Integration of Scanning Technology for Tool Wear Analysis in the Electrical Discharge Machining Process

Osama Sameer Sabbar
Department of Production Engineering and Metallurgy, University of Technology, Iraq
pme.22.01@grad.uotechnology.edu.iq (corresponding author)

Ali Abbar Khleif
Department of Production Engineering and Metallurgy, University of Technology, Iraq
ali.a.khleif@uotechnology.edu.iq

Baraa M. H. Albaghdadi
Department of Production Engineering and Metallurgy, University of Technology, Iraq
baraa.m.albaghdadi@uotechnology.edu.iq

Nader Abdulhameed
Division of Prosthodontics, Restorative Dental Sciences, University of Florida, USA
naderf@ufl.edu

Received: 15 July 2024 | Revised: 2 August 2024 | Accepted: 4 August 2024

 DOI: https://doi.org/10.48084/etasr.7989

ABSTRACT

There is a direct correlation between surface roughness and electrode tool status in the Electrical Discharge Machining (EDM) process. The quality of the machined surface of workpieces is becoming even more critical in recent industries. In general, electrode wear evaluation plays a vital role in the EDM process, affecting the operation cost and the accuracy of the required dimensions and geometric shape. This study presents a new method to evaluate the copper electrode wear during machining AISI 1005 carbon steel in the EDM process using a 3D laser scanner that measures the lost volume of the electrode. The results of the proposed method were compared with those of the conventional method. Laser technology was used to accurately measure the dimensions and surface characteristics of the electrode by scanning the electrode surface and the electrode view topology before and after the machining process. The processed data was saved on a computer connected to the laser scan device, converted to STL files, and sent to a 3D system (Geomagic Control X software). This software utilizes accurate mathematical algorithms to determine the available volumetric differences in the electrode. The experiments used Design-Expert 13 software, selecting three machining parameters: Current (I_p), pulse on time (T_{on}), and pulse off time (T_{off}). The results showed that the Tool Wear Rate (TWR) obtained by the two methods showed a mean absolute deviation of 3.6%, with an insignificant error on the effect of the machining parameters on TWR (1.01% for I_p, 1.92% for T_{on}, and 2.29% for T_{off}).

Keywords-EDM; laser scan technique; electrode wear; Geomagic Control X; TWR measurement

I. INTRODUCTION

The working principle of the EDM process is based on generating a repeated electrical spark between the tool and the workpiece. In recent years, electrode wear in the EDM process, which depends on the quality of the product, has become a main criterion for evaluating its performance. Wear can occur for mechanical, electrical, or thermal reasons, combined or separately, leading to the removal of materials from the workpiece and causing wear and tear on the electrode tool (Figure 1).

The EDM process is used in the manufacturing and shaping of complex parts and is considered one of the most important unconventional cutting methods [1]. The cutting tools used in conventional methods must be harder and stronger than the workpiece part. Industrial process products have high surface quality and high precision [2, 3]. Due to its characteristics, the EDM process has attracted great interest in different industrial sectors [4]. This technology is used in different hard and brittle materials that are difficult to operate utilizing traditional methods. It has been used in different fields, such as medicine, aviation, electronic devices, and ultra-precision parts [5, 6]. The operating parameters have a significant impact on the performance of the EDM process, the most important being the current and the pulse on and off times [7]. Electrode geometry plays a vital role in the EDM process. Evaluating electrode wear is very important to determine the performance of the EDM process. [8].

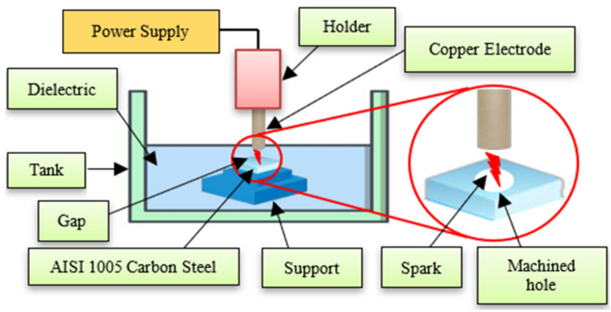

Fig. 1. Working principle of the EDM technique.

