Investigation an assisting electrode powder mixed electrical discharge machining of nonconductive ceramic

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Abstract
This research is aimed to describe a new approach for machining zirconia ceramics. The purpose is to develop an electrical discharge machining with assisting electrode and dielectric mixed with graphite powder to enable processing of nonconductive material and improve machining performance. Methodology that used in this paper is Box-Behnken design. Three controllable parameters were selected, namely discharge current, pulse duration, and graphite powder concentration. The material removal rate, surface roughness, and relative tool wear were chosen as machining performances. The proposed approach uses the concept of response surface methodology to develop mathematical models. Although the discharge current and pulse duration proved to be the most influential input parameters, the finding that resulted in this research is the positive effect of graphite powder on machining performance. The proposed approach provides a very beneficial option of EDM input parameters to achieve the performance improvement: increase in material removal rate, reduction in surface roughness and relative tool wear.

Keywords Response surface methodology · Hybrid assisting electrode · Zirconia ceramics · Surface roughness · Material removal rate · Tool wear ratio

1 Introduction

Despite their exceptional properties compared to metallic materials, ceramics are becoming increasingly popular in the manufacturing industry. One of the reasons for this is the sintering process, which limits the production of complex geometries and also limits the machinability of the final product. Various processes can be used to machine ceramic materials, such as diamond tool grinding, ultrasonic machining, laser machining, waterjet machining, and ion beam machining [1, 2]. However, these machining methods have some limitations in terms of productivity, quality, and economy of machining, i.e., they do not fully meet the requirements of modern production. Therefore, it is necessary to consider other methods by which ceramic materials can be machined.

Electrical discharge machining (EDM) is a machining process that can process all electrically conductive materials, regardless of their physical and metallurgical properties [3]. To machine electrically nonconductive materials using EDM, electrical contact must be established [4]. This is solved by the method of assisting electrodes, which help to start the discharge between the tools and the nonconductive materials. The discharges can continue if favorable conditions for the formation of a secondary electrically conductive layer are present [5].

Existing literature indicates that by applying an electrically conductive layer (assisting electrode (AE)) to the top surface of the workpiece, it is possible to machine electrically nonconductive ceramic materials assisting electrode electrical discharge machining (AEEDM). The detailed description of EDM technique with assisting electrode in the academic world was recorded by Japanese scientists Fukuzawa et al. [6] in 1995. In their work, a new method was described which enables electrical discharge machining of electrically nonconductive ceramic materials with the help of a metal plate (as assisting electrode) attached to the workpiece. They concluded that AEEDM is realized by continuously forming
an electrically conductive layer. The assisting electrode enables an initial electrical discharge between the tool and the workpiece. After the assisting electrode layer is removed by the high temperature in the discharge zone, dielectric dissolution occurs, whereupon the carbon particles are deposited on the surface and form an electrically conductive layer (carbon layer). During the AEEDM process, an electrically conductive carbon layer is continuously formed on the workpiece, which is responsible for the stability of the process [7]. The process of forming the electrically conductive layer is also described by Mohri et al. [8]. It is mentioned here that the dielectric must be carbon-based for ablation of non-conducting ceramics to be stable. Similar phenomena were found by Hanaoka et al. [9].

The AEEDM process is illustrated in Fig. 1. The surface of the workpiece is covered with an electrically conductive material, allowing the first electrical discharge, i.e., the discharge between the tool and the assisting electrodes. Thereafter, the discharge proceeds through the conductive layer to the workpiece material on which the carbon layer (pyrolysis layer) is produced. During the electrical discharge process, a conductive carbon layer is continuously generated on the workpiece, which is responsible for the stability of the process.

For AEEDM of non-conducting materials to be possible, a hydrocarbon-based dielectric must be used. By converting electrical energy to thermal energy, the resulting high temperature visibly affects the dielectric in the discharge channel zone. In the absence of oxygen in the spark region, the high temperature causes thermochemical decomposition of the dielectric. The decomposition of a substance under the influence of high temperature, without the action of other agents, is called pyrolysis. As a result of the hydrolysis-induced pyrolysis of the dielectric, a carbon layer is formed (pyrolysis layer). The resulting carbon layer corresponds to the melt layer formed during metal removal and is structurally similar to graphite, which makes it electrically conductive.

The influence of the material AE on the technological properties of AEEDM was analyzed by Tani et al. [10]. In this work, a comparison of different designs of assisting electrode is carried out, first with a metal plate and then with a metal grid deposited in several layers. It was found that the application of a copper grid significantly reduces the surface roughness. The same authors [7] processed zirconia ZrO₂ with copper and graphite tools. They found that the carbon layer was not fully formed when copper tools were used, resulting in a rough surface roughness. In the next work [11], the effect of thermal conductivity of alumina with purity of 99.99% on machining productivity was studied. At higher values of thermal conductivity of the material, higher machining productivity is achieved. In [12], the die-sinking EDM of alumina with high discharge energy was carried out. High discharge voltage and very high capacitance per unit area was used, which resulted in very high discharge energy and explosive force. They concluded that tool polarity is the
most important factor affecting crater volume and depth as well as relative tool wear. Sabur et al. defined that the formation and stability of the carbon layer (in addition to the material of the workpiece and tools, the type of dielectric and the polarity of the tool) is influenced by the discharge energy, which is the product of voltage, discharge current and pulse duration [13].

