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Evaluating Surface Roughness of Ductile Cast Iron Machined by EDM Using Solid and Hollow Cylindrical Copper Electrodes

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Abstract

This study reports a comparative analysis to evaluate the performance of solid cylindrical and hollow cylindrical copper electrodes in terms of average surface roughness 'R_a' for machining ductile cast iron (DCI) using the electrical discharge machining (EDM) process. Experiments were conducted by varying the peak current, spark-on duration, spark-off duration, and flushing pressure according to Taguchi's L_9 (4^3) orthogonal array experimental design matrix. Nine experiments were conducted using each tool electrode. Thus, a total of eighteen experiments were performed in this study. It was found that surface roughness increased with an increase in peak current and spark-on duration and decreased with an increase in spark-off duration and flushing pressure. Peak current and spark-on duration have a significant influence on surface roughness. Analysis of variance (ANOVA) was employed to identify substantial EDM variables and to develop a model for predicting the average surface roughness. The interaction graphs show the relationships between the considered EDM variables. Microstructural analysis of the best-finished machined surfaces was conducted using a scanning electron microscope (SEM). The SEM micrographs reveal that irregular, deeper, and non-uniform craters are formed on the DCI surface machined with the hollow cylindrical copper electrode. This comparative study concluded that the solid cylindrical copper electrode produced lower surface roughness than the hollow cylindrical copper electrode. Thus, a better surface finish of DCI can be achieved by EDM using the solid cylindrical copper electrode.

Keywords

ductile cast iron, EDM, Taguchi, surface roughness, SEM, validation

1 Introduction

In today's world, having materials with a broad range of mechanical properties is of considerable significance. This diversity in mechanical characteristics – such as strength, toughness, and durability – enables engineers and designers to select materials that meet specific performance criteria for various applications. As industries continually seek to optimize their operations, there is an increasing demand to reduce machining time and energy consumption. This has driven advancements in material science, leading to the development of materials that are not only lightweight but also offer high durability, exceptional fatigue resistance, and superior wear resistance. Additionally, these advanced materials are designed to be cost-effective, balancing performance with economic efficiency [1].

Ductile cast iron (DCI) is an exemplary material that embodies these properties and effectively fulfills industrial requirements. Its name originates from its notable characteristic – ductility – highlighting its ability to withstand significant deformation before fracture [2, 3]. Ductile iron is an iron-carbon alloy with a high carbon content where the graphite is organized into spherical shapes. This unique structure provides ductile iron with improved mechanical properties, making it a valuable material for various industrial applications [4–6]. DCI offers a range of mechanical properties that make it highly versatile for various applications. These properties include (i) good thermal conductivity; (ii) excellent fluidity and castability; (iii) excellent machinability; and (iv) good wear resistance. In addition to these properties, DCI has some characteristics similar to steel. These characteristics are high strength; excellent toughness; good ductility; hot workability (i.e. ability to withstand elevated temperature), and hardenability [7].

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Ductile iron exhibits corrosion resistance that is equal to or even better than grey cast iron and, in many cases, cast steel when exposed to various corrosive environments. Additionally, its wear resistance is comparable to some of the highest-grade steels, and it outperforms grey iron in applications involving heavy or impact loads [8–10].

Machining ductile cast iron, while generally manageable, presents some challenges compared to other materials like gray cast iron or steel. The unique properties of ductile cast iron, such as its higher tensile strength and toughness, impact the machining process [11]. The main challenges faced during machining DCI by conventional machining process are excessive tool wear, higher cutting force, excessive heat generation during machining, variation in dimensional accuracy, difficulty in achieving desired surface quality, chip clogging, required proper coolant, requirement of robust clamping and fixtures for machining, higher machining cost, and required regular tool maintenance. Other common challenges in conventional machining are burr formation, sharp edges, tool wear, tool marks on machined surfaces, vibration, and noise, and required skilled operators. Therefore, advanced machining processes are recommended to overcome the challenges encountered during the conventional machining of DCI. These modern machining processes can effectively mitigate the issues associated with conventional machining processes. Electrical discharge machining (EDM) is an advanced machining process also referred to as spark erosion machining 'SEM' which utilizes thermal energy for machining. EDM is a controlled metal-removal process that is used to remove excessive material from the workpiece by electric spark erosion [12]. In this process, a discrete spark generates excessive heat and melts and evaporates the material from the workpiece. A fabricated electrode is used as a tool and machining takes place in the presence of continuously moving hydrocarbon-based dielectric fluid. The workpiece is submerged in dielectric fluid and the tool electrode is moved downward to perform machining. A contestant gap is maintained between the tool electrode and the workpiece to avoid short- circuiting. EDM can machine any kind of electrically conductive materials regardless of their hardness [13]. Some advantages offered by EDM are (i) the ability to machine all kinds of electrically conductive materials, (ii) no contact between tool and workpiece, (iii) no burr formation, as well as machined surface, is free from mechanical stresses, (v) long-duration unattended operation; and (vi) no requirement of a skilled operator. Available past research works on machining cast iron are given below.

