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ORIGINAL ARTICLE

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# An experimental study for determination of the effects of machining parameters on surface roughness in electrical discharge machining (EDM)

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**Abstract** Electrical discharge machining (EDM) is a non-traditional production method that has been widely used in the production of dies throughout the world in recent years. The most important performance measure in EDM is the surface roughness; among other measures material removal and tool wear rates could be listed. In this study, experiments were performed to determine parameters effecting surface roughness. The data obtained for performance measures have been analyzed using the design of experiments methods. A considerably profound equation is obtained for the surface roughness using power, pulse time, and spark time parameters. The results are discussed.

**Keywords** Design of experiments (DOE) · Electrical discharge machining (EDM) · Surface roughness

## 1 Introduction

Electrical discharge machining (EDM) is a manufacturing method, which could be used to machine hard materials in complex shapes with high precision. EDM has been widely used in space industries and injection mold manufacturing throughout the world. The research in EDM processing has been focused on fast machining with better surface roughness and less tool wear. It has been classified in four groups mainly workpiece related, electrode, effective EDM methods, and optimization of EDM parameters.

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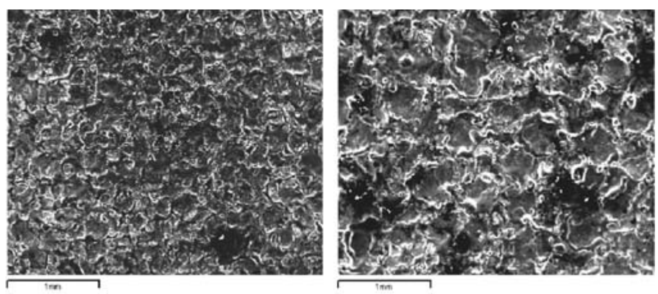
Successive electrical discharges occur at high frequencies, and each discharge result in a tiny crater both on the tool and the workpiece surface. The size of the craters is related to the released discharge energy at the discharge location. The shape of each crater is shallow and mostly symmetric around the vertical axis, where the discharge channel is developed and collapsed. The surface texture created by the sparks have a matte appearance covered by shallow craters, debris particles that are resolidified after the discharge, and pockmarks formed by entrapped gases escaping from the resolidifying material. Some of the debris are empty spherical shells, which is an indication of solidification from the gaseous state, and some others have irregular solid shapes, an evidence of solidification from the liquid state. Two typical magnified pictures of the surface of the workpiece materials are given in Fig. 1. In general, at low discharge energy the craters are shallow and the surface irregularities are smooth, shallow, and less frequent. Whereas at high discharge energy the craters are deeper and surface irregularities are larger and most evident. The debris scattered over the EDM'ed surface is resolidified by molten material droplets from the tool and workpiece electrodes. It is apparent from the figures that they are expelled violently during the electrical discharges and resolidified on the surface after the discharge ceases and cold dielectric liquid fills in the discharge gap. The resolidified layer of material may also include decomposition products of the dielectric liquid as an alloying agent.



**Power= 220 W, ts=200 µs, tp=50 µs** **Power= 413 W, ts=400 µs, tp=500 µs**

**Fig. 1.** Typical pictures of EDMed surfaces (courtesy B. Ekmekcı)

The research into EDM has been focused on not only the mathematical modeling of material processing but concentrated on producing emprical solutions by experimental studies [1–4]. The main interest among researchers is to identify effecting parameters on surface roughness [5] as well as parameters for workpiece and tool wear factors [4–6]. Nevertheless, there are still disputes among researchers and manufacturers in manufacturing by spark. There have been considerably many studies performed for the determination of performance parameters in electro erosion processing. Tsai and Wang [2] developed a semi emprical model in which parameters affecting the surface roughness were identified to be spark time, maximum current, polarity, input power, material density, conductivity of the material, specific heat capacity, heat conductivity, melting point, and boiling point of the material. Marafona [7] worked on an optimization model by design of experiments methods (DOE) when a copper-tungsten electrode is used in EDM processing. Guo and Tsai [8] focused on optimum processing of BaTiO semi-conducted material. They developed a model by DOE methods and further worked on an optimization model by using genetic algorithms.