Various metal foils can be used as assisting electrodes. The most common are metal foils of aluminum and copper, which are mechanically applied to ceramic surfaces. The main advantage of this method is simplicity [14]. The main disadvantage of clamping metal foils onto ceramics is the lack of solid contact between metal and ceramics. Due to the lack of direct contact between the foil and the ceramics, the formation of the carbon layer is difficult, which leads to the instability of the AEEDM process, i.e., the interruption of the process [15]. In cases where a graphite coating is used, it is usually heated to a temperature of approximately 200 degrees. After heating, the carbon layer became conductive (resistance of 200 Ω µm) and served as the first layer of AE [16]. In this case, the carbon layer is brittle, and when the EDM process is carried out at higher energies, the carbon layer often peels off in undesirable places [17]. Therefore, the surface is coated with an adherent copper layer to provide robustness and prevent the AE from peeling off at undesirable locations. The combination of metal foil and graphite coating is called hybrid assisting electrode [18]. The metal foil provides the robustness, i.e., the strength of the assisting electrode, while the graphite coating acts adhesively between the metal foil and the ceramic [19]. By applying an electrically conductive layer HAE to the surface of the workpiece, it is possible to process nonconductive ceramic materials. The assisting electrode enables the initial electrical discharge between the tool and the workpiece. After removing the assisting electrode layer, the dielectric decomposes due to the high temperature in the discharge zone, whereupon carbon particles are deposited on the surface of the workpiece and form an electrically conductive layer.

Key input parameters affecting machining performance were studied by Chen et al. [20]. They showed that discharge current and pulse duration have a significant effect on surface roughness. Moreover, they used two types of assisting electrodes, aluminum, and copper and concluded that the type of electrodes has a great influence on tool wear. Based on the research [21, 22], the main input parameters are discharge current, pulse duration, pulse off time, open voltage, and polarity. Discharge current is the most commonly considered parameter in EDM of insulating ceramics [6]. According to the previous studies in the field of AEEDM, discharge currents up to 6 A have been used for tool cross sections up to 1 cm² [7, 23].

However, the current application of AEEDM is limited due to the relatively low material removal rate and high surface roughness. AEEDM of electrically nonconductive materials by adding an electrically conductive powder to the dielectric results in a hybrid process called assisting electrode powder mixed electrical discharge machining ((AE + PM) EDM). It is believed that the addition of electrically conductive powder reduces the insulating properties of the dielectric, which leads to an increase in the working gap, thus achieving a more efficient flushing of the working space between the tool and the workpiece.

The first basic technology of electrical discharge machining with an assisting electrode in a powder mixed dielectric was established in 2002 by scientists Tani et al. [23]. Using the method ((AE + PM) EDM) with several types of powders of different sizes (silicon powder, nickel powder, graphite powder, aluminum powder, and zirconium boride powder), they successfully machined insulating silicon nitride ceramic (Si₃N₄). The results obtained show that the machining productivity was improved by using all five types of powders. However, contrary to their expectations, there was no significant improvement in surface roughness because a longer pulse duration was generated during machining than was primarily set on the machine. This phenomenon is common in EDM of high strength materials. They concluded that reducing the pulse duration below the value of 24 µs improves the surface roughness. In this way, the excessive pulse duration is prevented, which directly affects the increase of discharge energy. The study of surface roughness in (AE + PM) EDM was also prompted by Sabur et al. [18]. The discharge voltage and powder concentration of tantalum carbide (TaC) were input variables, while the other parameters were held constant. Modeling and analysis were carried out using response surface methodology. Discharge voltage was found to have a greater effect on surface roughness than powder concentration. The optimum values for discharge voltage and powder concentration, 94 V and 6 g/l, are also presented, where the minimum surface roughness is obtained. The application of the process of (AE + PM) EDM is also presented in paper [24]. In their work, several types of electrically nonconductive materials with an outer copper diameter of 3.5 mm and an inner diameter of 3 mm were processed in a dielectric containing mixed graphite powder with a grain size of 30 µm. In the mentioned study, it is not clearly stated what is the contribution of the addition of graphite powder to the dielectric. Different materials were machined, some of which were electrically nonconductive, with only one machining regime (Iₑ = 1.5 A, tₑ = 50 µs, and U₀ = 100 V). Raju et al. performed wire EDM of insulating zirconia and also tested the feasibility of the (AE + PM) EDM method [25]. They used graphite additives to aid secondary electrically conductive layer formation and achieve uninterrupted sparking when the insulating ceramic surface is exposed. In their case, the most stable processing was achieved at a graphite powder concentration of 4 g/l.
The results of previous studies, of which there are not many, indicate that electrically nonconductive EDM materials have significantly lower machining productivity, higher surface roughness, and higher tool wear than metallic EDM materials. Since it is very difficult to perform experiments, there are also very few mathematical models of the output power for this type of machining. Therefore, the main contribution of this research is the EDM of nonconductive material with an assisting electrode in a dielectric with mixed powder. One of the representatives of electrically nonconductive ceramics used in this research is zirconia (ZrO₂). A combination of self-adhesive copper metal foil and graphite layer was used as a hybrid assisting electrode, while the dielectric is mixed with graphite powder. The purpose of this paper is to demonstrate that by combining the AEEDM process with a mixed powder dielectric, an additional improvement in yield performance can be achieved in the processing of nonconductive ceramics. The main objective is the practical application, the development of mathematical models and the determination of influencing parameters for (AE + PM) EDM zirconium, such as $I_e$, $t_i$ and $GR$, as a function of process performance ($R_a$, $MRR$ and $TWR$). For this purpose, the response surface methodology with Box-Behnken design (BBD) was applied.

