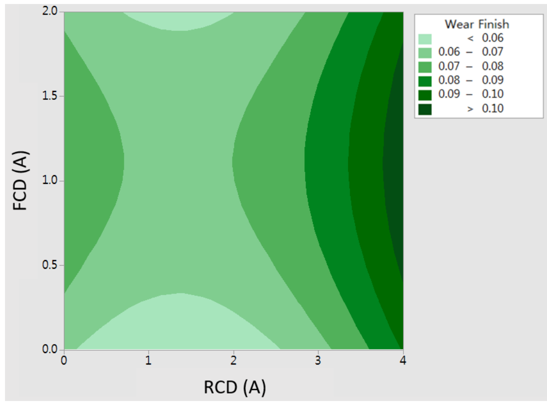
Figure 7. Surface Photographed by Optical Microscope, RCD 2A, Gap 0.07 mm

4.3 Analysis of Edge Wear

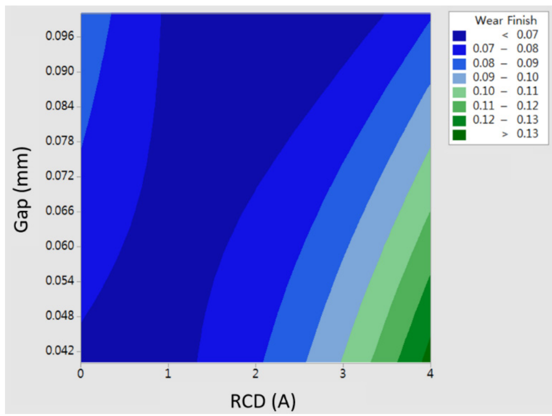
The edge wear *EW* of the finishing electrode is influenced by three variables. Equation (2) shows their effects, where ΔI_r is RCD. The adjusted R^2 and S are and 93.95% and 0.00535, respectively. The R^2 is 96.97%, which means that 97% of the experimental data variation is explained by Equation (2). Model adequacy checking with studentized residuals shows no severe violations with respect to normality, run order, and fitted values.

$$EW = 0.05 + 0.0069\,\Delta I_r + 0.0175\,\Delta I_f + 0.175\,W + 0.0055\Delta I_r^2 - 0.0129\,\Delta I_f^2 - 0.3125\,\Delta I_r \cdot W + 0.1583\,\Delta I_f \cdot W \quad (2)$$

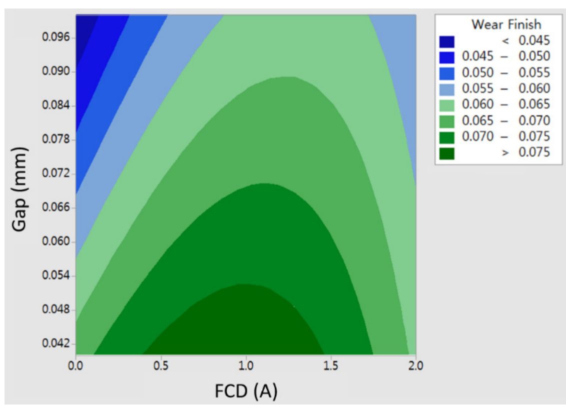
<Figure 8(a)> shows the estimated response surface of edge wear with respect to the RCD and FCD when the Gap remains constant at the intermediate value of 0.07 mm. The edge wear tended to be smallest when the RCD is set to 1.5 A and the FCD to either 0 or 2 A. <Figure 8(b)> shows the estimated response surface in terms of the RCD and Gap when the FCD is set to 1 A. The edge wear of the finishing electrode tends to be smallest when the RCD is 1 A and largest when the RCD is 4 A, showing that the roughing variable is linked to edge wear in the finishing stage. <Figure 8(c)> shows the estimated response surface of edge wear in view of the FCD and the Gap. Edge wear tended to decrease as the Gap increases. The FCD exerts a quadratic effect on edge wear.



