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Comparative Evaluation of Flat and Convex Copper-Nanographene Electrodes in EDM: Effects on Performance Measures

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Keywords:
EDM; Electrode Profile; MRR; Recast layer; TWR; SR.

Highlights:
- *Improving the EDM performance through the effect of the electrode profile.*
- *Convex profile electrodes produce a better surface finish.*
- *Improvement of material removal rate and tool wear rate.*

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Abstract: Electrical Discharge machining (EDM) is a nontraditional technology, adopted for machining hard materials and geometrically complex parts that cannot be obtained via traditional manufacturing operations. Due to the tool wear rate (TWR), material removal rate (MRR), and surface roughness (SR) usually impacting EDM performance, it is important to conduct a novel study to reduce the (TWR), increase the (MRR), and improve surface quality. The present study aims to analyze the effect of different profiles of electrodes, such as flat and convex, and select the optimal electrode profile for making the holes for EDM performance enhancement. The electrodes were made of copper-nanographene material, 10 mm in diameter, for machining AISI 1005 carbon steel as the workpiece. The experiments were designed using Design-Expert 13 software. Three factors were selected: Peak current (I_p), pulse on time (T_{on}), and pulse off time (T_{off}). A comparative discussion is provided on the specificities of the machined surface achieved by utilizing the electrode tool. The study results revealed that the TWR of flat profile electrodes could be overcome by employing electrodes with convex profiles, which were observed to decrease by 17.37%. Also, electrodes with convex profiles produced an SR of better quality than flat profile electrodes, which decreased by 23.52%. The MRR for hole drilling was higher by 19.34% than that of the flat profile electrode.

التقييم المقارن لأقطاب النحاس النانوغرافين المسطحة والمحدبة في عملية التفريغ الكهربائي: التأثيرات على مقاييس الأداء

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الخلاصة
عملية التفريغ الكهربائي (EDM) هي تقنية غير تقليدية ، تم اعتمادها لتصنيع المواد الصلبة والأجزاء المعقدة هندسيا التي لا يمكن الحصول عليها من خلال عمليات التصنيع التقليدية. نظرا لمعدل تآكل الأداة (TWR) ومعدل إزالة المواد (MRR) خشونة السطح (SR) عادة ما تؤثر على أداء EDM ، وبالتالي من المهم إجراء دراسة جديدة تهدف إلى تقليل (TWR) وزيادة (MRR) وتحسين جودة السطح. تهدف الدراسة الحالية إلى تحليل تأثير الملامح المختلفة للأقطاب الكهربائية مثل المسطحة والمحدبة واختيار ملف تعريف القطب الأمثل لعمل الثقوب لتحسين أداء EDM. مادة الأقطاب الكهربائية المستخدمة من مادة النحاس النانوغرافيني بقطر ١٠ مم لتصنيع الفولاذ الكربوني AISI 1005 كقطعة عمل. تم تصميم التجارب باستخدام برنامج Design-Expert 13 ، وتم اختيار ثلاثة عوامل: التيار(I_p) ، والنبض في الوقت المحدد (T_{on})، ووقت إيقاف النبض (T_{off}). يتم توفير مناقشة مقارنة حول خصوصيات السطح الآلي الذي تم تحقيقه باستخدام أداة الأقطاب الكهربائية. لاحظت نتائج الدراسة أنه يمكن التغلب على TWR للأقطاب الكهربائية المسطحة عن طريق استخدام أقطاب كهربائية ذات ملامح محدبة لوحظ انخفاضها بنسبة ١٧,٣٧٪ ، كما أن الأقطاب الكهربائية ذات الملامح المحدبة تنتج SR بجودة أفضل من الأقطاب الكهربائية المسطحة التي انخفضت بنسبة ٢٣,٥٢٪، و MRR لحفر الثقب أعلى بنسبة ١٩,٣٤٪ مقارنة بالقطب الجانبي المسطح.

الكلمات الدالة: EDM، ملف تعريف القطب، MRR، طبقة إعادة الصياغة، SR، TWR.