2 Materials and methods

The experiments in this research were designed to improve existing EDM. This is done by using methods such as assisting electrode and powder mixing dielectric. All with the aim of improving the machining performance such as surface roughness, material removal rate, and relative tool wear when machining zirconia. The flowchart used in this study to build RSM models of the output characteristics is shown in Fig. 2.

In order to obtain adequate models of the performance characteristics, the study was conducted in several steps. Based on the available literature and the capabilities of the machine tool, the analysis and assumption of the input parameters were carried out. Due to the unavailability of data on electrical discharge machining of nonconductive ceramics, preliminary tests were conducted to define the range of input parameters. Maximum values of the variable input parameters such as discharge current, pulse duration, and graphite powder concentration were determined. In the next step, the main experiments were carried out according to the Box-Behnken design. Using the analysis of ANOVA, the RSM models $R_a$, $MRR$, and $TWR$ were constructed. After the verification of the model, the analysis of the influence of the input parameters on the output performances was carried out, paying special attention to the influence of the

![Flowchart of the research methodology](image-url)
addition of graphite powder to the dielectric and the state of the eroded surface.

2.1 Machine, tool, and workpiece

A series of experiments was carried out on a die-sinking EDM machine Agie Charmilles of the SP1-U type. Isotropic graphite with a cross-section of $10 \times 10 \text{ mm}^2$ was used as the electrode for machining insulating zirconia $\text{ZrO}_2$. The dimensions of the workpieces were $15 \times 15 \times 8 \text{ mm}$. The reason for using graphite tools is that the formation of the electrically conductive layer is more stable than other types of tools, such as copper. This is because the formation of this layer is influenced by components from the machining zone, such as carbon from the dielectric and the tool material. The physical and mechanical properties of isotropic graphite and zirconia are shown in Table 1. Before conducting the experiments, all tools were surface ground to ensure normality with the workpiece.

2.2 Assisting electrode powder mixed method (AE + PM) EDM

The dielectric used in this study was a commercial mineral oil (Castrol Ilocut 180) with a flash point of 100 °C. Natural graphite powder (Asbury PM19) and surfactant (Tween 20 C58H114O26) are suspended in the dielectric oil. The powder material used was 95.5% pure graphite with an average particle size of 19 μm. The additive Tween 20 is added to the dielectric for better circulation in the discharge gap and to avoid particle agglomeration. A preparation tank with a capacity of 20 l was designed to circulate the dielectric, Fig. 3. In addition, a small pump and an agitator were used to prevent the particles from sinking. To ensure homogeneous mixing of the medium, an agitator set to 500 rpm and a side flush of 0.5 bar were used during processing.

In this study, the workpiece material was a nonconductive ceramic. Therefore, for the application of EDM to process insulating ceramic material, a basic technique was developed in which a graphite layer (graphite 33 varnish) and an adhesive layer of copper foil (3 M Grade 1181) were applied to the workpiece surface, Fig. 4. First, the graphite layer was applied to the surface of the zirconia ceramic. Then, the workpiece was heated in an oven at 200 °C for 2 h. Then, the copper foil is placed on the graphite layer. This additional electrically conductive layer is called a hybrid assisting electrode (HAE). The setup of the experiment is shown in Fig. 5.

2.3 Machining conditions: preliminary experiments

A preliminary test was performed at discharge current of 3.2 A. In this case, the eroded surface was obtained with a large particle size of 19 μm. The additive Tween 20 is added to the dielectric for better circulation in the discharge gap and to avoid particle agglomeration. A preparation tank with a capacity of 20 l was designed to circulate the dielectric, Fig. 3. In addition, a small pump and an agitator were used to prevent the particles from sinking. To ensure homogeneous mixing of the medium, an agitator set to 500 rpm and a side flush of 0.5 bar were used during processing.

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**Table 1** Tool and workpiece properties

| Tool          | Workpiece |
|---------------|-----------|
| Graphite TTK50 | ZrO₂      |
| Density [g/cm³] | 1.80      |
| Density [g/cm³] | 5.68      |
| Hardness [shore] | 70        |
| Melting point [°C] | 2720      |
| Electrical resistivity [μΩm] | 13        |
| Thermal conductivity [W/m·K] | 2         |
| Flexural strength [MPa] | 60        |
| Specific heat [J/Kg ·°C] | 400       |
| Average particle size [μm] | 6         |
| Electrical resistivity [μΩm] | 1010      |

**Fig. 3** Assisting electrode powder mixed method (AE + PM) EDM

**Fig. 4** Hybrid assisting electrode HAE
surface roughness that could not be measured, Fig. 6. Therefore, the discharge current up to 2 A is used for this study. In the AEEDM of ZrO$_2$, the electrical discharges could not be established in the machining gap between the tool electrode and the ceramic workpiece at an open voltage of 100 V. This phenomenon occurred because the discharge energy in the process was too low to produce an effective carbon layer. With an auxiliary current of 0.5 A and a high voltage of 300 V, the processing of insulating ceramics on the SPU-1 machine became possible.

