A Response Surface Methodology to Optimize Multiple Discharge Step Parameters for Sinking Electrical Discharge Machining

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Abstract

Conventional die-sinking electrical discharge machining (EDM) employs a single electrode operating under constant discharge conditions. We explored a two-electrode scenario, in which roughing and finishing were coupled. We developed a multiple discharge step (MDS) method that uses three discharge depths. The discharge current is highest in step 1 and lowest in step 3. Response surface methodology (RSM) was employed to optimize the discharge conditions. Experimentally, the MDS method combined with RSM decreased electrode edge wear and surface roughness compared to the conventional method, with no increase in the average discharge current.

1. Introduction

Die-sinking electrical discharge machining (EDM) is commonly used to manufacture molds. The workpiece material is removed by electrical discharge between the electrode and workpiece, which are separated by a dielectric fluid (Fig. 1). The shape of a soft copper or graphite electrode is stamped onto high-hardness tool steel, but the process time is long. Sinking EDM provides good geometrical accuracy when manufacturing high-aspect-ratio hardened tool steels, but a poorer surface finish than milling because discharge craters are created [1]. 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 volumetric relative wear of graphite and copper electrodes with positive polarity and long pulse duration is smaller than that with negative polarity on the finishing EDM [2, 3]. The pulse duration is most influential, but the discharge current is relatively less important on the relative wear of graphite electrode at the roughing stage [4]. The wear rates of copper electrodes increase as the discharge current rises, and decrease with shorter pulse duration [5]. Tungsten-carbide electrodes wear quickly; their high carbide contents and finer grain sizes make them inappropriate for EDM [6].

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 and front wear geometries are affected by machining parameters and dielectric flushing conditions [7]. The electrode wear pattern is affected by the electrode geometry and electrode path in multi-axis EDM [8]. A block-divided EDM process involving an electrode with a slender square cross-section was developed to compensate for electrode wear [9]. A cylindrical tool applied at a relief angle, and land thickness, reduced the machining time, radial overcut, and internal surface roughness of machined holes to a greater extent than a process involving a straight cylindrical tool [10]. Electrode wear geometry during die-sinking EDM has been simulated by searching the minimal gap associated with local discharge [11, 12]. Few studies have explored the geometry of serial machining using different roughing and finishing graphite electrodes.
A higher discharge energy increases material removal, but also makes the surface roughness worse. Rough EDM is highly productive but the surface quality is poor. The effects of discharge conditions on productivity and the surface qualities of molds and tool steel have been studied using graphite \[^{13}\] and copper \[^{14}\] electrodes. The peak current is the major factor affecting the surface roughness of mold steels machined using copper electrodes; pulse duration is the second most important factor \[^{13,14}\]. A high discharge energy increases material removal, surface roughness, and the thicknesses of the recast layer and heat-affected zone \[^{15}\]. The peak current during roughing is limited by the area of the eroding surface, which varies by machining depth \[^{16,17}\]. It is advisable to roughing using a current density of about 9 A/cm\(^2\), to ensure process stability \[^{18}\].

EDM finishing using a small peak current requires a long process time but ensures a good surface finish \[^{19}\]. The surface roughness of P20 steel improves with decreased machining depth and is not affected by the pulse-on time during finishing \[^{20}\]. When the discharge energy is fixed, a longer pulse-on time tends to increase the crater width \[^{21}\]. A higher discharge energy increases productivity and surface roughness, because it increases the amount of molten metal and thus the crater volume \[^{22}\]. Apart from the discharge energy, the pulse type also affects productivity and surface roughness \[^{23}\]. The formation of white layers and thermal cracks, which cause bending fatigue in cemented carbide, is reduced at lower discharge energies \[^{24}\]. Previous studies used only single-step discharge energy.

The EDM process occurs in a small gap between the workpiece and electrode immersed in a dielectric fluid. The gap distance is the clearance between the electrode and workpiece. Higher discharge energy is associated with a larger gap distance \[^{25}\]. The influence of gap distance on discharge characteristics was investigated using the impulse discharge method of micro-EDM \[^{26}\]. The gap distance was linearly proportional to the gap servo-voltage, which controls the discharge and arcing ratios \[^{27,28}\].