1.INTRODUCTION

A literature survey is a comprehensive review of previous studies that presents a description, a brief, and an assessment of each of them. It also offers the area for the present study. This section will play a vital role in obtaining more information on the EDM process and will introduce the concept of the electrode geometry's effect on EDM performance. Thus, the objective of the experimental work is to enhance the performance of the EDM process depending on the shape of the profile electrode for drilling AISI 1005 Carbon Steel as the workpiece. The impact of different operating conditions, such as I_p (16, 20, and 24) A, T_{on} (150, 225, and 300) µs, and T_{off} (75, 100, and 125) µs, was investigated. Researchers are focused on improving the performance of the EDM process to make it more economical. Various studies determined the operating parameters and the appropriate range of response parameters for each product, determining the quality and efficiency of the product, and thus determining the required design requirements [1,2]. The material removal rate is achieved with an increase in current, which leads to an increase in the strength of the electrical spark generated and thus an increase in metal loss. The increase in current also causes an increase in the roughness of the machined surface [3]. Effective and vital information can be provided about the mechanisms of removing materials from electrodes, electrode geometry, dielectric fluid effect, and other process parameters by studying and analyzing the subsurface damage formed [4]. Surface roughness and integrity of the machined surface are significantly affected by current and pulse on time, while ceramic compounds play a major role in generating surface and subsurface damage [5]. The effect of different machining parameters is discussed using response surface methodology (RSM) for peak current, pulse on time, pulse off time, and electrode angle, where a high impact on the surface roughness and microhardness is found [6]. Many performance measurements are improved through the influence of the electrode surface profile, such as tool wear rate, material removal rate, surface integrity, and machined surface roughness. These improvements will contribute to increased productivity and product quality during the machining process of Inconel 718 alloy [7]. Determining the ideal conditions in the EDM process depends mainly on the profile of the electrode. Improvements have been observed in various performance parameters, such as material removal rate and electrode wear rate [8]. However, the observed performance of the novel-designed tools was significantly superior to that of the traditional cylindrical tools. The novel-designed tools achieved a decrease in the roughness of the machined surface, machining time, and radial overcut, valued at approximately 50%, 30.6%, and 38.7%, respectively [9]. Studies have shown that the material removal rate in the EDM process can be significantly improved using different tool designs. In addition, the machining accuracy can be improved because the electrode wear rate was lower than that of the traditional tool design [10]. The new tool design improves the tool wear ratio and minimizes the radial overcut compared to traditional design tools [11]. The different angled electrode geometry and the method of modeling parameters observed have a high effect on parameters, such as material removal rate (MRR), pulse shape, and surface roughness of the EDM process [12]. The impact of electrode shape on MRR and other performance parameters was studied. Hollow and solid copper electrodes with a diameter of 7.5 mm were used to drill the holes. The shape of the electrode significantly impacts EDM performance [13]. However, a graduated cylindrical copper electrode for machining the workpiece AISI P20 significantly improved the performance of the EDM process and enhanced the surface quality of the workpiece machined [14]. The response parameters were also improved by modifying the geometric design of the electrode shape to create triangular, square, and hexagonal holes [15]. The extent to which the electrode angle contributes to response parameters, such as electrode wear rate, material removal rate, and surface finish, was studied [16]. The impact of operating parameters on the performance of the EDM process, such as electrode wear rate and material removal rate, was studied. Electrode wear was evaluated using laser scanning technology [17]. The effect of electrode profiles on EDM performance was studied and analyzed. Three shapes were selected for electrodes, namely, flat, convex, and concave. The experimental results revealed the effectiveness of convex electrodes compared to flat and convex electrodes in terms of electrode wear, operating time, and material removal rate [18]. In the Electrical Discharge Machining (EDM) process, flat profile electrodes are generally selected for the material removal. It has been observed that the wear on these electrodes tends to occur in a convex shape. To treat the wear influence observed in flat profile electrodes of the EDM process, the idea of utilizing electrodes with a convex profile was suggested. The goal is to optimize the EDM process by investigating the effect of a convex profile on different operating aspects. The study analyzed the effect of process conditions and the impact of two different profiles of electrodes on the machined workpiece surface. This analysis covered different aspects, such as material removal rate (MRR), tool wear rate (TWR), surface quality, morphology of electrodes, and recast layer thickness formation.

2.DETAILS OF EXPERIMENTAL

2.1.Optimal Operating Conditions

The present work utilized a Chemer EDM machine (CM 323+50N) to conduct all runs of the experimental work, as shown in Fig. 1. The EDM depends not only on a machine's capacities but also on machining parameters. To identify suitable machining parameters that will result in the required product quality, one must be knowledgeable of the process parameters. All these machining parameters play an important role in deciding machining properties. Various parameters were selected to be investigated from the literature, influencing the performance of the EDM process. The fundamental steps in this work involve parameter selection for the runs and selecting their different levels. Consequently, the process parameters are I_p, T_{on}, and T_{off}.

