Energy efficiency and sustainability enhancement of electric discharge machines by incorporating nano-graphite

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Abstract. The research paper endeavored to significantly improve the energy efficiency and sustainability of the electrode wear rate (EWR) in electric discharge machining (EDM) through a particular exploration of various parameters. These parameters included nano-powder concentration, electric current, and pulse-on time. By systematically analyzing and manipulating these variables, the study aimed to optimize the EDM process, thereby reducing energy consumption and enhancing the overall sustainability of the machining operation. We employed the Powder Mixed Electro-Discharge Machining (PMEDM) technique, a refined iteration of electric discharge machining. This innovative method blended graphite nano-powder with transformer oil to serve as the dielectric medium. The primary objective of this investigation is to examine the outcomes concerning crucial process parameters such as graphite powder concentration, electric current, and pulse-on time when machining high-speed steel, focusing mainly on electrode wear rate (EWR). Incorporating nano graphite (Gr) mixed powders into dielectric liquids has demonstrated a discernible enhancement in EWR across diverse operational conditions. The study found that the electrode wear rate (EWR) varied based on nano-powder concentration, electric current, and pulse-on time. Maximum EWR was observed at a concentration of 10 g/L, a current of 30 A, and a pulse-on time of 70 µs, while minimum EWR occurred at 0 g/L, 10 A, and 60 µs. The Full Factorial design, executed with MINITAB 17 software, validated these findings. The optimal EWR recorded was 1.154 mm3/min. The coefficient of determination (R-sq) for surface roughness prediction also stood at 91.15%.

Introduction

An essential player in non-traditional machining methodologies, electrical discharge machining (EDM) stands out as a proven, logical, and economical approach to the precision machining newly developed high-strength alloys. Its success lies in delivering tailored machining solutions with exceptional dimensional accuracy while reducing production costs. This technology holds promise in enhancing energy efficiency and sustainability in manufacturing processes due to its precise material removal capabilities and potential for optimizing resource utilization. Despite their inherent hardness and brittleness, conductive materials can undergo efficient and effective thermal energy treatment. This method mitigates wear and minimizes the expenses typically incurred in conventional machining processes. Ceramics, titanium, and steel are just a few materials amenable to this treatment [1]. Leveraging thermal energy in material treatment enhances the machining process and potentially reduces energy consumption and environmental impact, contributing to sustainability in manufacturing practices. Emerging materials with challenging machining characteristics continually evolve within electric discharge machining (EDM). These encompass ceramics, tool steel, superalloys, carbides, stainless steel, heat-resistant steel, and more. Widely applied across diverse sectors, including aerospace, nuclear, and die and mold-making industries, these materials pose intricate machining demands and underscore the necessity for advanced EDM techniques and technologies. By addressing the machining complexities of these materials, EDM plays a pivotal role in facilitating innovation and progress across various industrial domains. Furthermore, electric discharge machining (EDM) extends its influence into novel domains, encompassing sports equipment, medical and surgical instruments, optical devices, dental appliances, and jewelry manufacturing. Moreover, it permeates the research and development sector of the automotive industry [2-6]. This broadening scope reflects EDM's adaptability and versatility in addressing diverse machining needs across various industries, driving innovation and advancements in different sectors beyond traditional manufacturing applications. The swift solidification during the erosion process induces substantial internal thermal stress within the upper layers of the workpiece surface, thereby influencing the component properties. The cessation of discharge during erosion fundamentally characterizes a thermal erosion process [7]. This phenomenon underscores the intricate interplay between thermal dynamics and material behavior, highlighting the importance of understanding and managing thermal effects in erosion processes for effective material treatment and component performance enhancement.

Erosion arises from heat generation. Abrupt temperature surges in the machining process profoundly impact the physical attributes of the machined surface layer, leading to residual stress. This pivotal factor significantly influences machined surfaces quality and functional attributes, underscoring its importance in surface engineering and manufacturing practices. Understanding and effectively managing these thermal effects are paramount for achieving desired surface characteristics and optimal component performance [8-10]. A recent advancement in electric discharge machining technology is powder-mixed electric discharge machining (PMEDM). The finely graded powder material is meticulously mixed with the dielectric liquid to enhance its breakdown characteristics. This additional powder component improves the dielectric breakdown characteristics [11]. The study explored the effects of blending an Al and Cr powder mixture with kerosene. Findings indicated that this combination decreased the thermal insulating properties of the kerosene while widening the spark gap. Consequently, this stabilized the machining process and significantly boosted the material removal rate (MRR). Tzeng and Lee delved into the influence of different powder characteristics on the machining of SKD11 materials, which are equivalent to AISI H13 tool steel [12]. Despite promising results, the adoption of powder mix EDM in the industry has been gradual. A key contributing factor is the lack of clarity surrounding various aspects of this emerging technology, including the editing process. To address this gap, researchers employed response surface methodology (RSM) to examine the effects of process variables such as peak powder concentration, tool diameter, and current on the material removal rate (MRR) for EN8 steel [13], [14]. Researchers investigated the influence of fine metal powder grains such as aluminum (Al) and copper (Cu) when introduced into dielectric fluids during the EDM process of AISI D3 and EN31 steels using Taguchi design experiments. Numerous endeavors have aimed to simulate the EDM process and evaluate its effectiveness [15].