Venugopal et al. [14] made a hole in cast iron by EDM using a 2 mm diameter copper tool electrode and analyzed the effect of spark-on duration, spark-off duration, gap voltage, and current on material removal rate (MRR), and tool wear rate (TWR). They found that gap voltage and pulse on time have a significant impact on MRR and TWR, respectively. Results of analysis of variance (ANOVA) revealed that voltage has a notable influence on MRR. They recommended 45 µs spark- on duration, 3 µs spark-off duration, 25 V gap voltage, and 10 A current as the best machining combination for higher MRR and lower TWR according to the TOPSIS optimization technique. Wang et al. [15] investigated EDM for machining austempered ductile iron (ADI) using a copper electrode of varying profile to evaluate machinability in terms of the material removal rate, electrode wear rate and surface finish. They found that a higher removal rate and lower surface finish can be achieved by pitch electrodes compared to electrodes without pitch for machining ADI by EDM. Chiang et al. [16] studied a rapidly resolidified layer of spheroidal graphite cast iron machined by the EDM process. They observed that the quantity and area fraction of graphite particles are the primary factors influencing layer thickness and ridge density. Tsai et al. [17] studied the influence of a heterogeneous second phase on MRR for machining spheroidal graphite cast iron and Al-Si alloy with varying compositions by EDM process. It was concluded that the amount and morphology of second-phase particles critically affect MMR in the EDM process, with these effects being closely tied to ridge density and discharge density. In another study, Ram and Varma [18] studied the influence of EDM parameters on surface roughness for machining different materials namely SG Iron, Gray cast iron, and Ni-Cr alloy cast iron. Past research works on machining cast iron by EDM revealed that solid tool electrode was used for machining. This paper presents a comparative evaluation between solid and hollow cylindrical tool electrodes in terms of surface roughness for machining cast iron by EDM. The major objectives of this study are given below:

- Comparative evaluation between solid and hollow cylindrical tool electrodes for machining ductile cast iron 'DCI' by EDM in terms of surface roughness.
- To identify the influence of selected variable EDM parameters on surface roughness.
- Microstructural analysis of machined surface using scanning electron microscope (SEM).
- Validation of best machining result through confirmation test.

2 Materials and methods

In this study, CNC-EDM (Model: Sparkonix 35 A; Manufacturer: Sparkonix (India) Pvt. Ltd; Country: India) was used to machine rectangular ductile cast iron (DCI) specimen having dimensions of 100 × 20 × 20 (in mm). Fig. 1 shows the CNC EDM machine used for machining DCI. A total of nine specimens were prepared using a surface grinder to achieve a perfectly flat surface having uniform thickness throughout the surface of each face of the specimen. Fig. 2 shows the schematic view of the work specimen with detailed specifications. DCI is valued for its superior mechanical properties such as high strength and toughness, good wear resistance, improved impact resistance, good machinability and ductility, and cost-effectiveness, making it a popular choice in many industries. DCI is popularly used in automotive, heavy machinery, agricultural equipment, and structural applications. Solid and hollow cylindrical copper electrodes 60 mm long and 6 mm diameter were used for machining DCI by EDM. The detailed specifications of copper electrodes used in this study are shown in Fig. 2. Cooper tool electrode has excellent electrical conductivity, high thermal conductivity, good machinability, moderate wear resistance, and the ability to generate better surface finish at optimum EDM parameters. Thus, two different types of copper electrodes were used in this study to evaluate their performance in terms of surface roughness. Fig. 3(a) displays two-dimensional (2D) and three-dimensional (3D) views of the DCI work specimen with detailed specifications, while Fig. 3(b) shows the 3D schematic view with EDM machined holes at both ends of the DCI work specimen. Table 1 shows the details of the machine, materials, input parameters, their level and experimental design.