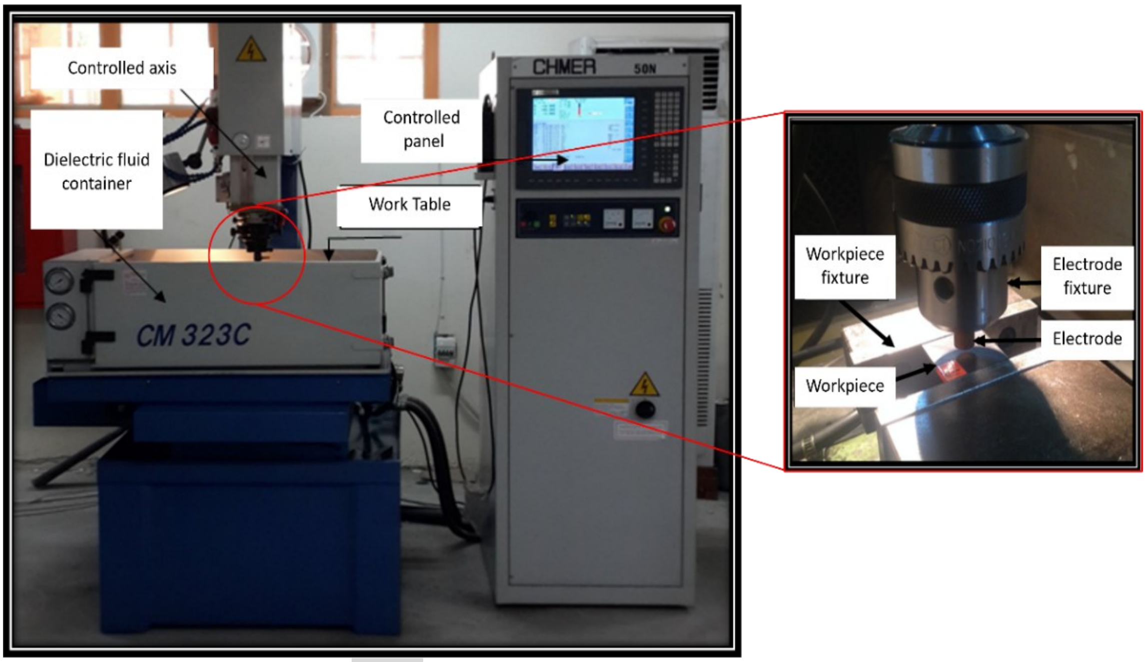


Fig. 1 EDM Machine (CM 323+50N).

The response parameters selected for evaluating the process performance are tool wear rate (TWR), material removal rate (MRR), recast layer thickness, machined surface roughness (SR), and surface morphology of electrodes. Optimal operating conditions values were obtained through performing runs on AISI 1005 carbon steel using copper-nanographene as an electrode by Design Expert 13. Table 1 shows the parameters with three levels that were selected in this experimental work. Other process parameters that remained constant were not changed throughout the experimental work such as voltage, polarity, dielectric fluid, depth of cut, and gap.

Table 1 Machining Parameters and Their Values.

Machining parameters	Range and levels		
	Level 1	**Level 2**	**Level 3**
I_p (A)	16	20	24
T_{on} (μs)	150	225	300
T_{off} (μs)	75	100	125

2.2 Material of Workpiece

The material of the workpiece selected in the present work was AISI 1005 Carbon Steel, in the form of a square plate (30 × 30 mm) with a thickness of 2mm to make a diameter hole of 10mm. Figure 2 shows the workpiece with a sketch before machining. The workpiece was linked to the negative polarity terminal of the EDM machine. The chemical composition of the workpiece was evaluated by utilizing the Master Xpert machine for analysis of materials, as depicted in Table 2. The Mechanical properties of the workpiece are listed in Table 3.

2.3.Electrode Tool

The electrodes used were copper-nanographene cylindrical solid shapes of 10mm diameter. Electrodes with flat and convex profiles were selected for the experimental work for machining holes in AISI 1005 Carbon Steel, as indicated in Table 4.