This study aimed to analyze the impact of EDM parameters on the induced electrode wear rate when employing copper electrodes, with or without the incorporation of Nano-graphite powder mixed in transformer oil dielectric, for A 240 stainless steel 304. The experimental design matrices for the materials were generated using the Full Factorial Design (FFD) approach. The electrode wear rate was analyzed using ANOVA models, with separate models developed for two sets of trials. The first set utilized transformer oil as the dielectric, while the second set employed nano-graphite particles mixed with the dielectric fluid (PMEDM) at concentrations of 5 and 10 g/l. This approach aimed to enhance machining efficiency, mitigate instability in arcing effects, and analyze the electrode wear rate resulting from process modifications.

Experimental work

As depicted in Figure 1, an experimental investigation was conducted using a CHEMER EDM machine (CM323C). The workpiece employed in the experiment was stainless steel 304, ASTM A 240, measuring (40 x 30 x 1.7 mm) in dimensions.

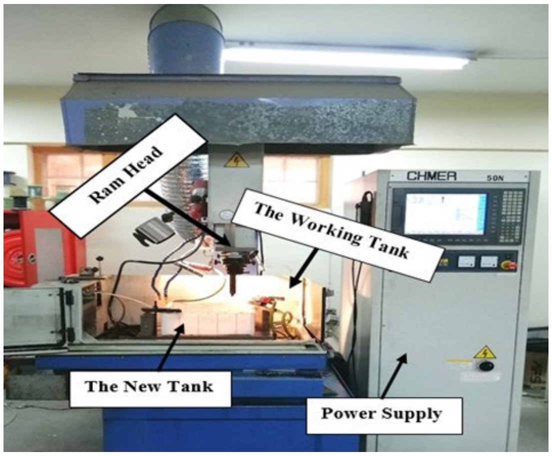

Fig. 1. Model of the EDM machine (CM 323C).

Chemical composition percentages of the 304 stainless steel workpiece materials per the ASTM E415 standard are summarized in Table 1 (tested at the Central Organization for Standardization and Quality Control Center).

***TABLE 1**. Stainless steel 304 Chemical composition of samples.*

Material	C	Si	Mn	P	S	V	Cr	Mo	Ni	Fe
Weight (%)	0.06	0.6	1.1	0	0	0.14	19	0.2	9	Balance

Table 2 outlines numerous mechanical and physical characteristics of the workpiece. The electrode comprises 99.74% pure copper and possesses a diameter of 5 mm. Additionally, the dielectric solution, a form of transformer oil, incorporates a nano-powder mix of graphite .

***TABLE 2**. The mechanical and physical characteristics of the samples*

Ultimate Strength	621 MPa
Density	8030 kg/m^3
Hardness	1667 N/mm^2
Ductility	60 mm/mm
Melting point	2552-2642°F

The experiment occurred in a newly designed tank, which housed a blend of graphite nano-powder and transformer oil. A small pump was integrated into the reservoir to put off powder accumulation at the bottom or the formation of insulating surface deposits. This measure ensured the efficient separation of the internally mixed nano-powder. The viscosity of the transformer oil used in the practical experiments was measured at 28.01 Pa.s at a room temperature of 23°C. A sample of graphite nano-powder was obtained, with particle sizes measuring 80 nanometers. Before and after machining, the weight of the sample and electrode was thoroughly determined using an electronic weighing scale at a precision of 0.0001g. Following NPMEDM machining, the surface roughness of each workpiece was evaluated using a portable surface roughness tester, boasting an accuracy of 0.05 µm. The operational mechanism of nano-powder-mixed EDM is depicted in the following figure.

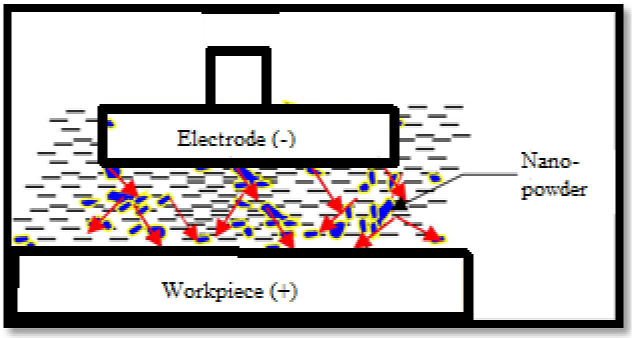

Fig. 2. Mechanism of nano-powder-mixed EDM.