Fig. 1 Electrical discharge machine used for machining ductile cast iron in this study

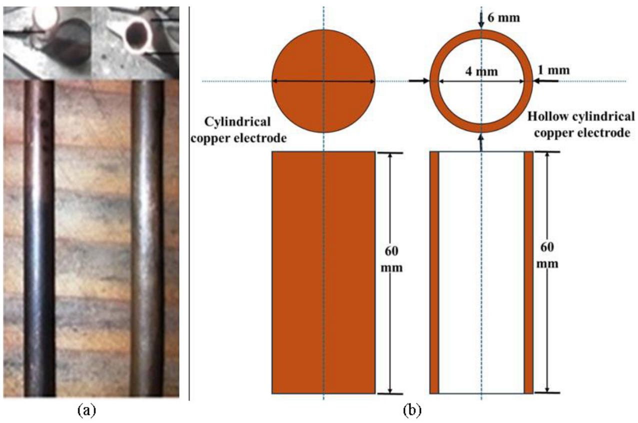


Fig. 2 Cylindrical copper electrode used for machining DCI by EDM: (a) Pictorial 3-D view of both electrodes; and (b) schematic two-dimensional view of copper electrodes with detailed specifications

2.1 Experimentation and machining procedure

In this study, peak current, spark-on duration, spark-off duration, and flushing pressure were selected as EDM variable parameters. These parameters and their levels were selected on the basis of machine constraints, trial experiments, and available previous work. Other electrical parameters (i.e. gap voltage, discharge voltage, servo feed, and polarity) and non-electrical parameters (i.e. tool electrode material; electrode shape; and workpiece material) were kept constant during experimentation. "One-factor-at-a-time" (OFAT) approach was used for trial experimentation. In trial experiments, only one variable was changed at the time while keeping all other variables constant during the experiment. A total of twelve trial experiments were conducted to select the variable and constant parameters, along with their respective ranges, ensuring reliable results for the next stage of experimentation. In the next stage, Taguchi's L_9 (4^3) orthogonal array was used to design nine different machining combinations for experimentation. Thus, nine experiments were conducted by varying

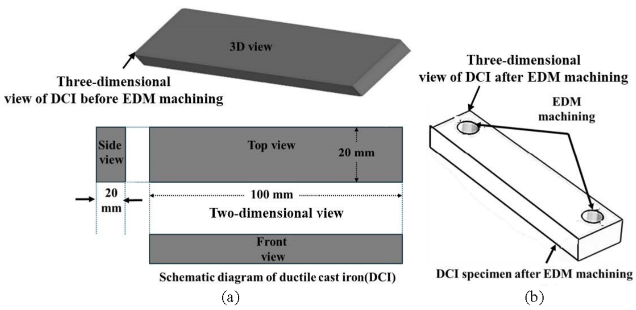


Fig. 3 Schematic 2D and 3D views of work specimen with detailed specifications: (a) 2D views; and (b) 3D view showing holes at both ends after EDM machining

Table 1 Details of experimentations along with machining combination of experimental runs

EDM variable parameter				Taguchi Experimental runs				
Name, symbol' and (unit)	Actual (coded) Levels			Ex. Runs	T_{on} (µs)	T_{off} (µs)	C_p (A)	D_f (V)
	Low (−1)	Medium (0)	High (1)					
Spark-on duration 'T_{on}' (µs)	6 (−1)	8 (0)	10 (1)	01	6	5	5	10
Spark-off duration 'T_{off}' (µs)	5 (−1)	7 (0)	9 (1)	02	6	7	10	15
Peak current 'C_p' (A)	5 (−1)	10 (0)	15 (1)	03	6	9	15	20
Flushing pressure 'D_f' (kg/cm^2)	10 (−1)	15 (0)	20 (1)	04	8	5	10	20
Performance outcome indicators	Surface roughness 'SR' (i.e. average roughness 'R_a')			05	8	7	8	7
				06	8	9	8	9
				07	10	5	10	5
	In-situ responses: Machining time			08	10	7	10	7
				09	10	9	10	9
Constant parameters	Dielectric, Tool and work materials, Gap voltage, and Polarity							
Electrode Specifications	Material: Copper, Shape; Cylindrical (Hollow and Solid); Outer diameter: 6 mm; Inner diameter: 4 mm; and Length: 60 mm							
Workpiece Specifications	Material: Ductile cast iron; Shape: Rectangular; Dimensions: 100 long, 20 mm wide and 20 mm thick							
EDM Machine Specifications	Model: Sparkonix 35 A, Manufacturer: Sparkonix (India) Pvt. Ltd; Power supply: 415 V; 3 ϕ, 50 Hz; Power: 4KVA; Display: Digital hand pendant; Best surface finish: 0.8 µm (R_a), Worktable: 550 × 350 mm, X, Y and Z travel: 300, 200, and 200 (in mm); Maximum electrode weight: 50 Kg; X and Y axis: LM guideway							