In [9], electrode wear was investigated and the material removal rate was predicted based on regression models. Other approaches have also been used to predict electrode wear, indicating that the depth of the cut can be controlled with high accuracy. In [10], a method was proposed to measure electrode wear using an image processing algorithm and a computer-assisted wear prediction algorithm. In [11], an approach was presented to assess electrode wear, using computer vision with a camera to capture images and determine the decrease in electrode length using MATLAB. In [12], a machine vision method was effective in evaluating the wire electrode and the pattern data of aluminum-silicon nitride composite workpieces in the EDM process [12]. In [13], an automated system was developed to evaluate electrode wear, using MATLAB to process and analyze images. In [14], electrode wear in the EDM process was evaluated by analyzing laser-scanned electrode images using Geomagic Control X software. In [15], a laser scanner was used to measure depth and volume loss to evaluate wear in the field of dentistry, and the results demonstrated the effectiveness of the proposed technique compared to traditional ones. In [16], an image-based approach was proposed to assess electrode wear in the EDM process. Copper electrodes were employed on an AISI 314 machine, and images were analyzed using MATLAB.

In [17], a method was proposed to assess electrode wear along the cross-section compared to the longitudinal section in the EDM process. The results showed that the wear increased with increasing voltage (V) and current (A) supplied, but the wear in the longitudinal section was less than in the cross-section. In [18], a laser scanner was used to measure wear and compare it with the optical profilometry (WLP) method. The results verified the effectiveness of the proposed method compared to others. In [19], electrode wear was evaluated using the conventional method, and the influence of current on the Electrode Wear Rate (EWR) was demonstrated. In [20], the effect of volumetric wear and variance in electrode geometry was examined. This method showed that the variance in wear amount due to different factors cannot be neglected in the WEDM process [20]. In [21], a technique was proposed based on generating pre- and post-process data, using a laser scanner method (3D) to evaluate the wear in a steel ladle through a data comparison, ensuring precise and rapid wear profiles.

In [22], electrode wear was determined using a vision system to minimize test costs. In [22], a method was proposed based on determining the approximate location of the tool and recording images. In [23], a monitoring system was employed to measure electrode wear, collecting signals related to the vibration strength and acoustic emissions of the tool using special sensors. This technique was effective in monitoring electrode wear compared to others. In [24], a method was proposed to determine tool wear by processing signals caused by cutting tools, allowing for the determination of tool data and processing. In [25], electrode wear was evaluated using Infrared Radiation (IR), using three camera devices to collect the reflected infrared light. Tool wear was measured from images using a multiview neural network. In [26], an image analysis system was developed to automate tool wear measurement, using a single camera installed on the device. The wear evaluation process was carried out in three stages. The error rate for the average wear was estimated to be 3.57% and 2.92%, respectively.

With an increasing reliance on modern devices and technologies to measure wear, their accuracy must be verified. This study uses a laser scanner to measure electrode wear and compare its results with the conventional method. The proposed method can also be used in future applications to measure the dimensions and wear of manufactured parts and reverse engineering using CAD/CAM systems.

II. MATERIALS AND METHODS

A. Materials

Twelve experiments were carried out using cone-shaped electrodes with a diameter of 10 mm and a length of 20 mm, connected to the positive polarity terminal of the EDM machine. The chosen workpiece material was AISI 1005 carbon steel, as a piece of plate 20×20 mm with a thickness of 2 mm to make a hole with a diameter of 10 mm. Figure 2 shows the workpiece and electrode before EDM machining. The workpiece was linked to the negative polarity terminal of the EDM machine. Table I shows the machining parameters with different levels.

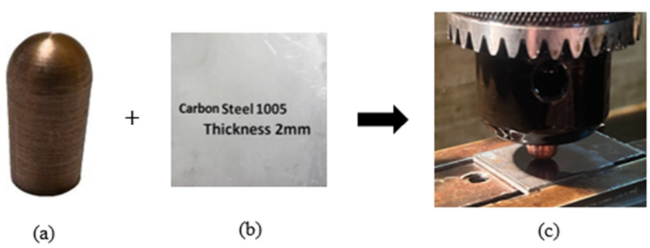

Fig. 2. Materials used: (a) cone copper electrode, (b) AISI 1005 carbon steel, and (c) EDM machine.