The machining parameters encompassed varying concentrations of nano-powder (graphite), current, pulse-on time, and pulse-off time. Besides, nano-powder graphite concentrations ranged from 0, 5, to 10 g/l, while 10, 20, and 30 amperes discharge currents were employed. Furthermore, pulse-on times were selected at 50, 60, and 70 µs, with a pulse-off time set at 55 µs. Following the manufacturer guidelines, the remaining electric impulse parameters were maintained constant, including an open gap voltage of 140V and a negative tool electrode polarity. The goal is to explore the impact of nano-powder-mixed dielectric on the electrode wear rate (EWR) by varying input machining parameters. Table 3 shows the three parameters used in this study, each with three levels. Furthermore, Table 4 displays the input machining settings that haven't changed.

TABLE 3. *Machining Parameters and their corresponding stages.*

Parameters	Stages		
	1	2	3
Concentration (Nano-Graphite), gram/Liter	0	5	10
Current, Ampre	10	20	30
Pulse-on time, micro-Second	50	60	70

TABLE 4. *unchanged input parameters.*

Workpiece polarity	Positive
Electrode polarity	Negative
Dielectric fluid	Transformer oil with Mixture nano-powder of Gr
High voltage	140 V 1.2 A
Pulse-off time	25 µsec
Working time	5.0 sec
Jumping time	2.0 mm
Depth of cut	1 mm
Gap code	10
Servo feed	75 %

Results and discussion

The impact of process variables like powder concentration, discharge current, and pulse-on time on the response variable, namely the electrode wear rate (EWR), was investigated. Analysis of variance (ANOVA) was conducted using MINITAB 17 software to analyze the experimental data and ascertain the significance of these factors on EWR. The conclusions of the ANOVA analysis for EWR are presented in Table 5. ANOVA was employed to assess the importance of the model. Model terms are considered statistically significant if their "P-Value" is below 0.05, indicating a 95 percent confidence interval [16]. Furthermore, Table 6 presents the model summary, including the coefficients associated with the terms (Coef.), the standard error of each coefficient (SE Coeff), the t-statistic, and the p-value of each term. These values aid in assessing whether to accept or reject an invalid assumption. All of the terms' p-values are below the predetermined threshold, indicating their significance within the model. An R-squared value of 91.15% suggests that the predictors or factors in the model elucidate 91.15% of the total variance in the response. Additionally, the adjusted R-squared value of 88.50% factors in the number of predictors in the model and defines the significance of the association.

TABLE 5. *Analysis of Variance for EWR*

Source	Model	Linear	Nano Powder	Current	Ton	Error	Total
DF	6	6	2	2	2	20	26
Adj SS	15.741	15.741	7.727	3.033	4.981	1.528	17.269
Adj MS	2.62355	2.62355	3.86353	1.51673	2.49039	0.0764	
F-Value	34.34	34.34	50.57	19.85	32.6		
P-Value	0	0	0	0	0		

TABLE 6. *Model summary*

Term	Coeff	SE Coeff	T-Value	P-Value
Constant	2.7952	0.0532	52.55	0.000
Nano Graphite				
0	-0.6612	0.0752	-8.79	0.000
5	0.0121	0.0752	0.16	0.873
Current				
10	-0.3691	0.0752	-4.91	0.000
20	0.0731	0.0752	-0.97	0.343
Ton				
50	-0.5153	0.0752	-6.85	0.000
60	-0.0209	0.0752	-0.28	0.784
S	R-sq	R-sq (adj)	R-sq (pred)	
0.276406	91.15%	88.50%	83.87%	

The significant effects plot of the electrode wear rate (EWR) revealed that an increase in nano-powder concentration correlates with higher EWR. Similarly, elevating both currents (10, 20, and 30 A) and pulse-on times (50, 60, and 70 μs) and maintaining a pulse-off time of 55 μs contributed to this trend. This phenomenon can be attributed to the heightened spark energy between the workpiece and electrode due to increased temperature on the workpiece, resulting in an escalation of the EWR. Moreover, the longest pulse-off time (Toff) corresponds to the highest electrode wear rate (EWR) due to its role in prolonging the re-solidification period within the dielectric medium. This extension results in larger surface grains, leading to a higher EWR. Nano-powder concentration, current, and pulse-on time (Ton) are also observed to influence EWR, as depicted in Figure 3.