peak current, spark-on duration, spark-off duration, and flushing pressure according to machining combinations designed by Taguchi's L_9 (4^3) orthogonal array to identify their influences on surface roughness. Each experimental run was conducted by using both solid and hollow cylindrical electrodes to compare the performance in terms of surface roughness. Thus, a total of 18 experiments were conducted for comparative evaluation in this study. Before each experiment, the specimen was placed on the worktable and held firmly with the help of clamps. Similarly, the tool electrode also holds firmly in the tool holder with the help of a screw as shown in Fig. 4. The photographs shown in Figs. 4(a) and 4(b) were captured by a digital

(a) (b)

Fig. 4 Pictorial view of experimental procedure for setting tool electrode and work specimen, (a) application of dial gauge to ensure perfect positioning of tool and specimen, and (b) during machining of specimen

camera during the experimentation. Tool electrodes can move in upward and downward directions only. While the worktable moves in X and Y directions. After holding the tool electrode and specimen, the next step is ensuring their perfect positioning with the help of a dial gauge because minor variations in their perfect positioning significantly affect the dimensional accuracy as well as the quality of the machined surface. Figs. 5(a) and 5(b) show photographs of the actual specimens captured by a digital camera, before and after machining, respectively. Machining was performed on both ends of the specimen by hollow and solid cylindrical electrodes as shown in Fig. 5(b).

Surface roughness refers to the small, closely spaced irregularities on a material's surface, typically resulting from machining processes. It directly affects the functional performance and durability of machined parts. Average surface roughness (R_a) is a key parameter used to quantify surface texture, representing the average height deviation of the surface profile from a mean line, measured over a specified length. R_a is a critical measure for indicating the surface finish of a material after machining. Lower values of average roughness indicate smoother surfaces and a better surface finish, while higher values correspond to rougher surfaces. Increased roughness in machined parts can lead to excessive noise, vibration, and friction, contributing to premature wear and failure. Surface roughness is

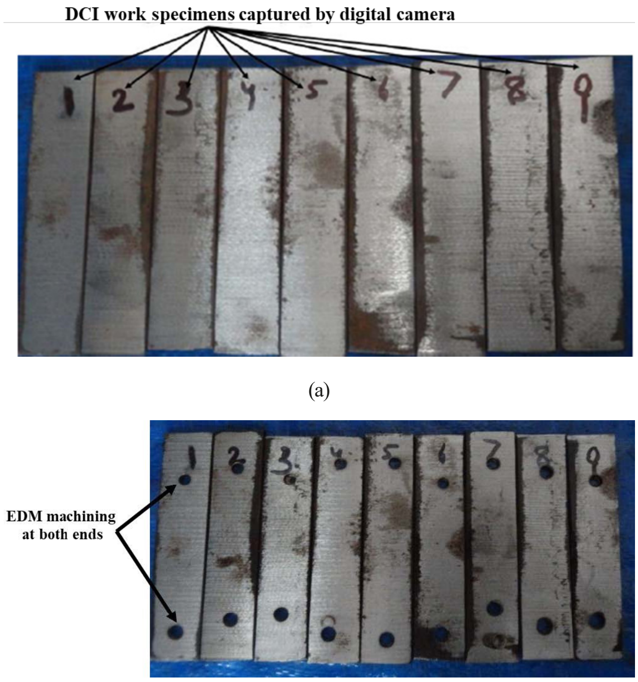


Fig. 5 Photographs of the actual work specimens used in this study, captured by a digital camera: (a) before machining; and (b) after machining

typically expressed in micrometers (μm) or microns (μ). In this study, a portable roughness tester, Mitutoyo Surftest SJ-301, manufactured by Mitutoyo, Japan, was used to measure the average surface roughness 'R_a' of each DCI specimen machined by EDM using hollow and solid cylindrical tool electrodes. This device uses a diamond-tipped probe to trace the diagonal of the EDMed surfaces, with an evaluation length of 3 mm, a cut-off length of 0.8 mm, and a Gaussian filter to distinguish between waviness and roughness. Average surface roughness was measured from five different points of the machined surface, and their average values were calculated for comparative evaluation. The microstructure of specimens having the better surface quality obtained from both electrodes were examined by scanning electron microscope 'SEM' (Model: JSM-6510LV; Manufacturer: JEOL; and Country: Japan).