Response surface methodology (RSM) has been used to optimize discharge parameters like the discharge current, pulse on-time, pulse off-time, and voltage to improve the material removal rate, surface quality, and electrode wear \[^{29–34}\]. Although EDMs using two electrodes in series have been employed in production, this setup has not been researched. Here, we used RSM to optimize a procedure employing two electrodes in series and a varying discharge current.

Earlier studies considered only roughing or finishing. All processes involved only a single discharge step (SDS). We explored the effects of serial roughing and finishing (using two electrodes) on surface quality and productivity. We used a multiple discharge step (MDS) approach for each stage. The MDS consists of three steps; the first uses a high discharge current, the second the conventional current, and the third a lower current. We consider the common current differences (ΔI\(_b\)) between the first and second, and second and third, steps. The currents of the roughing and finishing stages were RSM-optimized to enhance EDM quality \[^{35}\]. The Box-Beihken design (BBD), one of the most popular response surface designs, is employed to estimate the linear, quadratic, and interaction effects. Empirical models were
established for the three responses (surface roughness, edge wear, and machining time) and simultaneously optimized using the popular desirability function approach [36].

Three EDM approaches (One-electrode SDS, two-electrode SDS, and two-electrode MDS) are compared in Section 2, and the experimental results presented in Section 3. To optimize the two-electrode MDS approach, RSM is employed in Section 4. The conclusions are summarized in Section 5.

2. Three Edm Approaches

In this article, we are going to investigate the influence of the number of electrodes and discharge steps for the sinking EDM. Our MDS method divides sinking EDM into six steps involving the sequential use of two electrodes at three energy discharge levels, depending on the discharge depth. A roughing graphite electrode rapidly removes metal, and the finishing graphite electrode provides a precise workpiece. The discharge energy level is high initially, decreases during the second step, and then decreases further during the final step, thus improving discharge efficiency.

2.1 One-electrode SDS approach

Conventional EDM research used single electrodes and an SDS system, as shown in Fig. 2(a). The use of one electrode for both roughing and finishing is cheaper than a two-electrode approach. A One-electrode SDS approach is appropriate if the removal volume is very small. However, this approach is inappropriate when machining large volumes; use of a single electrode increases the machining errors caused by severe electrode wear. In particular, extensive edge wear causes rounding errors [11, 12].

2.2 Two-electrode SDS approach

The sharp convex edge of the roughing electrode becomes worn after extensive machining, causing errors in the concave edges of the workpiece. We employed a new approach using two sequential electrodes. The roughing electrode has high discharge power, thus increasing material removal. This electrode was replaced by a new, sharp-edged finishing electrode to improve the surface in the finishing stage. The approach is shown in Fig. 2(b).

2.3 Two-electrode MDS approach

We also considered another approach based on MDS. During both roughing and finishing, discharges were applied over three steps, to increase die-sinking EDM efficiency. The three steps are shown in Fig. 2(c). High discharge energy during roughing shortens the machining time but increases surface roughness. The MDS approach divides roughing into three steps. The high discharge energy of the first step increases the material removal rate, and the low energy of the third step reduces surface roughness. The low discharge energy during finishing guarantees a good surface finish but increases the finishing time. In the MDS approach, finishing is also divided into three steps. 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 approaches defined in Section 2 were compared in terms of the wear, surface roughness, and machining time. The die-sinking EDM machine was used to fabricate wedges of HP1 mold steel, using graphite electrodes and our MDS method. The One-electrode SDS method, and the two-electrode SDS and MDS methods, were compared.

3.1 Equipment and materials

The MDS experiment used a die-sinking EDM machine (U2610-2H; UNiTECH) [Fig. 3(a)]. The HP1 mold steel was placed on a magnetic table, and the graphite electrode was bonded to the head of the machine. The dielectric fluid jet was flushed in six directions to remove debris in the gap between the electrode and workpiece. The wedge-shaped graphite electrode and fabricated HP1 mold steel are shown in Fig. 3(b). The HP1 workpiece composition was 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 mold steel workpieces were milled to create 20 × 20 × 50-mm “boxes” prior to EDM. The graphite electrodes are milled into wedge shapes with a transverse area of 10mm × 10mm. The edge wear of the electrode is measured by a digital microscope (ISM-PM200SA), as shown in Fig. 3(c). The graphite electrodes were milled into wedges with transverse areas of 10 × 10 mm. Electrode edge wear was measured using a digital microscope (ISM-PM200SA, Insize) [Fig. 3(c)], with image acquisition software (ISM-PRO) used to collect and process images. We used an SJ-201 roughness tester to measure the roughness values of the inclined wedge surfaces [Fig. 3(d)].