The range of pulse duration was selected based on preliminary tests. As can be seen in Fig. 7, the machining performance deteriorates as the pulse duration increases. The pulse duration was between 40 and 100 μs, and the duty cycle $\tau$ was constant 50%. Based on the literature for AEEDM of insulating ceramics, the duty cycle is between 20 and 50%.

Some experiments were conducted to verify the effectiveness of the powder concentration. The machining input parameters were kept at constant values as shown in Fig. 8, and the powder concentration was varied from 0 to 8 g/l. When machining zirconia ceramics by the developed method (AE + PM) EDM, it is obvious that the addition of a graphite powder in the dielectric gives better output performance in machining. Preliminary experiments showed that surface roughness and tool wear rate increase with concentration above 4 g/l of graphite powder. Therefore, 8 g/l was adopted as the upper concentration limit.

### 2.4 Machining performance

The machining performance characteristics selected for this study were surface roughness ($R_a$), material removal rate (MRR) and tool wear ratio (TWR). The surface roughness measurements for the eroded surface were carried out using Perhometer, Mahr Surf PS1. The average surface roughness $R_a$ [μm] was used to quantitatively assess the quality of the machine surface. To achieve the highest possible accuracy, the surface roughness tests were repeated three times for each test point, and the average value was taken to obtain the surface roughness value.
The erosion depth of a workpiece is measured directly from a display of the machine (resolution of 1 μm) and checked manually with a comparator, Fig. 9. The material removal rate is expressed in cubic millimeters per minute (mm³/min) and refers to the machining efficiency of the EDM process and is defined as Eq. 1.

\[
MRR = \frac{\text{cross section electrode (mm}^2\text{)} \times \text{depth of cut (mm)}}{\text{time of machining (min)}} \text{ [mm}^3\text{/min}] \tag{1}
\]

Tool wear can be expressed as a percentage of the original effective length of the electrode. The measured final wear is divided by the depth of the machined cut in the workpiece. Multiplying this number by 100 gives the percentage of wear, Eq. 2. Accurate quantification of the tool wear ratio was possible with a precise length Abbe microscope resolution of 1 [μm], Fig. 10.

The reason for using this method is that the graphite tools may absorb a certain amount of the dielectric during the EDM process due to their porosity [26]. Therefore, it is difficult to determine the tool wear rate by a loss mass of the electrode.

\[
TWR = \frac{\text{Start length - final length (mm)}}{\text{Eroded depth (mm)}} \times 100 \text{ [%]} \tag{2}
\]

### 2.5 Experimental setup and design

To study the effects of input parameters on machining performances, Box-Behnken design (BBD) is used. The BBD is a rotatable experimental design based on three-stage incomplete factorial experimental designs [27], which has the advantage of requiring a smaller number of runs. This experimental design is more economical compared to other three-stage experimental designs due to the smaller number of experimental runs and allows the effects of input parameters on machining performance to be analyzed with a minimum number of trials [28].

The detailed machining conditions performed in this study, or the electrical and nonelectrical parameters of EDM, are shown in Tables 2 and 3. The ranges of input parameters were selected based on preliminary tests, literature, and machine constraints.

The objective of this study is to determine the empirical formulas of \(R_m\), \(MRR\), and \(TWR\) for (AE + PM) EDM. In the present study, only discharge current \(I_e\), pulse on-time \(t_i\), and \(GR\) are considered as processing parameters as design factors for (AE + PM) EDM of ZrO₂ insulating ceramics, Table 4. A commercially available software package (Design-Expert) was used for the experimental design and analysis.
Results and discussion

RSM is a useful method for modeling and predicting the reactions affected by the input parameters with the aim of optimizing the reactions [29]. Therefore, this method is used to build mathematical models for each output processing power in terms of discharge current, pulse duration, and powder concentration to express the predicted surface roughness, material removal volume, and tool wear rate. As mentioned earlier, a series of 17 experiments were performed according to the BBD. All machining parameters and measured output power with respect to each test are shown in Table 4.

There are four types of models that can be used in reaction modeling, such as linear, two-factor interaction (2FI), quadratic, and cubic polynomials for the reaction. To examine the adequacy of the models for the responses, the analysis of variance method (ANOVA) is performed. For each model, the probability is tested (“Prob F”) to see if it falls below 0.05 [30]. The fitting summary recommended that the quadratic models are statistically appropriate for the analysis of $Ra$, $MRR$, and $TWR$.

### 3.1 Surface roughness

After fit summary, a quadratic model for surface roughness was proposed. To test the significance of the terms, an analysis of variance was performed, which is mainly used to determine the $p$ value. It is known that a $p$ value of 0.05 or
0.1 indicates that the modal terms are significant. Using 10 levels of significance, a model is considered significant if the p value is less than 0.1. The non-significant terms were then removed using a backward elimination procedure. Table 5 shows the analysis of variance for the reduced quadratic model for estimating surface roughness after excluding the non-significant terms. The F value of the proposed model is 38.68, which indicates that the model is highly significant at 0.04% probability level. According to Table 6, the values of $R^2$ and Adj. $R^2$ are 0.9678 and 0.9428, respectively, while Pred. $R^2$ is 0.8161 which are close to 1. These statistical parameters called coefficient of determination indicate how well a regression model predicts the responses for new observations. Results higher than 0.7 usually indicate that the predicted values follow the actual values. The Adeq. Precision of 23.330 implies a reasonable signal. This parameter measures the ratio of signal to noise, and a ratio greater than 4 is desirable.