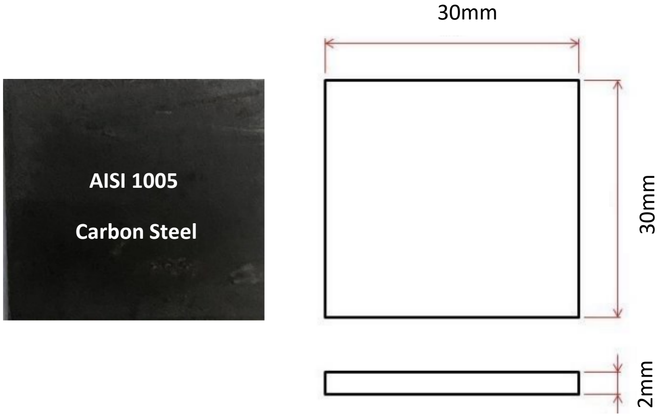


Fig. 2 Workpiece Before Machining.

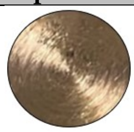
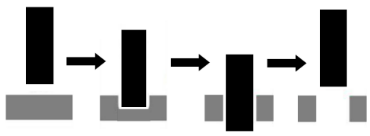
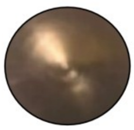
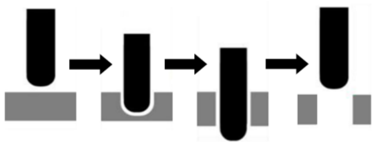
Table 2 Chemical Composition of (AISI 1005 Carbon Steel).

Materials	C%	Si%	Cu%	Mn%	P%	S%	Cr%	Mo%	Ni%	Ti%	Fe%
Weight %	0.049	0.003	0.028	0.231	0.008	0.01	0.014	0.004	0.011	0.0005	Balance

Table 3 Mechanical Properties of (AISI 1005 Carbon Steel).

Mechanical properties	Values
Tensile strength (MPa)	310
Upper yield strength (MPa)	260
Lower yield strength (MPa)	240
Percentage elongation at max load (%)	26.5

Table 4 Profile of the Electrode Tool.

Tool Electrode	Electrode geometry	Electrode end profile	Machining of AISI 1005 Carbon Steel
Flat electrode (Copper-Nanographene)			
Convex electrode (Copper-Nanographene)			

3.RESULTS AND DISCUSSION

Experimental works were conducted using the Design Expert 13 software experiments and the response parameters of TWR and MRR for flat and convex types of electrodes, as listed in Table 5. The TWR and MRR were measured using the following mathematical formulas:

$$\mathbf{TWR} = \frac{Wi - Wf}{Dt \times T}\ \mathbf{(mm^3/min)} \qquad \mathbf{(1)}$$

where Wi:- is the tool initial weight (mg), Wf:- is the tool final weight (mg), T:- is the machining time (min), and Dt:- is the density of the tool (g/mm^3).

$$\mathbf{MRR} = \frac{Wi - Wf}{Dw \times T}\ \mathbf{(mm^3/min)} \qquad \mathbf{(2)}$$

where Wi:- is the workpiece initial weight (gm), Wf:- is the workpiece final weight (gm), T:- is the machining time (min), and Dw:- is the density of the Workpiece (g/mm³).

Table 5 Experiments of Flat and Convex Profile Electrodes.

No	Flat profile Electrodes		Convex Profile Electrodes	
	TWR (mm³/min)	**MRR (mm³/min)**	**TWR (mm³/min)**	**MRR (mm³/min)**
1	0.044	13.131	0.017	16.451
2	0.322	14.604	0.271	17.889
3	0.028	13.106	0.012	16.334
4	0.216	15.307	0.135	18.903
5	0.123	13.330	0.081	17.197
6	0.131	13.662	0.104	17.482
7	0.038	14.336	0.031	16.098
8	0.235	14.801	0.177	17.942
9	0.013	14.123	0.042	16.663
10	0.121	14.751	0.107	16.813
11	0.142	13.420	0.116	16.979
12	0.275	14.958	0.203	18.829

3.1.Tool Wear Rate (TWR)

The convex electrodes in the EDM process for machining AISI 1005 carbon steel significantly improved the TWR of the electrode tool. When comparing the TWR mean of the flat and convex electrodes, the observed TWR of the electrodes decreased by 26.66%, as shown in Fig. 3. The possible decrease in TWR reason for this result could be that the convex profile electrodes had a lesser surface area of the electric contact with the workpiece than the flat profile electrodes and for the same operation condition. Also, the thermal energy for each spark with the convex profile electrodes was smaller. Moreover, the amount of the electrode material to be melted and evaporated was also less.