TABLE I. CONTROL PARAMETERS OF EDM

Parameters	Levels		
	L1	L2	L3
Current (I_p)	20	25	30
Pulse on time (T_{on})	100	200	300
Pulse off time (T_{off})	25	35	45

B. Methods

This study used a Chemer EDM machine (CM 323+50 N) for the experimental work. The conventional method was utilized as the gold standard to measure TWR (mm^3/m) using the following formula:

$$TWR = \frac{Wi - Wf}{D_t \times T} \text{ (mm}^3\text{/min)} \quad (1)$$

where W_i is the initial tool weight (mg), W_f is the final tool weight (mg), T is the machining time (min), and D_t is the density of the tool (gm/mm^3).

The proposed method for examining and measuring the electron wear in the EDM process uses a 3D scanner, which is used in many applications such as quality inspection and control. The topography of each electrode surface is scanned over several experimental runs of the EDM process using an Open Technologies LMT mag 3D Scanner to accurately measure the dimensions and surface characteristics of the electrode and its topology view before and after the machining process. The processed data are saved in the computer connected to the laser scan device. The scanning time for every electrode was about two minutes. The working principle of the laser scanner is based on projecting a beam parallel to the desired target to obtain its profile shape through a high-resolution Coupled Charged Device (CCD) imaging device to obtain complete data with fine details, such as wear, cracks, sculpture, etc. These devices are placed at certain angles. Figure 3 shows the schematic of the laser scanning for the electrode tool. If there is an obstacle, it leads to distortion of the beam emitted from the source, which is observed through the CCD camera.

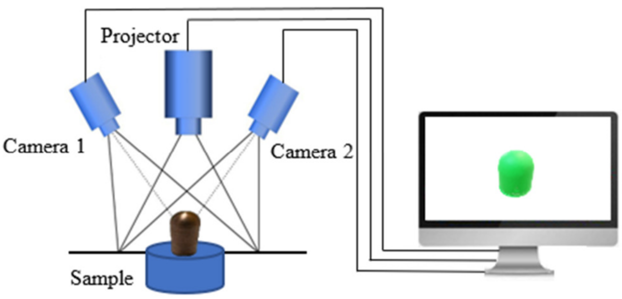

Fig. 3. Schematic of laser scanning the electrode.

After completing the electrode scanning process before and after EDM machining, the data are saved in the form of an STL file and then sent to the 3D System (Geomagic Control X software). This is a modern reverse engineering software that is effective in ensuring quality in various industrial and engineering sectors. It can provide data and measurements that other techniques cannot provide, such as examining the deformations, bends, and wear to which an electrode is exposed in the EDM process. This program digitally analyzes 3D models and utilizes accurate mathematical algorithms to calculate volumetric differences on the electrode. Previously scanned electrode data are imported, and the best-fit alignment is used between the electrode data before (reference data) and after the machining (target data) [27]. Overlapping the electrode data can specify a certain tolerance between the electrodes, making it easier to identify the area that requires further study and analysis, as the difference in color intensity between the electrode data increases, as shown in Figure 4.

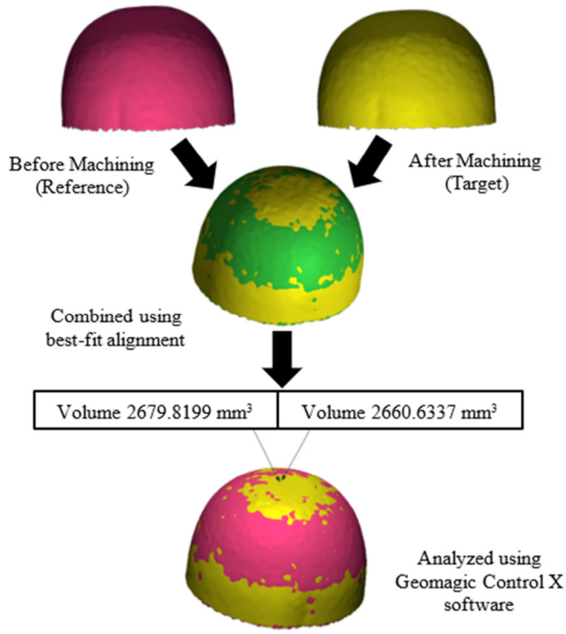

Fig. 4. Digital analysis method for electrode data using Geomagic Control X software.