Rebelo and others [9] investigated parameters for material removal rate and surface roughness when processing of hard copper-berilium alloys. Ghoreishi and Atkinson [10] researched on EDM processing when a rotating electrode, vibrated electrode and both are used. Halkacı and Erden [11] performed an experimental study and identified relations between $Ra$ and spark time and, $Ra$ and power as follows:

$$Ra = Ax^B \quad (1)$$

where $x$ is the power or spark time, $A$ and $B$ are constants. However, whether an interaction between power and spark time exists is not studied.

In this study, the experiments were concentrated on a steel workpiece with a copper electrode in die manufacturing. The effects of power, spark time, and pause time on surface roughness have been determined by experimental studies.

## 2 Experiments

The specifications of electrodes used in the experiments are given below.

*Tool electrode.* A cylindirical copper electrode with 16 mm diameter and 50 mm length.

*Work piece electrode.* A steel rectangular with $15 \times 50 \times 30$ mm dimensions, 0.16 C, 0.194 Si, 0.674 Mn. There have been at most eight processing on every workpiece. The processing parameters were followed up by an osiloscope. The tools and workpieces were cleaned and dried in proper places before measurements of $Ra$, arithmetical mean roughness. In the experiments, power, spark time, and pause time parameters are considered while other parameters were assumed to be constant. A wide spectrum for power, spark time, and pause time are considered. The power level of 118, 220, and 413 kW, spark time ($t_s$), 4.5, 8,14, 26, 51, 100, 200, and 400 µs, pause time ($t_p$), 10, 13, 25.5, 50, 100, 200, and 500 µs. A total of 504 experiments were performed by using three levels of power, eight levels of spark time, and seven levels of pause time. Each experiment is repeated three times by using the same parameter levels. Results of each experiment were tested by Chauvenet criteria [11], a method of identifying false measurements.

## 3 Evaluation of experimental results

The evaluation of experimental results for surface roughness is presented in detail. An interaction is present between power and spark time ($t_s$) to surface roughness, and a statistical analysis is performed.

Table 1 illustrates the effects of these three parameters on surface roughness. Although all parameters are found to be statistically meaningful, spark time, power, and the interaction of the two are relatively high. For this reason, a multiple regression model is decided to be formed.

It is seen from Table 1 that the interaction between spark time and power to surface roughness is statistically significant. In order to clarify this effect, the spark time for the three levels of power is graphed and shown in Fig. 2. When the power level is at 413 kW, the effect of spark time on surface roughness is relatively high, yet at the level of 118 kW this effect is considerably low. It can be concluded that the interaction between spark time and power has an effect on $Ra$ by observing that these curves are not parallel.

**Table 1.** ANOVA summary

| Source of variation | Sum of squares | Degrees of freedom | Mean square | Calculated $F_0$ | $F_0$ Critical value (%5) | $F_0$ Critical value (%1) |
|---|---|---|---|---|---|---|
| A[a] | 1127.37 | 7 | 161.05 | 1664.19 | 2.01 | 2.64 |
| B[a] | 1237.95 | 2 | 618.97 | 6395.94 | 3.00 | 4.61 |
| C[a] | 1.71 | 6 | 0.28 | 2.94 | 2.10 | 2.80 |
| AB | 535.42 | 14 | 38.24 | 395.19 | 1.70 | 2.08 |
| AC | 12.44 | 42 | 0.30 | 3.06 | 1.38 | 1.58 |
| BC | 4.81 | 12 | 0.40 | 4.15 | 1.75 | 2.18 |
| ABC | 26.10 | 84 | 0.31 | 3.21 | 1.28 | 1.41 |
| Error | 16.26 | 168 | 0.10 | | | |