(a) Estimated response surface of edge wear vs. RCD and FCD



(b) Estimated response surface of edge wear vs. RCD and gap

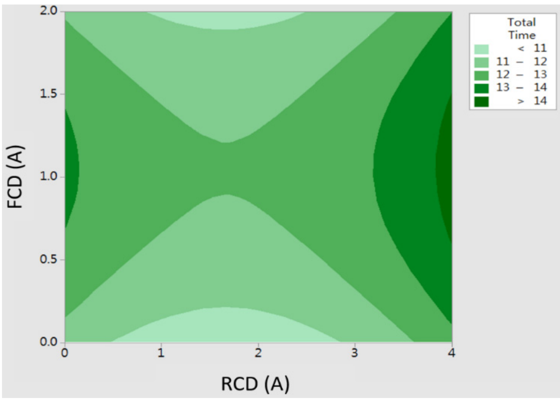


(c) Estimated response surface of edge wear vs. FCD and gap

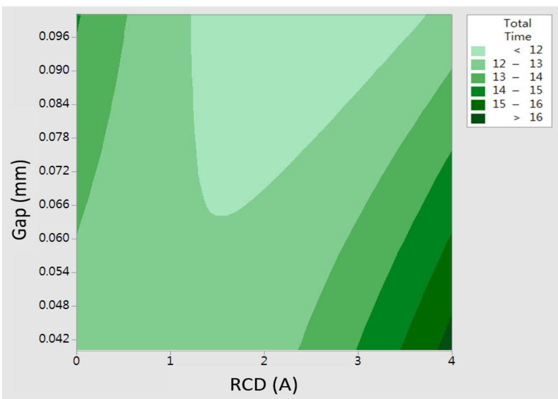
Figure 8. Estimated Response Surface of Edge Wear

4.4 Analysis of Machining Time

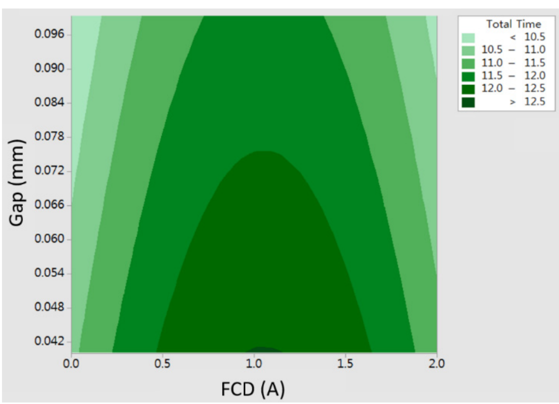
Machining time (MT) is also influenced by three variables, as shown in Equation (3), with the adjusted R^2 = 89.23%, S = 0.564, and R^2 = 93.85%. Model adequacy checking with studentized residuals shows no severe violations.



(a) Estimated response surface of machining time vs. RCD and FCD



(b) Estimated response surface of machining time vs. RCD and gap



(c) Estimated response surface of machining time vs. FCD and gap

Figure 9. Estimated Response Surface of Machining Time

$$MT = 9.35 + 0.114\,\Delta I_r + 3.579\,\Delta I_f + 28.0\,W + 0.462\Delta I_r^2 - 1.628\,\Delta I_f^2 - 24.04\,\Delta I_r \cdot W \quad (3)$$

<Figure 9(a)> shows the estimated response surface of the machining time with respect to the RCD and FCD when the Gap is fixed at its intermediate value of 0.07 mm. The machining time is shortest when the RCD is 2 A and the FCD is 0 or 2 A. The effects of the RCD and Gap are shown in <Figure 9(b)>. When the FCD is set to the intermediate value of 1, the machining time is minimized if the RCD is 2 A and the Gap is 1 mm. The estimated response surface of the machining time with respect to the FCD and Gap is shown in <Figure 9(c)>. The machining time decreases as the Gap increases to 0.1 mm and the FCD is either 0 or 2 A. The response surface of the machining time exhibits a trend similar to that of the edge wear of the finishing electrode, indicating that a longer machining time increases edge wear.