3.2 Experimental conditions

The discharge current in the roughing stage was set to 14 A based on the results of Kiyak and Cakır [14], while the discharge current at the finishing stage was set to 5 A according to Jeong et al. [19]. The other experimental parameters were determined based on the equipment maker’s recommendation. The pulse duration was 10 µs/A of peak current; all other conditions were unchanged. The pulse off-time, roughing gap distance, and roughing allowance (finishing depth) were 40 µs, 0.07 mm, and 0.15 mm, respectively.

The experimental conditions and results of the three approaches are shown in Table 1. With the One-electrode SDS approach, roughing and finishing were performed by the same electrode. The two-electrode SDS approach uses one electrode for roughing and the other for finishing. The discharge current in the roughing stage is 14 A, to remove material quickly, and 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 were 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 were 6 A for the first step, 5 A for the second step, and 4 A for the third step. All three approaches were repeated three times to determine the reproducibility of surface roughness, edge wear, and machining time.
Table 1
Comparative experimental conditions and results

| EDM approaches | Electrodes     | Current (A) | Pulse duration (µs) | Roughness (µm) | Wear (mm) | Time (min) |
|----------------|----------------|-------------|---------------------|----------------|-----------|------------|
| One-electrode SDS | Rough & Finish | 14          | 140                 | 4.09           | 0.216     | 11.28      |
|                 |                | 5           | 50                  |                |           |            |
| Two-electrode SDS | Rough         | 14          | 140                 | -              | 0.176     | 7.58       |
|                 |                | 5           | 50                  | 4.27           | 0.065     | 3.07       |
| Two-electrode MDS | Rough         | 16 → 14 → 12 | 160 → 140 → 120   | -              | 0.156     | 7.54       |
|                 |                | 6 → 5 → 4   | 60 → 50 → 40        | 4.01           | 0.072     | 4.57       |

### 3.3 Edge wear

To explore the relationship between discharge depth and electrode wear, the workpiece plane was discharged using a wedge-shaped electrode \(^{37}\). After EDM, the electrode was divided into cross-sections with 1-mm intervals and the edges were photographed using an optical microscope (Fig. 4). Fig. 4(a) shows 0.054 mm of edge wear at a discharge depth of 1.2 mm, while Fig. 4(b) shows 0.109 mm of wear at a discharge depth of 3.6 mm. The points in the graph of Fig. 4(c) are the data of three repeated experiments, and the single dotted line is the wear model obtained by regression analysis. It can be seen from the graph that edge wear \(EW\) is proportional to the square root of the discharge depth \(d\) as follows, where \(c\) is the experimental constant depending on the other conditions. The points in Fig. 4(c) are the data of three repeat experiments; the dotted line is the wear model obtained via regression analysis. The edge wear \(EW\) is proportional to the square root of the discharge depth \(d\), as follows, where \(c\) is an experimental constant that depends on the other conditions:

\[
EW_1(d) = c\sqrt{d}
\]  

The edge wear of the vertex where two sides and one front face meet is greater than the upper cross-section edge where the single side and one front face meet. Fig. 5(a) presents the edge wears of the One-electrode SDS approach. The One-electrode approach results in large edge wear of 0.216 mm because one electrode is used to remove the entire 4 mm depth. Dull electrode edges rounded out the concave edges of the mold steel. The edge wear of the vertex where two sides and one front face meet was greater than that at the upper cross-section edge where a single side and one front face meet. Fig. 5(a) shows the edge wear with the One-electrode SDS approach. The edge wear is substantial (0.216 mm) because one electrode is used to remove the entire 4-mm-deep metal. The dull electrode edges rounded the concave edges of the mold steel. In the two-electrode SDS approach, the precision of the final shape is determined by the wear of the finishing electrode. The machining allowance \(a\) after roughing is removed by the electrode in the finishing stage. The edge wear of the finishing electrode is given by equation (2):
In this model, the final edge wear of the finishing electrode of the two-electrode SDS approach is predicted to be approximately 70% less than that of the single-electrode SDS approach. Fig. 5(b) shows the edge wear of the two-electrode SDS approach. As expected, the edge wear of the finishing electrode was reduced to 0.065 mm. The machined edge became more concave because the rounded edges were removed by the sharp finishing electrode after roughing. The edge wear of the two-electrode MDS approach was the same as that of the two-electrode SDS approach; the number of steps did not affect edge wear.