III. RESULTS AND DISCUSSION

A. Maximum and Minimum TWR

Table II shows the results of TWR measured using the conventional and the proposed laser scan methods. The absolute deviation between them was computed to determine the extent of data dispersion using

$$Absolute\ Deviation = \Sigma\ |x - \mu| \quad (2)$$

where $\Sigma|x - \mu|$ is the sum of the absolute value of the difference between each value (x) and the mean (μ).

The highest value for the absolute deviation was 5.2% for run No. 11, while the lowest value was 1.8% for run No. 5. Figure 5 shows the wear of the copper electrodes evaluated and recorded using the conventional method and laser scanning. The experimental results show a significant agreement with a small deviation in the values obtained, thus concluding the acceptance of the results, which is considered to be precise. Additionally, the data can be reliable and used to support the decision-making process in electrode wear measurement in the EDM process.

TABLE II. CONVENTIONAL AND LASER SCAN WEAR MEASUREMENTS FOR COPPER ELECTRODES

No.	I_p (A)	T_{on} (μs)	T_{off} (μs)	TWR (mm^3/min) using the conventional method	TWR (mm^3/min) using the laser scan method	Absolute deviation %
1	20	300	35	1.566	1.519	4.7
2	30	300	35	1.844	1.886	4.2
3	20	200	45	1.549	1.587	3.8
4	30	200	25	1.658	1.623	3.5
5	25	100	35	1.555	1.573	1.8
6	25	300	25	1.573	1.539	3.4
7	20	200	25	1.415	1.452	3.7
8	30	100	35	1.621	1.649	2.8
9	20	100	35	1.334	1.369	3.5
10	25	100	25	1.443	1.491	4.8
11	25	300	45	1.664	1.612	5.2
12	30	200	45	1.797	1.748	4.9

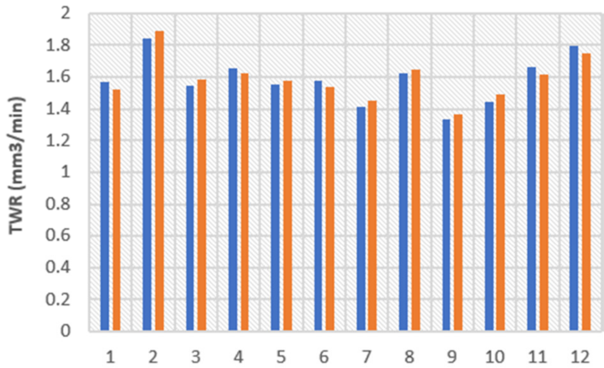

Fig. 5. Tool wear measurements using the traditional and the laser scanning methods (mm^3/min).

This discrepancy in the TWR values measured by the two methods represents the result of deviations in the size of the distance measured by laser scanning. The rationale for this contradiction between the values is that the scanning method is subject to the influence of reflected rays that are divided as a result of the various angles of the electrode edge, which leads to the formation of a series of bumps or ridges along the measured indentation edge. To eliminate this difference, a single reference plane was taken to calculate the basic volume of the electrode edge, by removing the formed bump from the indentation edge, as shown in Figure 6.

The effect of the location of the reference plane in determining the volume of metal removed is significant since the volume difference resulting from the reference plane will have a deviation, which has the effect of giving false readings for measuring the electrode wear. There could be another explanation for the effect of metal type and the wavelength of the laser scanner, in addition to the operator experience. The two profiles manifest similar trends for the morphology of the electrode surface. However, the electrode profile produced by the scanner does not depict the actual electrode surface roughness. However, this difference is unclear in the electrode surface measurement profile. This is the result of the precise scanner measurement, which produced 3000-4600 data points for each scan. The 3D laser scanner used in this study is a red laser beam with a high wavelength. Depending on the type of metal, the laser can penetrate it to provide accurate data on the electrode's morphology.