The results of ANOVA show that the surface roughness is affected by all input parameters. Finally, the model was constructed based on the remaining terms as shown in Table 6. The mathematical model for determining the surface roughness is shown in the decoded form, Eq. 3.

$$R_a = 0.93019 + 3.51369 \cdot Ie + 0.014234 \cdot ti - 0.29084 \cdot GR + 0.035860 \cdot Ie \cdot ti - 0.26312 \cdot Ie \cdot GR - 0.000535 \cdot ti \cdot GR + 0.11757 \cdot GR^2$$

Figure 11 shows the normal probability plot of the residuals for $R_a$. This plot compares a data set with the normal distribution. The plot of the theoretical percentiles of the normal distribution versus the observed percentiles of the sample is approximately linear. This shows that the model is good.

The effect of the input parameters on the surface roughness is shown in Fig. 12. As can be seen, the surface roughness of the insulating ceramic is low at low discharge current and low pulse duration, and the surface roughness is high at high values of these input parameters. This is because higher discharge energy directly increases the thermal energy in the discharge zone, and the high discharge current and pulse duration results

| Source   | Sum of squares | df | Mean square | $F$ value | $p$ value    | Contribution% |
|----------|----------------|----|-------------|-----------|--------------|---------------|
| Model    | 87.28          | 7  | 12.47       | 38.68     | <0.0001      | 55.08         |
| A-Ie     | 49.68          | 1  | 49.6        | 154.08    | <0.0001      | 16.42         |
| B-ti     | 14.81          | 1  | 14.81       | 45.93     | <0.0001      | 2.15          |
| C-GR     | 1.94           | 1  | 1.94        | 6.03      | 0.0364       | 1.21          |
| AB       | 1.09           | 1  | 1.09        | 3.39      | 0.0989       | 1.23          |
| AC       | 1.11           | 1  | 1.11        | 3.44      | 0.0968       | 1.72          |
| BC       | 1.55           | 1  | 1.55        | 4.80      | 0.0562       | 16.62         |
| C$^2$    | 14.99          | 1  | 14.99       | 46.48     | <0.0001      | 3.22          |
| Residual | 2.90           | 9  | 0.32        |           |              |               |
| Lack of fit | 2.51        | 5  | 0.50        | 5.12      | 0.0694       |               |
| Pure error | 0.39          | 4  | 0.098       |           |              |               |
| Cor total | 90.19          | 16 |             |           |              |               |

Table 5 ANOVA for $R_a$ reduced quadratic model

Table 6 Basic statistical data of the adopted model for $R_a$

| Std. Dev | Mean | C. V. % | PRESS | R-Squared | Adj. R-Squared | Pred R-Squared | Adeq Precision |
|----------|------|---------|-------|-----------|----------------|----------------|----------------|
| 0.57     | 9.64 | 5.89    | 16.59 | 0.9678    | 0.9428         | 0.8161         | 23.330         |
in increasing discharge energy of the single pulse, which in turn results in large surface roughness. In general, the surface roughness depends mostly on the discharge current and then on the pulse duration. This is a well-known statement that has been confirmed in scientific circles from the aspect of processing advanced materials [31, 32]. Minimum surface roughness can be expected with the following process parameters: discharge current of 1 A, pulse duration of 42 µs, and concentration of graphite powder of 4 g/l. A similar concentration of powder obtained by the authors Raju and Babasaheb [25].

3.2 Material removal rate

The quadratic model between the input parameters and the time chip volume is proposed and developed based on the RSM. Table 7 shows that the p-value of the model is 0.01 and $F$ value is 113.92, which means that the model is strongly significant at 99% confidence level for its adequacy. The $p$ values for A, B, C, AB, AC, and $A^2$ are 0.1 which expresses that these terms are significant.

Table 8 shows basic statistics of the assumed model for MRR. The values of $R^2$ and Adj. $R^2$ are 0.9856 and 0.9769, respectively, which are close to 1. Moreover, the Adeq. Precision of 30.829 is greater than 4, which implies an adequate signal. Therefore, the developed model can navigate the material removal rate.

The mathematical model is quite well fitted based on the previous analysis with the observed values. After eliminating the non-significant terms by backward elimination, the final mathematical Eq. 4 for the response in actual factors for MRR is as follows:

$$MRR = +3.24496 - 3.65821 \cdot I_e - 0.00805 \cdot t_i - 0.033969 \cdot GR + 0.00807 \cdot I_e \cdot t_i + 1.41324 \cdot I_e^2$$

A normal plot of the residuals for the material removal volume is shown in Fig. 13. It can be seen that the residuals are negligible in predicting each response, i.e., the actual values have a strong agreement with the predicted values.