3 Results and discussions

This section presents the results obtained from experimental runs by machining ductile cast iron (DCI) specimens by EDM using solid cylindrical copper electrodes and hollow cylindrical copper electrodes. Nine experimental runs, representing combinations of EDM variables with their actual values and coded levels, are summarized in Table 1. Analysis of variance (ANOVA), SEM analysis of the DCI specimens having the lowest roughness among nine experimental runs, and influence of EDM variables on average surface roughness are also discussed in this section. Fig. 6 illustrates the variation in average surface roughness across the experimental runs and shows the corresponding values for each run. The red and blue lines represent the trends of average surface roughness for DCI specimens machined by EDM using solid and hollow cylindrical electrodes, respectively. Experiment 5 yielded the highest R_a value (4.97 μm for solid electrode and 5.09 μm for hollow electrode), while the lowest R_a value (2.16 μm for solid electrode and 2.23 μm for hollow electrode) was observed in experiment 1. ANOVA test is a key statistical tool for assessing data fit, model adequacy, and identifying influential parameters [19]. ANOVA test was conducted using a 95% confidence interval for p-values ($p < 0.05$), as discussed in this section. The key findings from the ANOVA analysis are as follows:

- The developed linear models of average surface roughness 'R_a' for both solid and hollow electrodes are significant as their p-values are less than 0.05.
- P-values less than 0.05 indicate that the respective model terms are significant. Therefore, for both electrodes, peak current 'C_p' was found to be statistically significant for R_a.
- The R-squared values for solid and hollow electrodes are 94.24% and 96.11%, respectively, close to 1, confirming the adequacy of the developed models for predicting surface roughness.
- The predicted R-squared values of the roughness models closely align with the adjusted R-squared, indicating a strong correlation between experimental and predicted values.

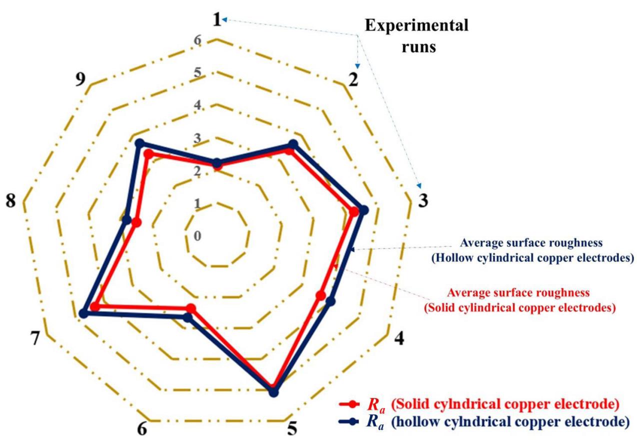


Fig. 6 Variation of the average surface roughness across experimental runs

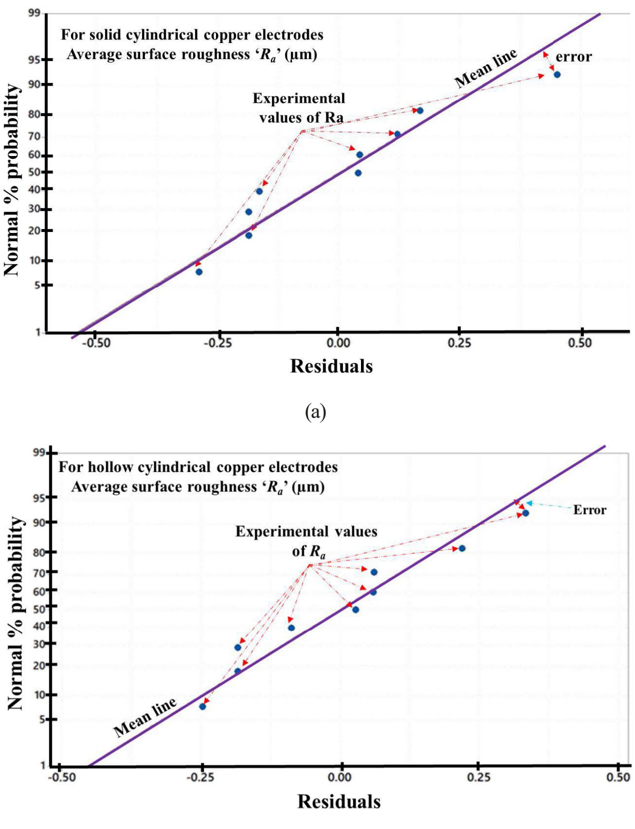
- Fig. 7 shows that the residuals from each experiment are distributed around the mean line and tightly clustered, indicating a normal distribution.
- The developed empirical equations 1 (for solid cylindrical electrode) and 2 (for hollow cylindrical electrode) are linear (i.e., without square terms or interaction terms). They can be used to predict the values of Ra in the future.