3.4 Comparison of results among approaches

Figure 6 compares the edge wear, surface roughness, and machining time among the approaches. The edge wear of the two-electrode SDS approach was about 70% less than that of the one-electrode SDS approach. The edge wear result of the two-electrode MDS approach was inferior to that of the two-electrode SDS approach. The average surface roughness (Ra) values were similar among all three approaches. The two-electrode SDS approach was 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 roughing gap is also fixed at 0.07 mm. In the next section, we use RSM to determine conditions minimizing edge wear, surface roughness, and machining time when the MDS approach is employed.

4. Response Surface Methodology For Mds

As shown in Section 3, two-electrode EDM performed better in terms of edge wear than one-electrode EDM. However, for the two-electrode cases, the MDS approach was no better the SDS approach in terms of edge wear, surface roughness, or machining time. We used a Box-Behnken design (one of the most popular second-order RSM) to optimize the roughing and finishing currents of the MDS and the roughing gap.

4.1 Experimental plan

The process parameters and their respective levels are shown in Table 2. We considered three parameters: the discharge current differences in the roughing and finishing stages, and the roughing gap. 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 the roughing current difference (RCD), fixed to 14 A during the second step and decreased during the third step by an amount equivalent to the RCD. The RCD was set to 0, 2, or 4 A. The minimum RCD was 0 A (equivalent to that of the SCD approach), the intermediate RCD was 2 A (equivalent to the MDS approach before RSM optimization) and the maximum RCD was double the intermediate value. During finishing, the discharge current was increased, fixed, and then decreased in the first, second, and third steps, respectively. The finishing current

\[ EW_2(d, a) = c_2 \sqrt{a + c \sqrt{d - a}} \]
difference (FCD) was set to 0, 1, or 2 A, using a method similar to that applied to derive the RCDs. The roughing gap distance W is the clearance between the workpiece and electrode. The gap was 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; i.e., 0.03 mm away from both the minimum and maximum levels.

| 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 shows the BBD 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.
## 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     | 12.53      |
| 1         | 2         | 0       | 0       | 0.07     | 4.36           | 0.065     | 11.58      |
| 12        | 3         | 2       | 2       | 0.1      | 3.50           | 0.061     | 11.15      |
| 10        | 4         | 2       | 2       | 0.04     | 3.20           | 0.060     | 11.90      |
| 15        | 5         | 2       | 1       | 0.07     | 3.93           | 0.072     | 13.05      |
| 3         | 6         | 0       | 2       | 0.07     | 2.97           | 0.067     | 12.33      |
| 2         | 7         | 4       | 0       | 0.07     | 4.63           | 0.088     | 13.47      |
| 8         | 8         | 4       | 1       | 0.1      | 3.73           | 0.076     | 12.18      |
| 6         | 9         | 4       | 1       | 0.04     | 3.68           | 0.14      | 16.02      |
| 4         | 10        | 4       | 2       | 0.07     | 4.31           | 0.096     | 13.25      |
| 13        | 11        | 2       | 1       | 0.07     | 4.01           | 0.067     | 13.05      |
| 14        | 12        | 2       | 1       | 0.07     | 4.11           | 0.070     | 11.77      |
| 7         | 13        | 0       | 1       | 0.1      | 3.95           | 0.082     | 14.55      |
| 11        | 14        | 2       | 0       | 0.1      | 7.64           | 0.045     | 9.14       |
| 9         | 15        | 2       | 2       | 0.04     | 4.60           | 0.063     | 10.81      |

### 4.2 Analysis of surface roughness

Analysis of variance (ANOVA) was performed to draw a model with significant terms. Using the adjusted $R^2$ as the criterion of model adequacy, the model with the largest adjusted $R^2$ was selected. Equation (3) is the regression equation for the average surface roughness ($Ra$) with respect to the FCD $\Delta I_f$ and gap $W$ in the coded units estimated from the experimental data:

$$ Ra = 2.43 - 0.7 \Delta I_f + 37.7 W - 22.9 \Delta I_f \cdot W \ (3) $$

As the roughing stage is followed by the finishing stage, the $Ra$ should be unaffected by the RCD. ANOVA revealed that the $R^2$ of the fitted model was 62.51%, and the adjusted $R^2$ was 52.28. Thus, 62.51% of the surface roughness variation is attributable to linear effects of the FCD, the gap, and their interaction. The smaller $R^2$ value may reflect surface roughness variations among the milled electrodes, and errors when measuring inclined surfaces. Fig. 7 shows the estimated $Ra$, with respect to FCD $\Delta I_f$ and gap $W$ when RCD is fixed at 2 A. The FCD had a greater influence on $Ra$. When the FCD increased, $Ra$ tended to
decrease to a minimum. The graph also shows that the gap had less effect on Ra when the FCD increased by up to 2 A.