The effect of discharge current and pulse duration on MRR is shown in Fig. 14. As can be seen from this figure, the MRR tends to increase significantly with increasing discharge current for each value of pulse duration. Therefore, the maximum MRR is obtained at a high discharge current of 2 A, a pulse duration of 100 µs, and a concentration of graphite powder of 4 g/l. This is because these parameters dominantly control the input energy. From the aspect of the available literature [30], MRR increases with increasing

| Source        | Sum of squares | df  | Mean square | $F$ value | $p$ value | Contribution% |
|---------------|---------------|-----|-------------|-----------|-----------|---------------|
| Model         | 4.47          | 6   | 0.74        | 113.92    | <0.0001   | 77.92         |
| A-Ie          | 3.53          | 1   | 3.53        | 540.88    | <0.0001   | 77.92         |
| B-ti          | 0.11          | 1   | 0.11        | 17.36     | 0.0019    | 2.43          |
| C-GR          | 0.084         | 1   | 0.084       | 12.90     | 0.0049    | 1.86          |
| AB            | 0.060         | 1   | 0.060       | 9.13      | 0.0129    | 1.32          |
| AC            | 0.025         | 1   | 0.025       | 3.87      | 0.0775    | 0.55          |
| $A^2$         | 0.53          | 1   | 0.53        | 80.92     | <0.0001   | 11.70         |
| Residual      | 0.065         | 10  | 6.533E-003  |           |           |               |
| Lack of fit   | 0.058         | 6   | 9.706E-003  | 5.47      | 0.0610    |               |
| Pure error    | 7.100E-003    | 4   | 1.775E-003  |           |           |               |
| Cor total     | 4.53          | 16  |             |           |           |               |

Fig. 12 Variations of surface roughness with different input parameters
discharge current and pulse duration to a certain limit. Just as there is a limit to the processing of metallic advanced materials, there is a limit to the processing of non-conductive materials. Because with too much energy invested, the workpiece can crack. This input energy generates heat which leads to high temperature, resulting in local melting, vaporization, and dissociation (spalling) of the workpiece material.

### 3.3 Tool wear rate

The fit summary statistics suggested that the quadratic model is significant for the analysis of \( TWR \). The results of the quadratic model for \( TWR \), in the form of ANOVA, after elimination of non-significant terms are given in Table 9.

It is clear that the \( F \) value of the model is 113.92, which indicate that the model is significant with a probability of 0.01%. The \( p \) values of A, B, C, AB, AC, and \( A^2 \) are smaller than 0.1, which expresses that those terms are significant for model.

Basic statistical data of the adopted model for \( TWR \) are shown in Table 10. The value of \( R^2 \) and \( \text{Adjusted } R^2 \) is over 96%, and the \( \text{Pred } R^2 \) of 0.7909 demonstrates agreement with coefficients of determination. Also, \( \text{Adeq. Precision} \) of 25.594 suggests an adequate signal. This means that the mathematical model gives a very good explanation of the relationship between the input factors and the tool wear rate.

As with previous models, the residual plot for \( TWR \) is shown in Fig. 15. It is visible the residuals are normally distributed. That means the errors are normally distributed, i.e., the actual and predicted values have a good agreement. The final response equation for \( TWR \) is given in Eq. 5.

\[
TWR = 168.63046 - 92.91856 \cdot Ie - 0.34423 \cdot ti - 3.9714 \cdot GR - 0.15575 \cdot Ie \cdot ti + 1.21450 \cdot Ie \cdot GR + 23.30050 \cdot Ie^2 + 0.00536 \cdot ti^2 + 0.18984 \cdot GR^2
\]

(5)

To analyze the effect of (AE + PM) EDM parameters on \( TWR \), response surface graph has been plotted as shown in Fig. 16. In machining parameters, such as discharge current

| Table 9 | Reduced ANOVA for \( TWR \) quadratic model |
|---------|---------------------------------------------|
| Source  | Sum of Squares | \( df \) | Mean square | \( F \) value | \( p \) value | Contirbution% |
| Model   | 2331.17        | 8     | 291.40      | 63.50         | <0.0001       | 71.43        |
| A-Ie    | 1691.39        | 1     | 1691.39     | 368.58        | <0.0001       | 9.63         |
| B-ti    | 227.90         | 1     | 227.90      | 49.66         | 0.0001        | 2.15         |
| C-GR    | 50.97          | 1     | 50.97       | 11.11         | 0.0103        | 0.87         |
| AB      | 20.60          | 1     | 20.60       | 4.49          | 0.0670        | 0.87         |
| AC      | 23.60          | 1     | 23.60       | 5.14          | 0.0531        | 0.99         |
| A*2     | 142.87         | 1     | 142.87      | 31.13         | 0.0005        | 6.04         |
| B*2     | 81.69          | 1     | 81.69       | 17.80         | 0.0029        | 3.46         |
| C*2     | 38.84          | 1     | 38.84       | 8.46          | 0.0196        | 1.65         |
| Residual| 36.71          | 8     | 4.59        |              |              |              |
| Lack of fit | 31.14    | 4     | 7.78        | 5.59          | 0.0621        |              |
| Pure error | 5.57        | 4     | 1.39        |              |              |              |
| Cor total| 2367.88       | 16    |              |              |              |              |
2 A, pulse duration 42 μs, and graphite powder concentration 4 g/l, minimal tool wear rate was obtained.

It is noticeable that an increase in the discharge current leads to a decrease in the tool wear rate. A similar conclusion is reached by the author Akıncıoglu [30], where he states that the reduction in consumption was positively influenced by the increase in discharge current. This is due to the fact that at lower discharge currents, more time is spent in removing material from the assisting electrode and forming the carbon layer, where the tool is consumed the most. The limited experimental time of 60 min also contributes to this, although in some cases the time for layer formation was about 15–30 min, Fig. 9. This figure shows a typical erosion curve for electronically nonconductive AEEDM materials with an assisting electrode. The curve is divided into two regions, the transition region and the stable region. A similar conclusion was obtained from a study by [6]. In this study, the tool wear rate was monitored by three phases: (a) removal of the auxiliary electrode material, (b) formation of the transition layer, and (c) removal of the base material. The highest relative tool wear was recorded in the first and second phases, while a significant reduction occurred in the third phase. An increase in pulse duration also contributes to the increase in relative tool wear.