$$R_a(Solid) = 1.232 + 0.2163\ C_p + 0.0242\ T_{on} - 0.02\ T_{off} - 0.0013\ D_f \tag{1}$$

$$R_a(Hollow) = 0.820 + 0.222\ C_p + 0.0667\ T_{on} - 0.0058\ T_{off} + 0.0113\ D_f \tag{2}$$

3.1 Influence of selected variable EDM parameters on surface roughness

The influence of EDM variable parameters – namely spark-on duration 'T_{on}', spark-off duration 'T_{off}', peak current 'C_p', and flushing pressure 'D_f' – on average surface roughness 'R_a' is discussed through graphical representations, as shown in Figs. 8 and 9. In these figures, the abscissa represents the values of EDM variable parameters, while the ordinate shows the corresponding values of average surface roughness. Figs. 8 and 9 depict the influence of peak current, spark-on duration, spark-off duration, and flushing pressure on average surface roughness during machining by EDM using solid cylindrical copper electrodes and hollow cylindrical copper electrodes, respectively. It can be observed by Figs. 5 and 6 that (i) average surface roughness increased linearly with increase in peak current; (ii) average surface roughness increases with spark-on duration from 6 to 8 µs then decrease from 8 to 10 µs; (iii) average surface roughness slightly increases with increase in spark-off duration from 5 to 7 µs then it increase from 7 to 9 µs; (iv) average surface roughness slightly decrease from flushing pressure



(a)

(b)

Fig. 7 Graphs showing the normal probability distribution of residuals for average surface roughness: (a) solid cylindrical copper electrode; (b) hollow cylindrical copper electrode

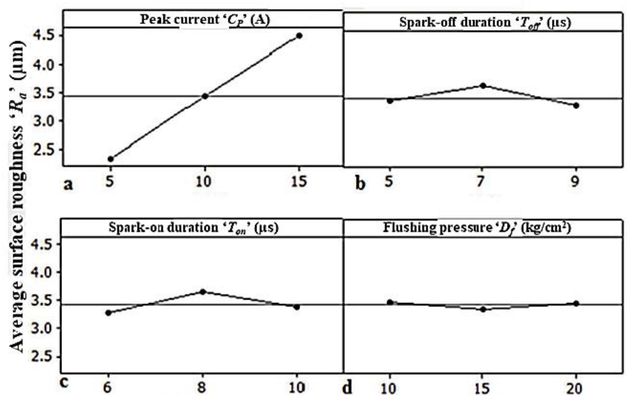


Fig. 8 Influence of variable EDM parameters on average surface roughness for machining DCI using solid cylindrical copper tool electrode

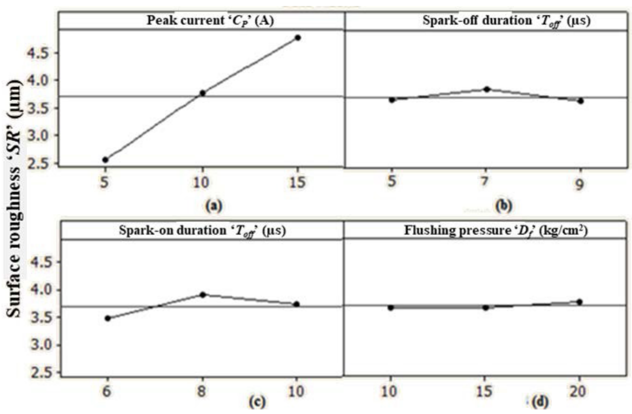


Fig. 9 Influence of variable EDM parameters on average surface roughness for machining DCI using hollow cylindrical copper tool electrode