4.5 Optimal Conditions

The desirability function approach is implemented to optimize the three response variables affected by the three process variables (Derringer and Suich, 1980). The desirability function approach is most often employed to optimize multiple responses simultaneously (Myers et al., 2016). This approach searches for variable settings that jointly optimize multiple responses by satisfying the requirements for each response under consideration. In this approach, the estimated response values of each response are transformed to scale-free desirability between 0 and 1. The individual desirability (*d*) for each response to be minimized is obtained by specifying the target value and upper bound required for the response. If the response is larger than the upper bound, d is set at 0. If the response is smaller than the upper bound, *d* increases from 0 to 1 as the response variable comes closer to the target value. If the response is smaller than the target value, *d* is determined to be 1. A weight factor, which determines the desirability function shape for each response, is then assigned to each response. Weight can be given as a value between 0.1 and 10. When the weight is 1, the desirability function is linear. When the response needs to be smaller than the upper bound, a weight less than 1 is determined. If the response should be close to the target value, the weight is set at a value greater than 1. In general, if the weight factor is not mentioned, it is set at 1 (Myers et al., 2016).

The individual *d* is combined into an overall desirability *D*, which is the geometric mean of the individual *d*. When the response variables vary in terms of importance, *D* is the weighted geometric mean of the individual *d*. The relative importance of response variables is reflected by the 'importance values'. The opti-

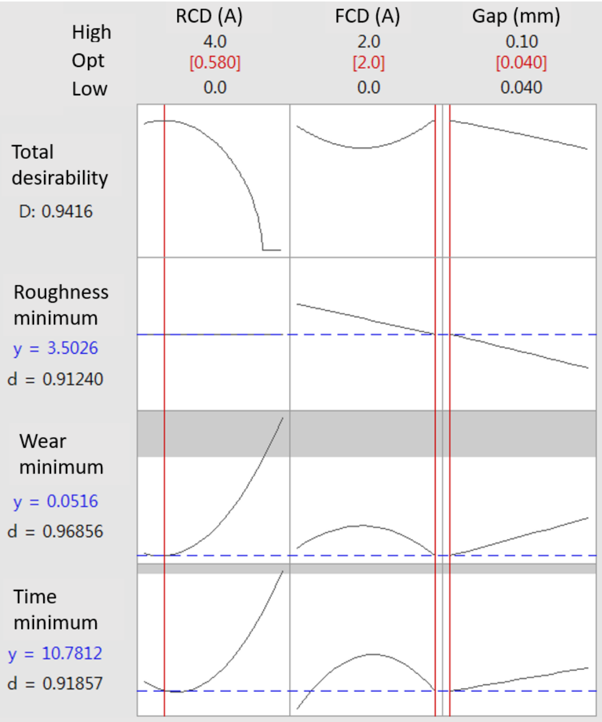


Figure 10. Optimal Conditions of the Desirability Function Approach

mal compromise among multiple responses is achieved by maximizing D (Derringer and Suich, 1980). The desirability function approach is employed to simultaneously minimize the average surface roughness Ra, the edge wear of the finishing electrode, and the machining time simultaneously. The target values and upper bounds are 3 and 6 μm for Ra, 0.05 and 0.1 mm for edge wear, and 10 and 15 min for the machining time, respectively. As it is more important that the surface roughness and machining time should be lower than their upper bounds than that they reach the important target values, their weights are set to 0.5. Moreover, edge wear is considered to be twice as important as surface roughness and machining time, and so it is assigned an importance value of 2.

Using the response optimizer in Minitab, the optimal conditions are shown to be (RCD, FCD, Gap) = (0.580, 2.0, 0.04) (<Figure 10>). These conditions optimize the three responses simultaneously. The estimated Ra, edge wear of the finished electrode, and the machining time are 3.50 μm, 0.052 mm, and 10.78 min, respectively. As the RCD is controlled in integral increments, we perform additional experiments at RCDs of 0 A and 1 A.