Figure 8 shows the surface finish improvement of the MDS approach using FCD 2 A compared to the conventional SDS approach using a single discharge current when the average discharge current is set to 5 A. The average surface roughness Ra was improved to 3.2 µm by increasing the discharge current at the first step and decreasing it at the third step, compared with 4.6 µm by the conventional approach.

4.3 Analysis of edge wear

The edge wear $EW$ of the finishing electrode is influenced by three parameters. Equation (4) shows their effects. The coefficient of determination $R^2$ and adjusted $R^2$ were 96.97% and 93.95%, respectively.

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

Figure 9(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 was set to 1.5 A and the FCD to either 0 or 2 A. Figure 9(b) shows the estimated response surface in terms of the RCD and gap when the FCD was 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 parameters are linked to edge wear in the finishing stage. Figure 9(c) shows the estimated response surface of edge wear in view of the FCD and the roughing gap. Edge wear tended to decrease as the gap increased. The FCD exerted a quadratic effect on edge wear.

4.4 Analysis of machining time

Machining time (MT) is influenced by three parameters, as shown in Equation (5), with $R^2 = 93.85\%$ and an adjusted $R^2 = 89.23\%$.

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

Figure 10(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 10(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 roughing gap is shown in Figure 10(c). The machining time decreased as the gap increased to 0.1 mm and the FCD was either 0 or 2 A. The response surface of the machining time exhibited a trend similar to that of the edge wear of the finishing electrode, indicating that a long 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 parameters \[^{36}\]. The desirability function approach is most often employed to optimize multiple responses simultaneously \[^{35}\]. This approach searches for parameter 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, weight is set at a value greater than 1. In general, if the weight factor is not mentioned, it is set at 1 \[^{35}\].

The individual \(d\) are 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 are reflected by the ‘importance values’. The optimal compromise among multiple responses is achieved by maximizing \(D\) \[^{36}\]. The desirability function approach was 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 were 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 are lower than their upper bounds than that they reach the importance target values, their weights were set to 0.5. Moreover, edge wear was considered to be twice as important as surface roughness and machining time, and was thus assigned an importance value of 2.

Using the response optimizer in Minitab, the optimal parameter combination was shown to be \((RCD, FCD, Gap) = (0.580, 2.0, 0.04)\) (Fig. 11). These conditions optimize the three responses simultaneously. The estimated Ra was 3.50 µm, the edge wear of the finished electrode was 0.052 mm, and the machining time was 10.78 min. As the RCD is controlled in integral increments, we performed additional experiments at RCDs of 0 A and 1 A.

### 4.6 Confirmation experiment

The optimal conditions (subsection 4.5) were \((RCD, FCD, Gap) = (0.58 A, 2 A, 0.04 mm)\). As the current can be controlled only in integral units, we tested two conditions \([(0 A, 2 A, 0.04 mm)\) and \((1 A, 2 A, 0.04 mm)\)] three times, and compared the data (Table 4). The three responses were optimized when the RCD was 1 A.
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      |

Table 5
Comparative experimental conditions and results with two electrodes

| EDM approaches | RCD (A) | FCD (A) | Gap (mm) | Roughness (µm) | Wear (mm) | Time (min) |
|----------------|---------|---------|----------|----------------|-----------|------------|
| SDS            | 0       | 0       | 0.07     | 4.27           | 0.065     | 10.65      |
| MDS before RSM| 2       | 1       | 0.07     | 4.01           | 0.072     | 12.11      |
| MDS after RSM  | 1       | 2       | 0.04     | 3.26           | 0.052     | 12.13      |