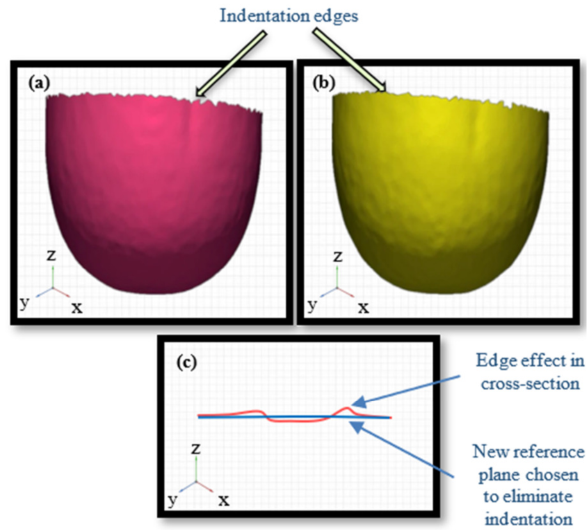

Fig. 6. Actual scans from the laser scanner of the electrode displaying: (a) the electrode edge before machining, (b) the electrode edge after machining, and (c) the plane of reference selected to remove the bump.

B. *Analysis of Variance for TWR*

Table III shows the ANOVA results for the TWR of the copper electrode using the conventional method. The analysis indicates that I_p has the highest contribution of 74.87%. This suggests that I_p has the most significant impact on the machining process, resulting in the highest TWR. Additionally, T_{on} contributes 19.84%, T_{off} contributes 4.92%, indicating an interaction effect, and the residual is attributed to a fault. The correlation coefficient R^2 value is 95.3% for TWR using the conventional method.

TABLE III. ANOVA FOR TWR USING CONVENTIONAL METHOD

Source	Sum of squares	DF	Mean squares	F-value	P-value	
Model	0.0737	6	0.0107	7.92	0.0251	Significant
A-I_p	120.232	1	120.232	28.20	0.0113	
B-T_{on}	31.874	1	31.874	2.02	0.0377	
C-T_{off}	7.901	1	7.901	0.0217	0.8178	
AB	0.311	1	0.311	1.82	0.1534	
AC	0.152	1	0.152	0.4303	0.3991	
BC	0.113	1	0.113	0.2561	0.6082	
Residual	0.0041	5	0.0051			
Cor. Total	160.587	11				

R^2 = 95.3%, Adjusted R^2 = 91.54%, Predicted R^2 = 90.18%

Table IV shows the ANOVA results for the laser scan method. I_p has a significant impact on TWR, contributing 75.63%. I_p is crucial for evaluating the thermal energy over the sparking region. T_{on} has the second influence on the TWR, with a contribution of 20.22%. The T_{off} parameter demonstrated an insignificant effect on TWR, with a contribution of 4.81%, and the residual is attributed to an interaction effect between variables. The correlation coefficient R^2 is 94.1%.

TABLE IV. ANOVA FOR TWR USING LASER SCAN METHOD

Source	Sum of squares	DF	Mean squares	F-value	P-value	
Model	0.0842	6	0.0122	12.86	0.0317	Significant
A-I_p	193.964	1	193.964	94.66	0.0243	
B-T_{on}	51.871	1	51.871	8.23	0.0424	
C-T_{off}	12.666	1	10.606	1.43	0.5331	
AB	2.213	1	3.213	0.75	0.2274	
AC	1.668	1	1.668	0.46	0.1692	
BC	0.505	1	1.205	0.3393	0.4437	
Residual	0.276	5	0.0007			
Cor Total	263.163	11				

R^2 = 94.1%, Adjusted R^2 = 93.53%, Predicted R^2 = 91.93%

Figure 7 compares the percentage error for the machining parameters of TWR using the conventional and the laser scan methods. The error percentage for the effect of machining parameters on the TWR between the two methods is 1.01% for I_p, 1.92% for T_{on}, and 2.29% for T_{off}, indicating that the TWR measurement using the laser scan method produced insignificant errors. Figure 8 shows a scatter plot between the TWR measurements for the laser scanner and the conventional method. It can be observed that all data points are clustered along the red upward regression line, and the scatter around the line is quite small, which means there is a strong linear correlation. This indicates a positive correlation between the two methods, showing that they are in high agreement.