10 to 15 kg/cm^2 in case of solid copper tool electrode then slightly increase from 15 to 20 kg/cm^2 and observed similar roughness value as obtained at 10 kg/cm^2. Whereas, in hollow copper cylindrical electrodes, no variation in roughness was observed from 10 to 15 kg/cm^2 of flushing pressure. Average surface roughness is negligible and increases with an increase in flushing pressure from 15 to 20 kg/cm^2. It can be concluded from Figs. 8 and 9 that hollow cylindrical copper tool electrodes produce higher surface roughness than solid cylindrical copper tool electrodes. The above conclusion can be explained by the fact that intense sparks with high thermal energy occur at higher peak currents resulting in the formation of non-uniform and deeper craters on machined surfaces. Sparks are generated for longer periods at a higher value of spark- on duration, resulting in the formation of non-uniform and deep craters due to excessive heat generation that erodes materials quickly and forms rough surfaces. A higher value of spark-off duration causes a longer time gap between two consecutive sparks, resulting in lower material removal as well as surface roughness. In this, lower flushing pressure is recommended to achieve better surface finish. The vibration of the tool as well as the workpiece takes place at higher flushing pressure that affects smooth machining operation and results in higher roughness of the machined surface.

Figs. 10 and 11 show the interaction graphs for solid and hollow cylindrical copper electrodes, respectively, illustrating the relationship between EDM variables and the mean of average surface roughness. The nonparallel and intersecting lines indicate that the relationship between one EDM variable (X-axis) and average surface roughness (Y-axis) is influenced by the value of another EDM variable (auxiliary Y-axis), suggesting an interaction between the variables.

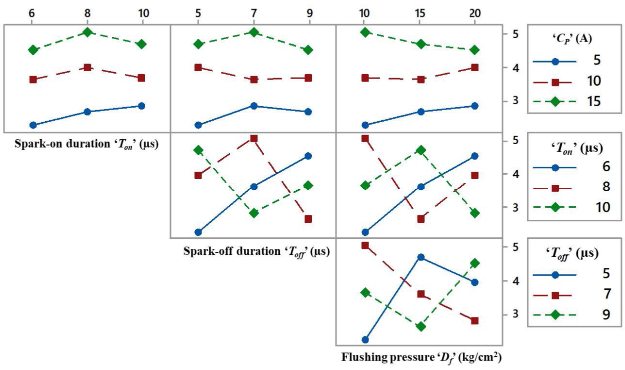


Fig. 10 Influence of variable EDM parameters on average surface roughness for machining DCI using solid cylindrical copper tool electrode

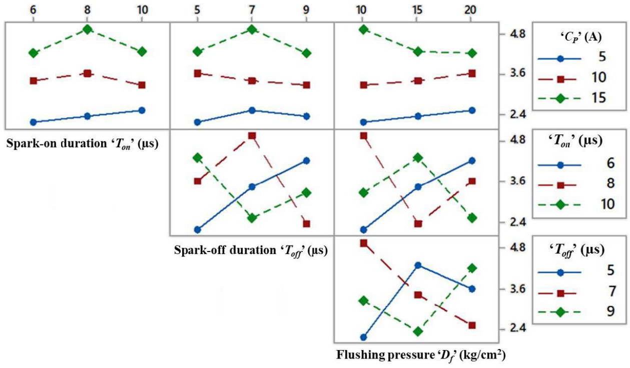


Fig. 11 Interaction among EDM variable parameters for machining DCI using hollow cylindrical copper tool electrode

3.2 Microstructural analysis

Microstructural examinations were conducted on the specimen with the best surface finish (i.e. lower average surface roughness), machined by EDM using both solid and hollow cylindrical copper electrodes. Thus, two specimens were examined for microstructural analysis using a scanning electron microscope (SEM). Figs. 12 and 13 display micrographs of specimens machined with solid cylindrical copper electrodes and hollow cylindrical copper electrodes, respectively. These micrographs reveal the formation of craters on the EDM-machined surfaces, which contribute to surface roughness. The presence of larger, deeper, and irregular craters indicates higher surface roughness. As seen in Figs. 12 and 13, the formation of deep and non-uniform craters is more prominent on the surface machined with the hollow cylindrical electrode compared to the solid cylindrical copper electrode. Additionally, microcracks and debris are visible on the surface machined