4.7 MDS optimization results

The comparisons in Section 3 showed that the two-electrode MDS approach was somewhat inferior to the two-electrode SDS approach (Fig. 6). In this section, we used an RSM to optimize the RCD, FCD, and gap in terms of edge wear, surface roughness, and machining time. Fig. 12 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 contributed to the improvement of edge wear and surface roughness. Through RSM optimization for the MDS approach, the edge wear of the finishing electrode was improved from 0.072 mm to 0.052 mm, and the average surface roughness was 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, where the discharge current is not changed. 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.
The RSM of the two-electrode MDS approach improved edge wear and surface roughness. RSM optimization improved the edge wear of the finishing electrode from 0.072 to 0.052 mm, and reduced the Ra from 4.01 to 3.27. The RSM-optimized MDS approach reduced edge wear by 20%, and the Ra by 24%, compared to the SDS approach. However, the machining time of the MDS approach increased by 15% compared to the that of SDS approach (where the discharge current does not change). The MDS machining time is longer than that of SDS because the time saved by using a high discharge current in the first step is less than the extra time required by the low discharge current in the third step. Overall, the two-electrode RSM-optimized MDS approach performed better than the two-electrode SDS approach.

5. Conclusion

Conventional die-sinking EDM studies use one electrode operation under constant discharge conditions. In this article, we employed two electrodes for roughing and finishing, an MDS approach and three discharge steps to improve edge wear, surface roughness, and machining time. Compared to a One-electrode SDS, the edge wear of a two-electrode SDS was reduced from 0.216 to 0.065 mm, i.e., by more than three-fold. However, for the two-electrode case, application of the MDS approach before RSM led to poorer performance than the SDS approach.

A 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 = 0.58 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.

The MDS approach combined with RSM can be beneficial to EDM practitioners who want to optimize process parameters 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 future research topic.

Abbreviations

SDS  Single discharge step
MDS  Multiple discharge step
RSM  Response surface methodology
RCD ($\Delta I_r$)  Roughing current difference
FCD ($\Delta I_f$)  Finishing current difference
Declarations

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With the consent, the authors give the publisher license of the copyright which provides the publisher with the exclusive right to publish and sell the research findings in all languages, in whole or in part.

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The first author did literature review, determined the parameters and their levels, analyzed the data, and wrote the paper with the corresponding author. The corresponding author designed the experiments and analyzed data. The third and fourth authors collected the experimental and measurement data.

References

1. Klink A, Arntz K, Johannsen L, Holsten M, Chrubasik L, Winands K, Wollbrink M, Bletek T, Gerretz V, Bergs T (2018) Technology-based assessment of subtractive machining processes for mold manufacture. Procedia CIRP 71:401–406. https://doi.org/10.1016/j.procir.2018.05.052

2. Amorim FL, Weingaertner WL (2005) The influence of generator actuation mode and process parameters on the performance of finish EDM of a tool steel. J Mater Process Technol 166(3):411–416. https://doi.org/10.1016/j.jmatprotec.2004.08.026

3. Amorim FL, Weingaertner WL (2007) The behavior of graphite and copper electrodes on the finish die-sinker electrical discharge machining (EDM) of AISI P20 tool steel. Journal of the Brazilian society of Mechanical Sciences and Engineering 29(4):366–371. https://doi.org/10.1590/S1678-58782007000400004

4. Klocke F, Schwade M, Klink A, Veselovac D (2013) Analysis of material removal rate and electrode wear in sinking EDM roughing strategies using different graphite grades. Procedia CIRP 6:163–167. https://doi.org/10.1016/j.procir.2013.03.079

5. Straka L, Hašová S (2018) Optimization of material removal rate and tool wear rate of Cu electrode in die-sinking EDM of tool steel. Int J Adv Manuf Technol 97(5):2647–2654. https://doi.org/10.1007/s00170-018-2150-3

6. Uhlmann E, Polte M, Bolz R, Börnstein J (2020) Fundamental research of applying tungsten carbide-cobalt as tool electrode material for sinking EDM. Procedia CIRP 95:466–470. https://doi.org/10.1016 /j.procir.2020.03.137

7. Ozgedik A, Cogun C (2006) An experimental investigation of tool wear in electric discharge machining. Int J Adv Manuf Technol 27(5–6):488–500. https://doi.org/10.1007 /s00170-004-2220-6

8. Flaño O, Ayesta I, Izquierdo B, Sánchez JA, Ramos JM (2018) Experimental Study on the Influence of Electrode Geometry and Electrode Path on Wear Pattern in EDM. Procedia CIRP 68:405–410. https://doi.org/10.1016/j.procir.2017.12.103