4.6 Follow-up Experiment

As the current can be controlled only in integral units, we test two conditions (RCD, FCD, Gap) = (0 A, 2 A, 0.04 mm) and (1 A, 2 A, 0.04 mm) three times, and compared the data (<Table 4>). The three responses are optimized when the RCD was 1 A.

4.7 RSM-optimized MDS Results

<Figure 11> shows the average values of the three responses for the two-electrode SDS and two-electrode MDS approaches, before and after RSM. RSM for the two-electrode MDS approach contributes to the improvement of edge wear and surface roughness. Through RSM optimization for the MDS approach,

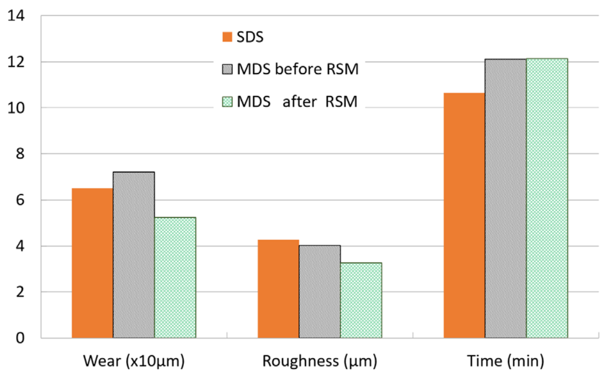


Figure 11. Comparison of SDS and MDS before and after RSM Optimization

Table 4. Comparing two Conditions for Optimal Parameter Settings

No.	RCD: 0A			RCD: 1A		
	Roughness (μm)	Wear (mm)	Time (min)	Roughness (μm)	Wear (mm)	Time (min)
1	3.55	0.065	11.53	3.27	0.047	12.33
2	3.50	0.069	12.23	3.24	0.057	12.25
3	3.42	0.069	12.70	3.27	0.053	11.82
Avg.	3.49	0.067	12.16	3.26	0.052	12.13
SD	0.066	0.0023	0.589	0.017	0.005	0.274

the edge wear of the finishing electrode is improved from 0.072 mm to 0.052 mm, and the average surface roughness is reduced from 4.01 to 3.27. The RSM-optimized MDS approach has reduced edge wear by 20% and average surface roughness by 24% compared to the SDS approach. However, the machining time of the MDS approach has increased by 15% compared to the SDS approach. The machining time of the MDS is longer than that of the SDS because the time saved from the high discharge current in the first step is smaller than the time increased from the low discharge current in the third step. Overall, the two-electrode MDS approach with RSM shows better performance than the two-electrode SDS approach.

5. Summary

In this study, we tried a new two-electrode MDS approach using three discharge steps to improve edge wear, surface roughness, and machining time of the sinking EDM. However, the application of the MDS approach led to worse performance than the SDS approach.

To improve the performance of the MDS approach, the Box-Behnken design was used to investigate the effects of RCD, FCD, and gap on edge wear, surface roughness, and machining time. The desirability function approach was employed to minimize the three responses. The optimal conditions were RCD = 0.58 A, FCD = 2 A, and gap = 0.04 mm. As the current can be controlled only in integral units, RCD was tested at 0 and 1 A, and then set to 1 A (which gave better performance). Three confirmation experiments performed under optimal conditions showed that the RSM-optimized MDS approach reduced edge wear by 20%, and improved the surface roughness by 24%, compared to the SDS approach.

Box-Behnken design is generally applied for continuous variables. In this case study, factors RCD and FCD should be determined to be integer values. However, they are first treated as continuous variables and optimized, resulting in RCD = 0.58 A, FCD = 2 A. RCD is then tested at two integral units of 0 and 1 A to explore better conditions. The MDS approach combined with RSM can be beneficial to EDM practitioners who want to optimize process variables to improve the edge wear, surface roughness, and machining time. The number of discharge steps during the MDS approach can be used to optimize the results; this can be a future research topic.

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