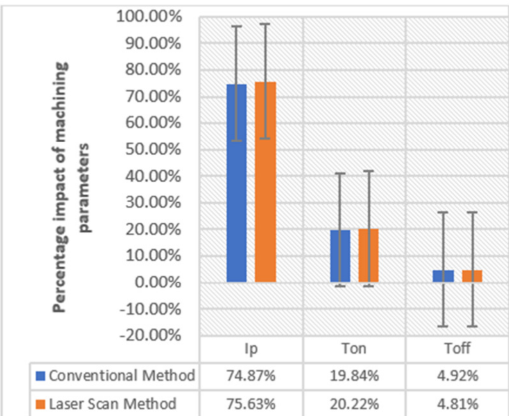

Fig. 7. Comparison of the difference in percentage error for the impact of machining parameters between thse two methods.

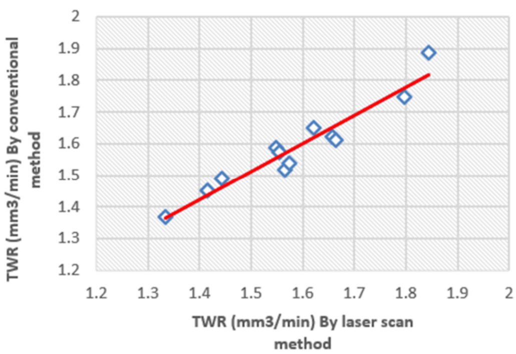

Fig. 8. Scatter plot for TWR with a diagonal line indicating perfect agreement between the two measuring methods.

IV. CONCLUSION AND FUTURE WORKS

The TWR of copper electrodes in the EDM process was evaluated using a novel method that depends on a 3D laser scan under different operating conditions. Although measuring the wear in this way is a difficult task, the results demonstrated the success of the proposed method, with a slight deviation from the results of the conventional method. The mean absolute deviation was 3.6% for TWR, with an insignificant error for the machining parameters that influence TWR (1.01% for I_p, 1.92% for T_{on}, and 2.29% for T_{off}). This difference is due to the effect of the electrode edge, the type of material, and the high wavelength of the laser beam. The 3D laser scanner is considered a very subjective method based on the operator's expertise. However, it achieves operational safety and a suitable machining environment. Therefore, scanning technology needs further technological development to provide devices with high accuracy for accurate and reliable measurements compared to other methods and to obtain information on the properties of electrodes in the EDM process. Future work can use laser scanning technology to identify the effect of the machining process in each area of the electrode and the areas most affected by wear to address the root factors that cause it.

ACKNOWLEDGMENT

The authors thank all the staff of the Engineering College, Production Engineering and Metallurgy Department, University of Technology, Iraq for their persistent assistance during the experimentation processes of this research.

REFERENCES

[1] S. Anjum, M. Shah, N. A. Anjum, S. Mehmood, and W. Anwar, "Machining and Surface Characteristics of AISI 304L After Electric Discharge Machining for Copper and Graphite Electrodes in Different Dielectric Liquids," *Engineering, Technology & Applied Science Research*, vol. 7, no. 4, pp. 1765–1770, Aug. 2017, https://doi.org/10.48084/etasr.1250.

[2] N. V. Cuong and N. L. Khanh, "Parameter Selection to Ensure Multi-Criteria Optimization of the Taguchi Method Combined with the Data Envelopment Analysis-based Ranking Method when Milling SCM440 Steel," *Engineering, Technology & Applied Science Research*, vol. 11, no. 5, pp. 7551–7557, Oct. 2021, https://doi.org/10.48084/etasr.4315.