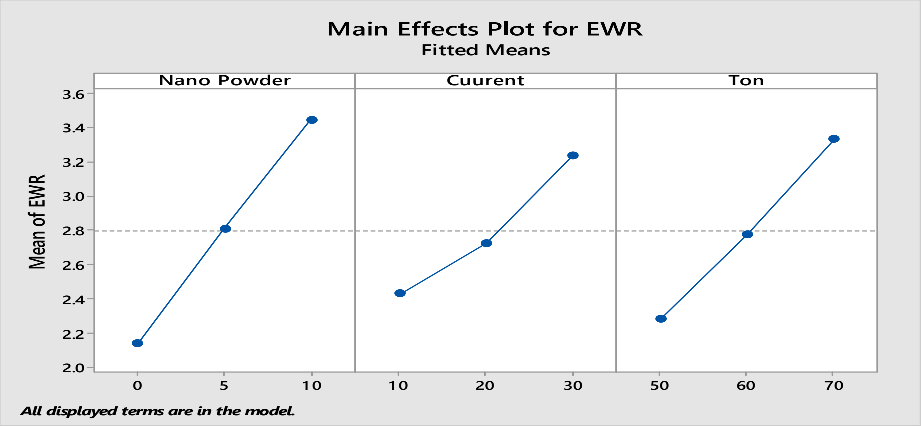

Fig. 3. Impact of Nano-graphite concentration, plus, and current on time on EWR

The nano-powder concentration correlates with the enhanced electrode wear rate (EWR) of the workpiece, along with increasing currents (10, 20, and 30 A) and pulse-on times (50, 60, and 70 µs). The impact of nano-graphite concentration, pulse-on time, and current on EWR is depicted in Figure 4.

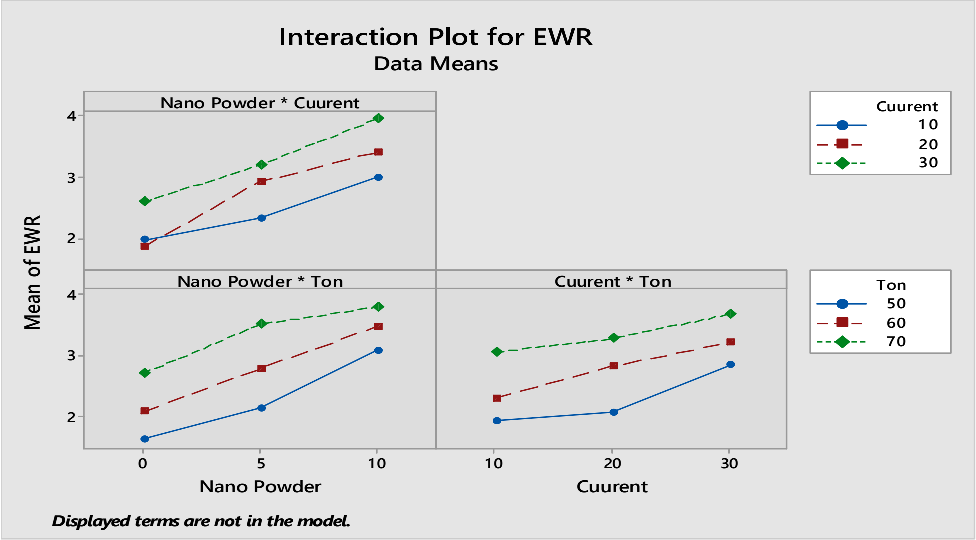

Fig. 4. The effect of Nano-graphite concentration, current, and pulse on time (T_{on}) on EWR.

Conclusions

In addition to exploring the impact of electrical process variables on the electrode wear rate (EWR) for high-speed steel with pure copper electrodes, this investigation highlights critical factors influencing machining efficiency and sustainability. The findings emphasize the significance of nano-powder concentration in transformer oil as a crucial determinant of electrode wear, with higher concentrations correlating with increased wear rates. Notably, the study reveals that the highest EWR occurs at ten g/l concentration, 70 µs at pulse-on time, and 30 Amp, current, emphasizing the sophisticated relationship of process parameters. Moreover, employing a Full Factorial design executed with MINITAB 17 software enhances our understanding of the machining process, facilitating the identification of optimal conditions for minimizing electrode wear. The finding of an optimal EWR value of 1.154 mm^3/min points out the potential for enhancing energy efficiency and sustainability in machining operations. The high coefficient of determination (R-sq) of 91.15% indicates the robustness of the predictive model, offering valuable understanding into future machining industries aimed at reducing wear rates while optimizing resource utilization. As industries strive for eco-friendly manufacturing practices, these findings provide a crucial foundation for developing more sustainable machining techniques that align with environmental and energy efficiency goals.

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