[a] A: Spark time, B: Power, C: Pause time

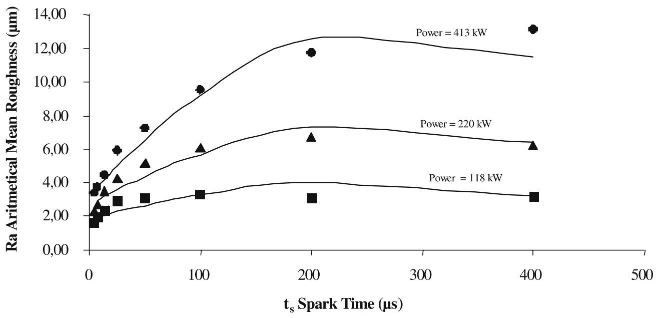



**Fig. 2.** Comparison of calculated and experimental values for *Ra* vs $t_s$

Results of the ANOVA suggest that only spark time and power has an effect on the surface roughness function. In order to identify which terms of parameters of spark time and power will be included in this function, a multiple regression model is needed. Table 2 summarizes the variance analysis performed for the determination of these terms.

The arithmetical mean roughness (*Ra*) function includes the spark time term, power term, and multiplication of spark time and power. The function is as follows:

$$Ra = a_0 + a_1 * A + a_2 * B + a_3 * A * B + a_4 * B^2 \qquad (2)$$

where $a_0, a_1, \ldots, a_4$ are coefficients, $A$ is the spark time in µs, and $B$ is the power in kWatt.

The $R^2$ value is obtained as 0.85 from the multiple regression model. The rest of the parameters are also included in the analysis and error terms are calculated. The best result is obtained by only the inclusion of the $A * B^2$ term. The $R^2$ value is increased to 0.96 with the addition of this term, and reached to an acceptable level. The function is found as:

$$Ra = 0.327 - 0.00357A + 0.01509B - 0.00001946B^2 + 0.0001811AB - 0.0000003067A^2B. \qquad (3)$$

The above *Ra* function has almost a one-to-one correspondence with experimental values as shown in Fig. 2. The deviation reaches a high level only when the power is at 413 kW and spark time 400 µs. It is hard to expect good results at these levels in real life applications because a bridge between the workpiece and electrode would be formed.

**Table 2.** Determinations of terms in *Ra* function

| Source of variation | Calculated $F_0$ | $F_0$ Critical value (%5) |
|---|---|---|
| (AL) | 256.13 | 3.92 |
| (AQ) | 0.02 | 3.92 |
| (BL) | 323.56 | 3.92 |
| (BQ) | 5.54 | 3.92 |
| (ABLL) | 43.11 | 3.92 |
| (ABLQ) | 2.44 | 3.92 |
| (ABQL) | 2.66 | 3.92 |
| (ABQQ) | 1.38 | 3.92 |

L: Linear term, Q: 2nd order term, A: Spark time, B: Power. For example, $AB_{QL}$ means that second order of spark time multiplied by linear term of power

## 4 Conclusions

An equation is obtained for surface roughness by using multiple regression. Experimental results comply with the equation.

These results could become a reference to EDM manufacturers especially when the workpiece is steel and a copper electrode is used. It would be possible to manufacture parts with certain surface roughness requirements using the results instead of trial and error. Therefore, the manufacturing time will be decreased.

Effects of machining parameters on the surface roughness values of machined components by EDM have been investigated experimentally. It is apparent that the surface roughness has an increasing trend with an increase in the discharge duration. This is mainly due to more discharge energy released during this time and expanding the discharge channel.

It would be more useful to do the analysis with more processing parameters. We plan to use a CNC electro discharge machine to be able to choose processing parameters freely and compare to the conventional machine tool. We also plan to use a two level designed experiment for further research.

It is believed that a better methodology would be more useful to measure surface properties. This is simply because of the overlapping craters over the surfaces that have a matte appearance, and the nature of the irregularities are completely different than the traditional processes. Surface roughness measurements for EDM should be used to compare similar experimental conditions, however, a comparison with surface properties of components machined by one of traditional processes may not be valid.

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