[3] V. C. Nguyen, T. D. Nguyen, and D. H. Tien, "Cutting Parameter Optimization in Finishing Milling of Ti-6Al-4V Titanium Alloy under MQL Condition using TOPSIS and ANOVA Analysis," *Engineering, Technology & Applied Science Research*, vol. 11, no. 1, pp. 6775–6780, Feb. 2021, https://doi.org/10.48084/etasr.4015.

[4] N. Mohri and T. Tani, "Recent evolution of electrical discharge machining," in *4M 2006 - Second International Conference on Multi-Material Micro Manufacture*, Oxford, UK, Jan. 2006, pp. 23–26, https://doi.org/10.1016/B978-008045263-0/50006-4.

[5] Y. Laibi and S. Shather, "Effect of SiC-Cu Electrode on Material Removal Rate, Tool Wear and Surface Roughness in EDM Process," *Engineering and Technology Journal*, vol. 38, no. 9, pp. 1406–1413, Sep. 2020, https://doi.org/10.30684/etj.v38i9A.552.

[6] J. E. A. Qudeiri, A. Zaiout, A.-H. I. Mourad, M. H. Abidi, and A. Elkaseer, "Principles and Characteristics of Different EDM Processes in Machining Tool and Die Steels," *Applied Sciences*, vol. 10, no. 6, Jan. 2020, Art. no. 2082, https://doi.org/10.3390/app10062082.

[7] A. R. Hayyawi, H. Al-Ethari, and A. H. Haleem, "Optimization of the PM-EDM Process Parameters for Ti-35Nb-7Zr-5Ta Bio Alloy," *Engineering, Technology & Applied Science Research*, vol. 14, no. 3, pp. 13982–13989, Jun. 2024, https://doi.org/10.48084/etasr.6845.

[8] J. E. Abu Qudeiri, A. Saleh, A. Ziout, A.-H. I. Mourad, M. H. Abidi, and A. Elkaseer, "Advanced Electric Discharge Machining of Stainless Steels: Assessment of the State of the Art, Gaps and Future Prospect," *Materials*, vol. 12, no. 6, 2019, https://doi.org/10.3390/ma12060907.

[9] M. Bellotti, M. Wu, J. Qian, and D. Reynaerts, "Tool Wear and Material Removal Predictions in Micro-EDM Drilling: Advantages of Data-Driven Approaches," *Applied Sciences*, vol. 10, no. 18, Jan. 2020, Art. no. 6357, https://doi.org/10.3390/app10186357.

[10] G. Malayath, S. Katta, A. M. Sidpara, and S. Deb, "Length-wise tool wear compensation for micro electric discharge drilling of blind holes," *Measurement*, vol. 134, pp. 888–896, Feb. 2019, https://doi.org/10.1016/j.measurement.2018.12.047.

[11] A. A. Khleif, "Computer Vision Aided Electrode Wear Estimation in Electrical Discharge Machining Process," *Journal of Engineering Science and Technology Review*, vol. 17, no. 1, pp. 197–206, 2022.

[12] H. R. Gurupavan, H. V. Ravindra, T. M. Devegowda, and R. Addamani, "Machine Vision System for Correlating Wire Electrode Status and Machined Surface in WEDM of $AlSi_3N_4$ MMC'S," *IOP Conference Series: Materials Science and Engineering*, vol. 376, no. 1, Mar. 2018, Art. no. 012120, https://doi.org/10.1088/1757-899X/376/1/012120.

[13] Z. Hamedon, I. Razemi, A. R. Abdul Manaf, and N. M. Yahya, "Innovative Method of Measuring Electrode Wear During EDM Drilling Process Using Vision System," in *Intelligent Manufacturing & Mechatronics*, Pekan, Malaysia, 2018, pp. 53–63, https://doi.org/10.1007/978-981-10-8788-2_5.

[14] A. A. Khleifa and O. S. Sabbar, "Electrode Wear Evaluation in E.D.M Process," *Engineering and Technology Journal*, vol. 37, no. 2C, pp. 252–257, May 2019, https://doi.org/10.30684/etj.37.2C.9.