3.2.Material Removal Rate (MRR)

Figure 4 shows that the mean MRR of the electrodes with a convex profile was much higher than that of the electrodes with a flat profile. The MRR of the convex profile electrode was greater than that of the flat profile electrode. The reason could be that the convex profile electrode had a larger area in the spread of the electric sparks in contact with the surface of the workpiece than the flat profile electrode and for the same operation condition, where the surface area of the flat electrode was a less than the convex electrode (58.64 mm² for flat vs 74.25 mm² for convex). Hence, the energy and sparks numbers were high in the operation area, increasing the melting and evaporation of the workpiece material, as shown in Fig. 5.

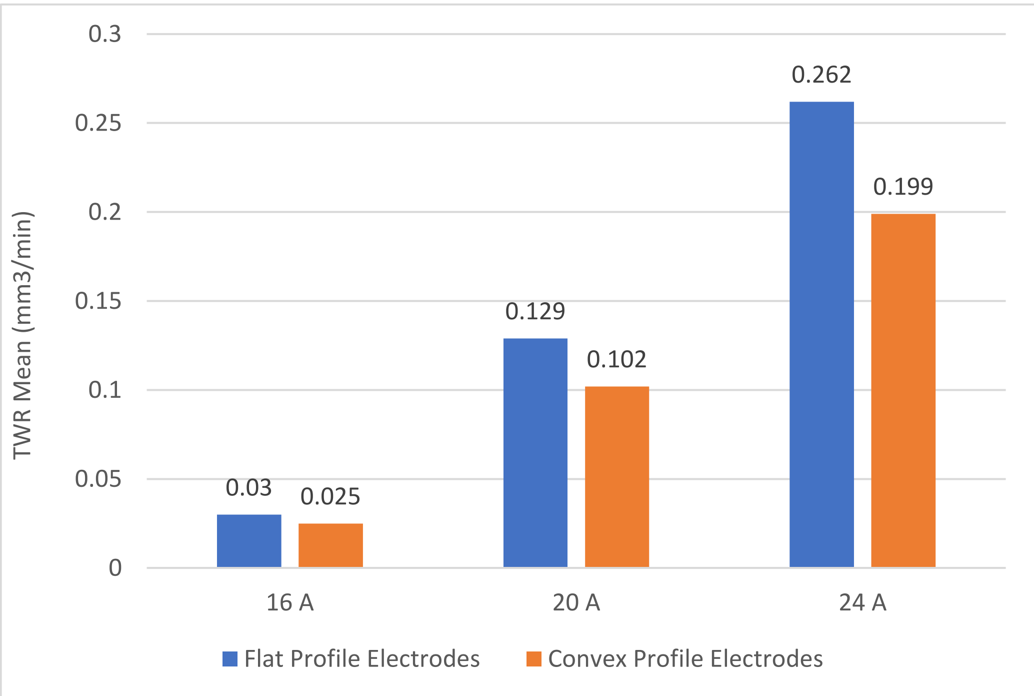


Fig. 3 TWR Mean of Flat and Convex Profile Electrodes.