9. Liang W, Tong H, Li Y, Li B (2019) Tool electrode wear compensation in block divided EDM process for improving accuracy of diffuser shaped film cooling holes. Int J Adv Manuf Technol 103(5–8):1759–1767. https://doi.org/10.1007/s00170-019-03591-8

10. Rafaqat M, Mufti NA, Ahmed N, Alahmari AM, Hussain A (2020) EDM of D2 Steel: Performance Comparison of EDM Die Sinking Electrode Designs. Applied Sciences 10(21):7411. https://doi.org/10.3390/app10217411

11. Zhao Y, Zhang X, Liu X, Yamazaki K (2004) Geometric modeling of the linear motor driven electrical discharge machining (EDM) die-sinker process. Int J Mach Tools Manuf 44(1):1–9.
12. Chen J, Sun Z, Lu. G (2013) Simulation for Electrode Wear Predication in Die-Sinking EDM Based on Geometry Model. Proceedings of the 2013 Fifth International Conference on Measuring Technology and Mechatronics Automation. IEEE, 1000-1004. https://doi.org/10.1109/ICMTMA.2013.248

13. Ramasawmy H, Blunt L (2004) Effect of EDM process parameters on 3D surface topography. J Mater Process Technol 148(2):155–164. https://doi.org/10.1016/S0924-0136(03)00652-6

14. Kiyak M, Cakır O (2007) Examination of machining parameters on surface roughness in EDM of tool steel. J Mater Process Technol 191(1):141–144. https://doi.org/10.1016/j.jmatprotec.2007.03.008

15. Klocke F, Schneider S, Ehle L, Meyer H, Hensgen L, Klink A (2016) Investigations on surface integrity of heat treated 42CrMo4 (AISI 4140) processed by sinking EDM. Procedia CIRP 42:580–585. https://doi.org/10.1016/j.procir.2016.02.263

16. Valentinčič J, Junkar M (2004) A model for detection of the eroding surface based on discharge parameters. Int J Mach Tools Manuf 44(2–3):175–181. https://doi.org/10.1016/S0924-0136(03)00652-6

17. Valentinčič J, Filipič B, Junkar M (2009) Machine learning induction of a model for online parameter selection in EDM rough machining. Int J Adv Manuf Technol 41(9–10):865–870. https://doi.org/10.1007/s00170-008-1532-3

18. Lauwers B, Oosterling H, Vanderauwera W (2010) Development of an operations evaluation system for sinking EDM. CIRP Ann Manuf Technol 59(1):223–226. https://doi.org/10.1016/j.cirp.2010.03.085

19. Jeong HJ, Byun JH, Cheng DJ, Oh YJ, Kim SJ (2017) The Comparison of Response Surface and Discharge Energy Methods in Predicting MRR and Roughness of Sink EDM. Journal of the Korean Society of Manufacturing Technology Engineers 26(5):466–471. https://doi.org/10.7735/ksmte.2017.26.5.466

20. Zeilmann RP, Ivaninski T, Webber C (2018) Surface integrity of AISI H13 under different pulse time and depths by EDM process. Procedia CIRP 71:472–477. https://doi.org/10.1016/j.procir.2018.05.031

21. Klink A, Holsten M, Hensgen L (2017) Crater morphology evaluation of contemporary advanced EDM generator technology. CIRP Ann 66(1):197–200. https://doi.org/10.1016/j.cirp.2017.04.137

22. Gostimirovic M, Radovanovic M, Madic M, Rodic D, Kulundzic N (2018) Inverse electro-thermal analysis of the material removal mechanism in electrical discharge machining. Int J Adv Manuf Technol 97(5–8):1861–1871. https://doi.org/10.1007/s00170-018-2074-y

23. Rajeswari R, Shunmugam MS (2019) Investigations into process mechanics of rough and finish die sinking EDM using pulse train analysis. Int J Adv Manuf Technol 100(5):1945–1964. https://doi.org/10.1007/s00170-018-2701-7

24. Bergs T, Petersen T, Tombul U, Klink A (2020) Analysis of the Influence of Surface Integrity of Cemented Carbides Machined by Sinking EDM on Flexural Fatigue. Procedia CIRP 87:456–461. https://doi.org/10.1016/j.procir.2020.02.096
25. Gostimirovic M, Kovac P, Sekulic M, Skoric B (2012) Influence of discharge energy on machining characteristics in EDM. J Mech Sci Technol 26(1):173–179. https://doi.org/10.1007/s12206-011-0922-x