[15] S. M. Hsu, F. Ren, N. Abdulhameed, M. Kim, D. Neal, and J. Esquivel-Upshaw, "Comprehensive analysis of laserscanner validity used for measurement of wear," *Journal of Oral Rehabilitation*, vol. 46, no. 6, pp. 503–510, 2019, https://doi.org/10.1111/joor.12778.

[16] A. A. Khleif, "Experimental investigation of electrode wear assessment in the EDM process using image processing technique," *Open Engineering*, vol. 13, no. 1, Jan. 2023, https://doi.org/10.1515/eng-2022-0399.

[17] A. A. Khan, "Electrode wear and material removal rate during EDM of aluminum and mild steel using copper and brass electrodes," *The International Journal of Advanced Manufacturing Technology*, vol. 39, no. 5, pp. 482–487, Nov. 2008, https://doi.org/10.1007/s00170-007-1241-3.

[18] C. Kühne, U. Lohbauer, S. Raith, and S. Reich, "Measurement of Tooth Wear by Means of Digital Impressions: An In-Vitro Evaluation of Three Intraoral Scanning Systems," *Applied Sciences*, vol. 11, no. 11, Jan. 2021, Art. no. 5161, https://doi.org/10.3390/app11115161.

[19] A. M. Abbas and A. A. Khleif, "EDM Electrode Design and Analysis to Enhance Process Performance," *Tikrit Journal of Engineering Sciences*, vol. 30, no. 4, pp. 145–152, Dec. 2023, https://doi.org/10.25130/tjes.30.4.15.

[20] D. T. Pham, A. Ivanov, S. Bigot, K. Popov, and S. Dimov, "A study of micro-electro discharge machining electrode wear," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 221, no. 5, pp. 605–612, May 2007, https://doi.org/10.1243/0954406JMES413.

[21] J. P. Santos, J. Macedo, H. Ávila, G. Lima, E. Arruda, and A. Lazaroni, "Innovative Refractory Wear Measurement Method for Steel Ladles Using 3D Laser Scanning," *RHI Magnesita Bulletin*, pp. 57–60, 2023.

[22] Ľ. Straka and P. Kuchta, "Dynamic control of discharge energy during wedm for the purpose of eliminating vibrations of the wire tool electrode," *Management Systems in Production Engineering*, vol. 29, no. 4, pp. 260–265, 2021, https://doi.org/10.2478/mspe-2021-0032.

[23] Z. Chaowen, J. Jing, and C. Chi, "Research On Tool Wear Monitoring Based On GRU-CNN," in *2021 6th International Conference on Intelligent Computing and Signal Processing (ICSP)*, Xi'an, China, Apr. 2021, pp. 729–733, https://doi.org/10.1109/ICSP51882.2021.9408717.

[24] D. Ninevski, Y. Yifrach, and P. O'Leary, "Instrumented Milling Process and Analysis for Tool Wear Measurement," in *2023 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Kuala Lumpur, Malaysia, May 2023, pp. 1–6, https://doi.org/10.1109/I2MTC53148.2023.10175934.

[25] W. K. Jang, D. W. Kim, Y. H. Seo, and B. H. Kim, "Tool-Wear-Estimation System in Milling Using Multi-View CNN Based on Reflected Infrared Images," *Sensors*, vol. 23, no. 3, Jan. 2023, Art. no. 1208, https://doi.org/10.3390/s23031208.

[26] R. G. Lins, B. Guerreiro, P. R. Marques de Araujo, and R. Schmitt, "In-Process Tool Wear Measurement System Based on Image Analysis for CNC Drilling Machines," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 8, pp. 5579–5588, Dec. 2020, https://doi.org/10.1109/TIM.2019.2961572.

[27] D. C. Viegas *et al.*, "Evaluation of the influence of the impression technique, scanning direction and type of scanner on the accuracy of the final model," *Brazilian Dental Science*, vol. 24, no. 1, 2021, https://doi.org/10.14295/bds.2021.v24i1.2179.