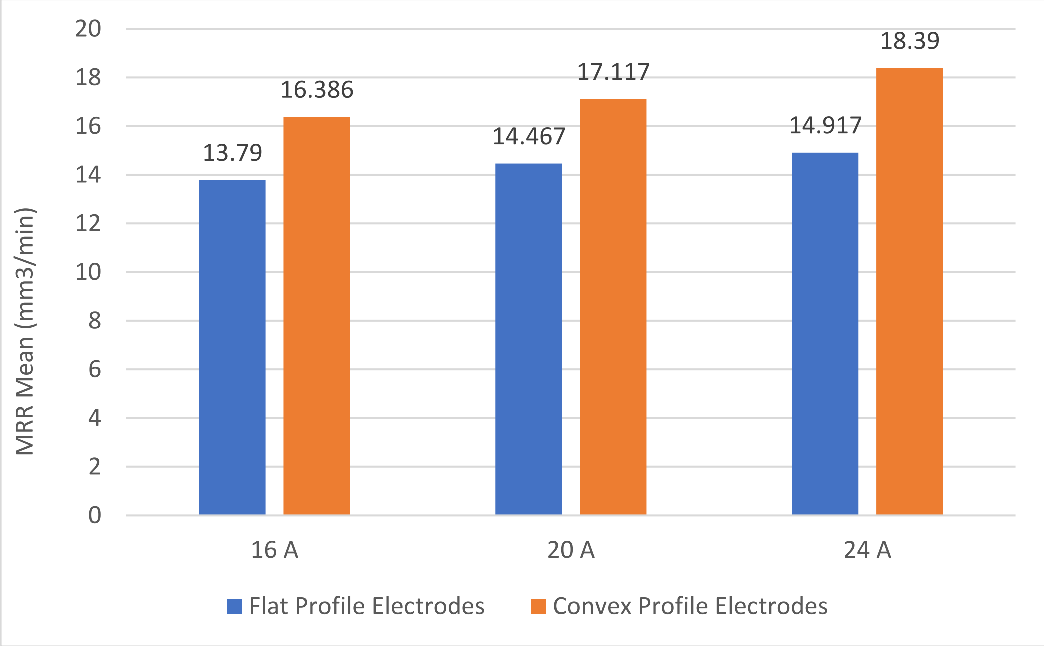


Fig. 4 MRR Mean of Flat and Convex Profile Electrodes.

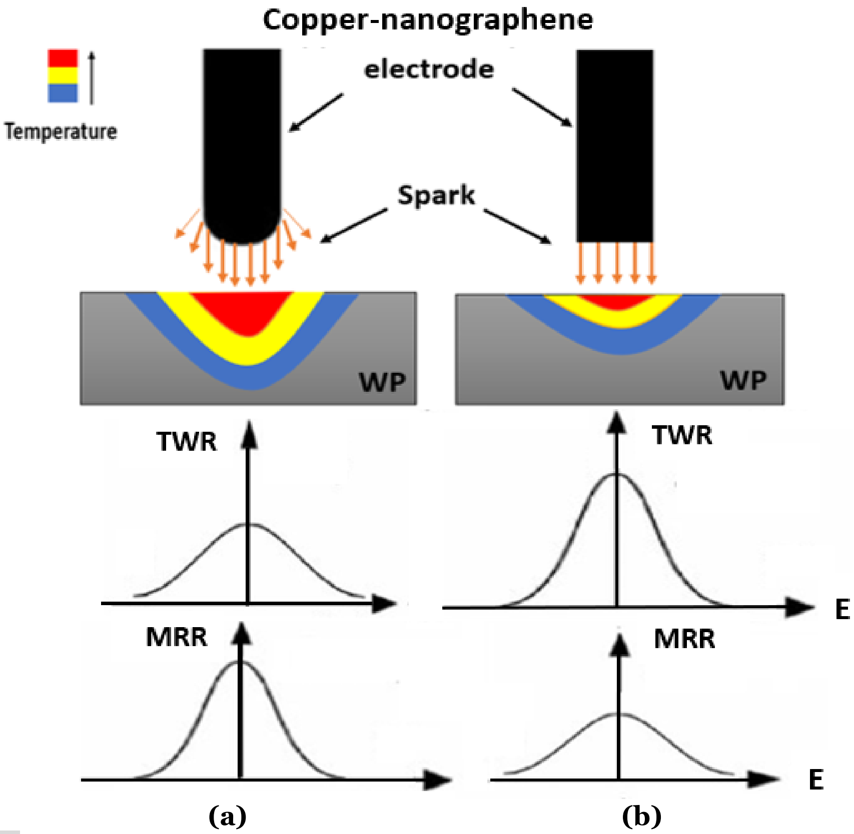


Fig. 5 Performance Measures of EDM Using Electrode Profile (a) Convex (b) Flat.

3.3.Recast Layer Thickness (RCL)

Figure 6 shows the contrast in the recast layer (RCL) thickness of the surface machined based on the shape of the electrode profile used by scanning electron microscopy SEM TESCAN/VEGA device. The outcomes showed that when using a convex profile electrode, the RCL was smaller than that of an electrode with a flat profile. This variation can be due to several factors. First, when utilizing convex profile electrodes, the effective surface area decreased, generating low thermal energy. As the electrode moved toward the workpiece, the active surface area gradually increased, resulting in significant thermal energy and great material removal. Further, convex profile electrodes easily reached the electrolyte, especially when compared to flat profile electrodes, enhancing access and cleaning the molten metal, therefore, minimizing the formation of the RCL thickness.