### 3.4 Models verification

Table 4 shows a comparative view of experimental and model values (EV and MV) for machining performance in (AE+PM) EDM of zirconia. Quantitative predictability was estimated in terms of the percentage deviation between the obtained and expected values (Eq. 6) for \( R_a \), \( MRR \), and \( TWR \), in other words by the relative error \( RE \):

\[
RE = \left| \frac{EV - MV}{EV} \right| \times 100\%
\]

Verification of the accuracy of the obtained models was performed using three additional experiments that did not participate in the model generation. Table 11 shows the additional experiments of (AE+PM) EDM zirconium and the results of the confirmation test. Based on the confirmation experiments, the average error of the obtained models is in

| No | Input parameters | Machining performance |
|----|-----------------|-----------------------|
|    | \( I_e \) (A)   | \( t_i \) (μs) | \( GR \) (g/l) | \( R_a \) (μm) | \( MRR \) (mm³/min) | \( TWR \) (%) |
|    |                 | Exp     | RSM     | Exp     | RSM     | Exp     | RSM     |
| 1  | 1.5             | 10.201  | 11.297  | 1.307   | 1.216   | 70.547  | 68.521  |
| 2  | 1.5             | 8.11    | 8.191   | 1.33    | 1.196   | 65.33   | 61.312  |
| 3  | 2               | 14.47   | 14.398  | 1.99    | 2.175   | 56.11   | 56.996  |
| Average error | / | 4.08 | / | 8.74 | / | 3.53 |
the range of 4.08 ÷ 8.74%. According to previous research [33], a model is considered predictive when the average error is about 10%. In this context, all the output power prediction models obtained using RSM can be considered as predictive since their percentage error is within the acceptable limits. In order to increase the reliability of the obtained models, a larger amount of data is needed to be used to build the model.

3.5 Effect of powder concentration

The space between the tool and the workpiece, i.e., the working gap, is filled with electrically conductive powder particles. Under the influence of voltage, a strong electromagnetic field is formed at the smallest local distance between the tool surface and the workpiece, i.e., at the point of least resistance to the passage of electric current. In the electric field, there is an intense accumulation of powder particles that create a bridging effect and form a kind of electrically conductive bridge, the so-called “zigzag” shape. The enhanced bridge effect reduces the discharge voltage and the insulation properties of the dielectric. At the same time, the powder particles change the properties of the discharge channel, which equalizes the distribution of sparks on the powder particles, thus reducing the current density. This uniform distribution of the discharge results in uniform material removal, i.e., flat craters on the workpiece, which leads to a reduction in surface roughness, a reduction in tool wear, and thus an increase in machining accuracy. It is also found that with the increase of discharge current, the material removal rate of machining increases, but the stability of machining process decreases, because the discharge current with higher intensity creates larger craters on the workpiece and directly affects the stability of electrically conductive layer. The insulating properties of the dielectric are reduced, which leads to an increase in the working gap, resulting in more efficient flushing of the working space between the tool and the workpiece. This is particularly pronounced at the maximum pulse duration. For it is known that for each material pairing (tool, workpiece), there is a maximum pulse duration which must not be exceeded. Otherwise, the material would be destroyed, because it is known that surface roughness and removal rate deteriorate with longer pulse duration. The presence of a concentration of graphite powder contributes to the formation of a carbon layer, which makes the (AE + PM) EDM process more stable.

The improved machining performance achieved when the graphite powder is suspended on the dielectric is related to the reduction in surface roughness, material removal rate, and tool wear rate. The effect of graphite powder concentration on machining performance is shown in Fig. 17. The best effect of graphite powder addition was found at a discharge current of 1.5 A and a pulse duration of 100 µs. Here, the surface roughness was reduced by about 18% with an additional graphite powder concentration of 8 g/l, while the MRR increased by 12% and the TWR decreased by 6%. This regime was not declared optimal, but it reflects the greatest influence of the addition of graphite powder. A comparative review of the various literature may lead to the conclusion that the use of graphite powder is justified. For example, the best results were obtained by Tani et al. at a graphite powder concentration of 6.8 g/l [23]. Then Sabur et al. found that the best concentration is 6.28 g/l when optimized from the point of view of minimum surface roughness [18], while authors Raju and Babasaheb used 4 g/l in wire EDM [25]. The concentration of graphite powder depends mainly on the machining regime (available in the machine) and particularly on the strength of discharge current, pulse duration and discharge voltage.

3.6 Analysis state of machined surface

In order to investigate the resulting surface integrity of the machined material, various microscope images of the surface and the state of the surface near the heat-affected zone were taken after making cross-sections of the specimens. As an example, Fig. 18 shows the optical images of zirconia after processing by (AE + PM) EDM. This process is characterized by the foamy and porous structure. Pits, craters, and cracks are mainly seen on the eroded surface. After machining, the surface is covered with a carbon layer, the continuous generation of which is essential for the machining of electrically nonconductive ceramics. The stable and continuous generation of a conductive layer is crucial for EDM.