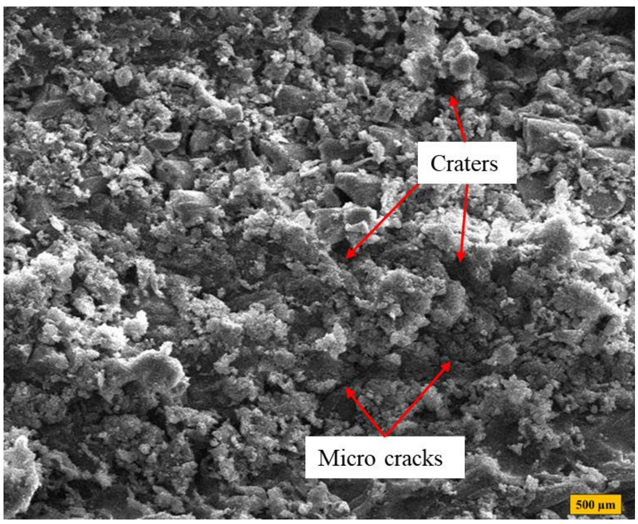


Fig. 12 Microstructure of eroded surface of DCI machined by EDM using solid cylindrical copper electrode

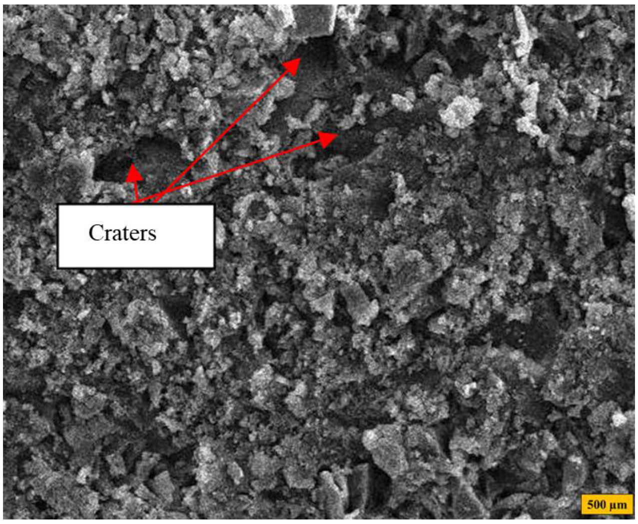


Fig. 13 Microstructure of eroded surface of DCI machined by EDM using hollow copper electrode

with the solid cylindrical copper electrode, as shown in Fig. 12. This can be attributed to the fact that while hollow cylindrical copper electrodes offer advantages such as better cooling and more focused energy, they can produce uneven discharges, resulting in deeper and larger craters, which lead to a rougher surface. In contrast, solid electrodes provide a more uniform and controlled discharge, aiding in achieving a smoother surface finish during EDM.

4 Conclusions

This study reports the comparative evaluation of machining ductile cast iron by EDM using solid cylindrical copper electrodes and hollow cylindrical copper electrodes in terms of surface roughness (average surface roughness 'R_a'). The following conclusions can be drawn from this study:

- Successfully performed comparative evaluation between solid cylindrical copper tool electrode and hollow cylindrical copper tool electrode in terms of surface roughness for machining DCI using EDM.
- Observed higher surface roughness of DCI specimen machined by EDM using hollow cylindrical copper tool electrode.
- Peak Current 'C_p' was found to be statistically significant for average surface roughness and average surface roughness increased linearly with increase in peak current.
- Average surface roughness increases with an increase in peak current and spark-on duration.
- Flushing pressure has a negligible impact on average surface roughness during machining DCI by EDM using both solid and hollow copper tool electrodes.
- Found interactions among selected variable EDM parameters.
- Microstructural analysis revealed the formation of more non-uniform, irregular, and deep craters on the DCI specimen machined by EDM using a hollow cylindrical copper electrode compared to the solid electrode.

Future research identified by this study is as follows:

- Sustainability and lifecycle analysis for machining DCI by EDM.
- Application of artificial intelligence and machining learning to optimize EDM process for machining DCI.
- Analysis of energy consumption, wire consumption, material removal rate, and tool wear for machining DCI by EDM.
- Experimentation on other difficult-to-machine materials by EDM using solid and hollow electrodes.

Author contributions

Conceptualization, experimentation, methodology, data curation, software, formal analysis, measurement, validation, R. M.; Conceptualization, methodology: H. S.; Formal analysis, supervision, writing original draft, review, and editing: S. C. All authors have read and agreed to the published version of the manuscript.

Data availability

Data will be available on request.

Funding

This research received no external funding.

Conflicts of interest

The authors declare no conflicts of interest.

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