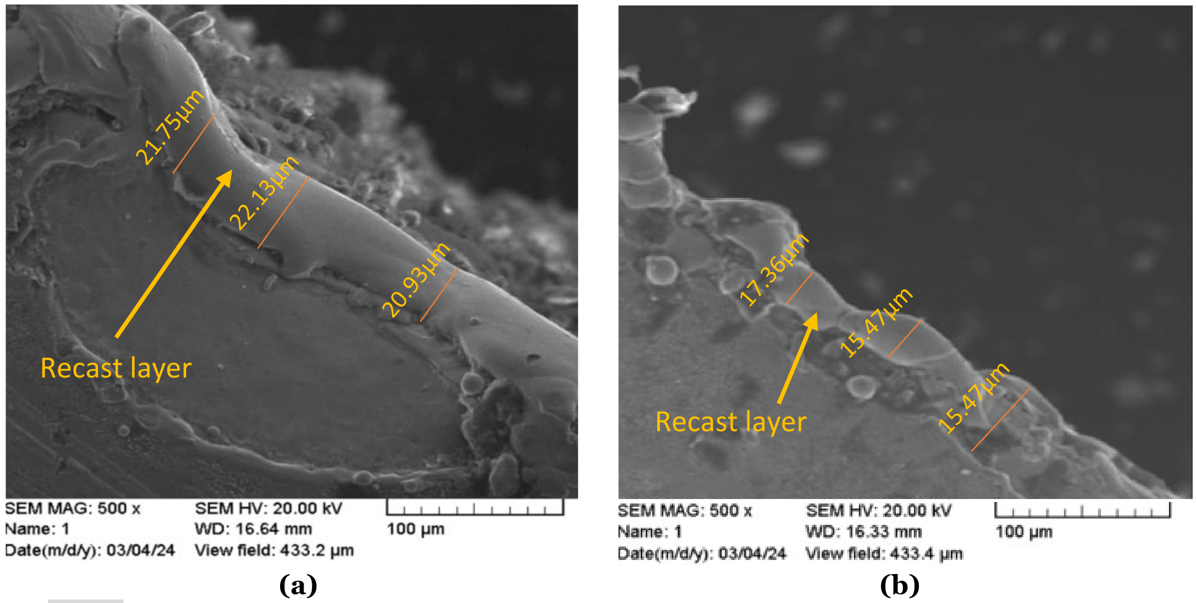


Fig. 6 SEM Micrograph of the Machined Surface (a) Flat Profile Electrode (b) Convex Profile Electrode. I_p (24 A), T_{on} (300 µs), and T_{off} (100 µs).

3.4.Quality of Machined Surface

Scanning electron microscopy (SEM) of the surface machined using the EDM process, using flat and convex profile electrodes, is illustrated in Fig. 7. The surface quality of the workpiece when using a convex profile was optimized because the surface area of contact with the workpiece was smaller than that of the flat profile electrodes when using the same machining parameters. This behavior is due to the high electric discharge density, which accelerates the separation of the metal from the workpiece. It is more effective in cleaning the molten metal, resulting in a better surface finish. In addition, the roughness of the machined surface (SR) was measured using the Marsurf Ps1. The SR was observed to be 5.1 µm using a flat electrode, while it decreased to 3.9 µm using a convex electrode for the same machining parameters.