26. Li Z, Bai J (2017) Impulse discharge method to investigate the influence of gap width on discharge characteristics in micro-EDM. Int J Adv Manuf Technol 90(5):1769–1777. https://doi.org/10.1007/s00170-016-9508-1

27. Zhou M, Mu X, He L, Ye Q (2019) Improving EDM performance by adapting gap servo-voltage to machining state. J Manuf Process 37:101–113. https://doi.org/10.1016/j.jmapro.2018.11.013

28. Zhou S, Yang Y, Zhou M, Sun H (2020) Electrical discharge machining Inconel 718 with adaptively regulating gap servo-voltage. Int J Adv Manuf Technol 109(9):2575–2585. https://doi.org/10.1007/s00170-020-05835-4

29. Salman Ö, Kayacan MC (2008) Evolutionary programming method for modeling the EDM parameters for roughness. J Mater Process Technol 200(1–3):347–355. https://doi.org/10.1016/j.jmatprotec.2007.09.022

30. Puertas I, Luis CJ, Alvarez L (2004) Analysis of the influence of EDM parameters on surface quality, MRR and EW of WC–Co. J Mater Process Technol 153–154:1026–1032. https://doi.org/10.1016/j.jmatprotec.2004.04.346

31. Habib SS (2009) Study of the parameters in electrical discharge machining through response surface methodology approach. Applied Mathematical Modelling, 33(12), 4397-4407. https://doi.org/10.1016/j.apm.2009.03.021

32. Srinivasan VP, Palani PK, Selvarajan L (2018) Experimental investigation on electrical discharge machining of ceramic composites (Si3N4-TiN) using RSM. Int J Comput Mater Sci Surf Eng 7(2):104–115. https://doi.org/10.1504/IJCMSSSE.2018.092541

33. Uthayakumar M, Babu KV, Kumaran ST, Kumar SS, Jappes JW, Rajan TPD (2019) Study on the machining of Al–SiC functionally graded metal matrix composite using die-sinking EDM. Part Sci Technol 37(1):103–109. https://doi.org/10.1080/02726351.2017.1346020

34. Bédard F, Jahazi M, Songmene V (2020) Die-sinking EDM of Al6061-T6: interactions between process parameters, process performance, and surface characteristics. Int J Adv Manuf Technol 107(1):333–342. https://doi.org/10.1007/s00170-020-05109-z

35. Myers RH, Montgomery DC, Anderson-Cook CM (2016) Response Surface Methodology: Process and Product Optimization Using Designed Experiments. John Wiley & Sons

36. Derringer G, Suich R (1980) Simultaneous optimization of several response variables. Journal of Quality Technology 12(4):214–219. https://doi.org/10.1080/00224065.1980.11980968

37. Oh YJ, Jeong HJ, Kim SJ (2020) A Study on Graphite Electrode Wear in Sink EDM of HP1MA Steel. Journal of the Korean Society of Manufacturing Process Engineers 19(8):35–42. https://doi.org/10.14775/ksmpe.2020.19.08.035

**Figures**
Figure 1

Die sinking electric discharge machining
Figure 2

Electrodes and discharge steps
Figure 3

Experimental equipment and measurement instruments

(a) Die sinking EDM machine

(b) Graphite electrode and mold steel

(c) Edge wear measurement by ISM FM200SA and ISM PRO

(d) Surface roughness measurement by Mitutoyo SJ-210P
(a) Section edge wear of test 3 depth 1.2 mm

(b) Section edge wear of test 2 depth 3.6 mm

(c) Experimental data and regression wear model

**Figure 4**

EDM depth and section edge wear
Figure 5

Edge wears of electrodes and the machined workpiece

Figure 6

Comparison graphs of three approaches
Figure 7

Estimated response surface of roughness vs. FCD and gap

(a) Conventional FCD 0 A  
(b) MDS with FCD 2 A

Figure 8

Surface finish improvement with MDS approach
Figure 9

Estimated response surface of edge wear
Figure 10

Estimated response surface of machining time
Figure 11

Optimal conditions of the desirability function approach
Figure 12

Comparison of SDS and MDS before and after RSM optimization