The machined surface of ZrO₂ is examined with an optical microscope. The results are shown in Fig. 19a for the surface roughness with and without graphite powder. Figures 19a...
and b show the surface roughness for weaker machining parameters. Here it can be seen that better quality is achieved by adding graphite powder. On the other hand, Figs. 19c and d show the surfaces for stronger machining parameters. Here the difference in machining quality is more obvious than for weaker machining parameters. After eroding in hydrocarbon oil, the eroded surfaces contain a significant amount of carbon. The carbon particles are mainly deposited by hydrocarbon oil, tool materials, and graphite powder [24, 25]. As can be seen, the carbon layers are characterized by the formation of regular craters and the presence of drops of molten material. The size of the craters decreases at lower process conditions, resulting in better surface roughness. At high discharge energy, large craters are formed, and the surface is more uneven and porous. In addition, the craters are reduced by the addition of graphite powder to the dielectric.

An optical micrograph of a polished cross-section through a machined surface is shown in Figs. 20, 21, and 22. Figure 20 shows the areas formed by the electroerosive machining of ceramic materials. The top layer is the plasma discharge passage, the middle layer is a carbon layer, and the bottom layer is a heated zone. The thermal energy generated during the erosion process contributes to the oxidation/decomposition of the ceramic, which ultimately leads to these effects. The thermal damage is pronounced in the lower region. The cracks generated in this area are the result of the high discharge energy, which leads to a large temperature gradient and higher tensile stresses.

Using the assisting electrode electroerosion without and with graphite powder, minimum and maximum coating thicknesses of 3.02 µm and 13.84 µm, respectively, can be achieved. According to literature [34], the thickness of conductive carbon layer varies from 30 to 50 µm. The reason for this is that a higher discharge energy level was used. Machining ceramic materials under high discharge energies is risky as it can damage the workpiece. Figure 21 clearly shows the inequality of carbon film thickness. The reason for this is the low discharge energy. This is because the
The discharge energy depends on the discharge current and pulse duration. Reduction of these two parameters also reduces the thermal energy which may be responsible for the formation of the carbon layer. Therefore, it is impossible to electronically conduct material with low energy.

On the other hand, Fig. 22 shows a thicker and more uniform carbon layer. One of the reasons for this is processing under higher energy and higher concentration of graphite powder. Higher energy input to cut the workpiece leads to higher amount of heat on the surface. These findings have also been confirmed in other scientific works [33, 35]. The heat is absorbed more deeply. As a result, the heat-affected zone also forms deeper, making the carbon layer thicker. The additional stabilization of the carbon layer is also affected by the addition of graphite powder. This is because the formation of the carbon layer is influenced not only by the carbon from the dielectric, but also by the carbon from the graphite powder. A stable ablation is found empirically for a parameter set with high discharge energy.

4 Conclusions

The paper presents the results of an experimental investigation carried out with the aim of modelling the electrical discharge machining of nonconductive ceramic material. By applying a graphite coating and placing an adhesive copper strip on the top of the workpiece, a hybrid assisting electrode was obtained, which is responsible for the successful electrical discharge machining of zirconia. The addition of graphite powder to the dielectric when machining zirconia in the presence of an assisting electrode results in an 18% reduction in surface roughness, a 12% increase in metal removal rate, and a 6% reduction in relative tool wear. These performance increases are achieved at a discharge current of 1.5 A, a pulse length of 100 µs, and a graphite powder concentration of 8 g/l. The structural shapes of the mathematical models for the output power $R_a, MRR$, and $TWR$ are obtained using the response surface methodology according to the plan Box-Behnken. On the basis of the experiments that were not involved in obtaining the model, the verification of the model was carried out, i.e., the evaluation of the ability to predict the output power with new experimental data. The model error obtained by the verification experiments for (AE + PM) EDM zirconium 4.08% for $R_a$, 8.74% for $MRR$, and 3.53% for $TWR$. In conclusion, the research results presented in this paper provide a better understanding of (AE + PM) EDM, which will contribute to its greater competitiveness in the industry. Considering that (AE + PM)
EDM are relatively new machining processes that have not been fully explored, there is certainly an opportunity for their further continuous improvement and refinement.

List of acronyms

EDM: Electrical discharge machining; AE: Assisting electrode; AEEDM: Assisting electrode electrical discharge machining; (AE + PM) EDM: Assisting electrode powder mixed electrical discharge machining; HAE: Hybrid assisting electrode; MRR: Material removal rate; TWR: Tool wear rate

Notations

$R_p$: Surface roughness; $I_p$: Discharge current; $t_p$: Pulse duration; $U_a$: Voltage; $GR$: Concentration of graphite powder

Author contribution

D. Rodic and M. Gostimirovic conceived of the presented idea. D.R. developed the theory and performed the computations. D. Rodic and M. Gostimirovic verified the mathematical methods. M. Sekulic and B. Savkovic conceived and planned the experiments. B. Srbrac assisted with all necessary measurements. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

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Data availability

The data underlying this article are available in the article.

Declarations

Ethics approval

This paper does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate

Publication is approved by all co-authors, as well as by the responsible authorities at the Department of Production Engineering.

Consent for publication

Our manuscript has not been previously published and is not under consideration for publication elsewhere. Paper represents original work.

Competing interests

The authors declare that they have no conflict of interest.

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