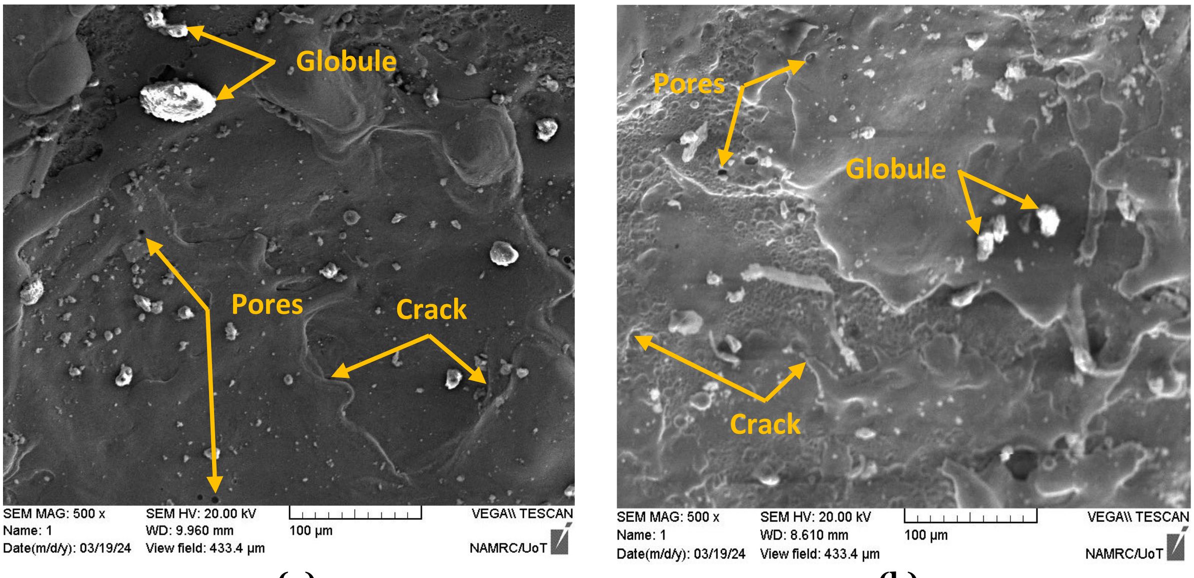


Fig. 7 SEM micrograph of the surface roughness (a) Flat profile electrode, (b) Convex profile electrode. I_p (24 A), T_{on} (300 µs), and T_{off} (100 µs).

3.5.Morphologies Comparison of Electrodes

The term morphology of the operated electrode surface is clearly illustrated by the images of the 3D laser scan technique using an LMT mag 3D Scanner device. It refers to the surface geometry of the electrode utilized in the EDM process. Figure 8 shows both flat and convex electrode surfaces before and after machining. It is evident from Fig. 8 that the geometry and surface defects of the electrodes observed on the electrode surface formed more easily when using flat profile electrodes than with the surface morphology observed at the convex profile electrodes for the same machining parameters. It showed a few small deformities because the spark formation of the electrodes with a convex profile was better than that of electrodes with a flat profile, resulting in a smaller thermal energy. Therefore, the overcut amount in the EDM process with the convex profile electrodes was smaller. Consequently, the machining accuracy was better than that with the flat profile electrodes.

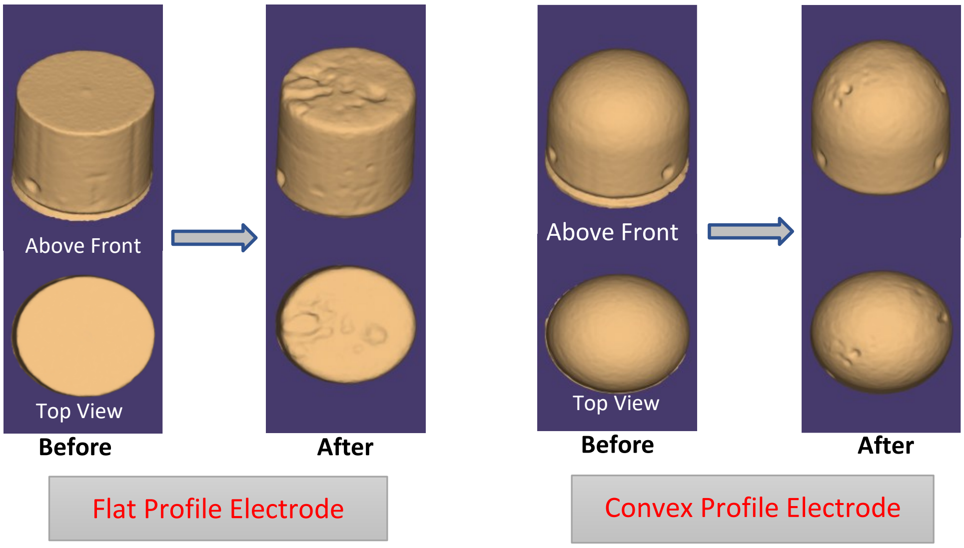


Fig. 8 Comparing Morphologies of Electrodes. I_p (24 A), T_{on} (300 µs), and T_{off} (100 µs).

4.CONCLUSION

The present study demonstrated the effectiveness of convex electrodes for making holes in the EDM process. The present study objective is to select the optimal electrode profile for making the holes for EDM performance enhancement, considering the effect of the practical input and output parameters. The following is a summary of the key conclusions derived from the work:

- The convex profile electrodes decreased the wear of the electrode tool by 17.37% compared with the flat profile electrodes.
- The convex profile electrodes increased the metal removal from the workpiece by 19.34% due to the increased electric spark generated in the machining region.
- Convex profile electrodes performed better than flat profile electrodes in terms of the recast layer thickness decreased (RCL).
- The convex profile radius of electrodes performed better surface roughness, i.e., decreased by 23.52%, and gave good machinability.
- The replacement of a flat profile electrode with a convex profile electrode for the hole machining experimentally overcame the harmful impacts of erosion in the EDM process.
- Convex profile electrodes contributed to the optimization of many quality indicators in the hole drilling in the EDM process. Electrodes of convex profile were considered more economically efficient than electrodes of flat profile and directly impacted their practical implementations in this domain.

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