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THE IMPACT OF GENERATOR PARAMETERS ON COATED ELECTRODE WEAR IN THE WEDM PROCESS

V. Simna[1]*
[1]Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava, Centre of Excellence of 5-axis Machining, Ulica Jana Bottu 2781/25, 917 24 Trnava, Slovak Republic
*Corresponding author; e-mail: vladimir.simna@stuba.sk

Abstract
This paper investigates the wear of a coated wire electrode during the WEDM process. The electrode used was a multi-layer coated wire with a copper core and a special GAMA Cu_5Zn_8 alloy coating. The electrode was electrolytically coated. The machined material was a K-grade cemented carbide rod with a diameter of 25 mm. Experiments were conducted on a Charmilles Robofil 310 machine. Electrode wear was evaluated based on the weight loss of a 3-meter wire, measured with 0.001 g resolution. The experiment was designed using the Taguchi methodology and evaluated by ANOVA. Machining stability was monitored using an oscilloscope.
Keywords:
WEDM, electrode wear, Taguchi method, ANOVA, machining stability

1 INTRODUCTION

Wire Electrical Discharge Machining (WEDM) is an advanced non-conventional machining process recognized for its ability to produce components with complex geometries, precise profiles, and sharp edges—features typically difficult to achieve through traditional machining methods [Altuğ 2016, Ho 2004, Goswami 2014, Singh 2018]. Over the past decades, extensive research has focused on optimizing the WEDM process by analyzing the influence of parameters such as pulse-on time, pulse-off time, servo voltage, and peak current on key machining outcomes including material removal rate (MRR), surface integrity, and dimensional accuracy. It is well documented that changes in these parameters can significantly affect efficiency, precision, and the surface quality of machined parts [Altuğ 2016, Goswami 2014, Singh 2018]. Recent developments have introduced adaptive monitoring and control strategies, leading to substantial improvements in process reliability and repeatability, thus meeting modern industrial demands for faster product development and improved cost efficiency [Ho 2004]. A critical factor that directly affects both cost and machining accuracy is wire electrode wear. This phenomenon, often quantified by the wire wear ratio (WWR), represents the rate at which the electrode is consumed relative to material removal. Excessive wear not only increases production costs but can also compromise dimensional precision [Altuğ 2016, Goswami 2014, Singh 2018]. Numerous studies have shown that wear is significantly influenced by operational parameters, particularly pulse-on time and peak current. Higher values of these parameters typically lead to increased electrode erosion and greater surface roughness. This emphasizes the need for careful tuning of discharge characteristics to optimize both tool life and component quality [Singh 2021, Kumar 2022, Stief 2020]. Microstructural investigations of worn wires have revealed the presence of recast layers and microcraters, which are attributed to the extreme thermal loads and spark energy in the discharge zone. Additionally, material migration between the wire and the workpiece has been identified as a significant contributor to chemical and structural changes on the wire surface during machining [Goswami 2014, Singh 2021, Stief 2020]. Despite this progress, electrode wear in WEDM remains a complex and insufficiently understood phenomenon. Further research is needed, particularly in the area of electrode materials, discharge stability, and real-time process control, to improve both productivity and cost-efficiency [Grigoriev 2020, Kumar 2022, Wilson 1990]. Most existing studies, including those by Altuğ [2016], Kumar [2022], and Singh & Misra [2018], have employed uncoated brass wires or diffused brass electrodes with a diameter of 0.25 mm. In contrast, the present work investigates a multilayer-coated GAMA Cu_5Zn_8 wire with a copper core, engineered to enhance thermal and electrical conductivity. Furthermore, this study introduces a novel methodology combining gravimetric analysis with oscilloscope-based discharge monitoring—an approach not previously reported in the literature. The objective of the research is to determine how selected electrical generator parameters influence the wear behavior of the coated wire electrode during rough cutting in WEDM. Given the complex interplay of thermal, electrical, and fluid dynamic phenomena in this process, it is not entirely clear how much mass the electrode loses during machining. Therefore, a well-structured experiment was designed to verify whether this mass loss is both consistent and measurable with sufficient precision.

2 MATERIALS AND METHODS

The machined material in this study was a K-grade cemented carbide (CTS20D, Binder 10%, Density 14,38 g/cm^3) selected for its high hardness and wear resistance. The workpiece was in the form of a cylindrical rod with a diameter of 25 mm. A wire electrode with a diameter of 0.25 mm and a tensile strength of up to 500 N/mm² was used. The electrode featured a pure copper (Cu) core, coated with a multi-layer GAMA Cu_5Zn_8 alloy, engineered to improve discharge efficiency and thermal stability during the WEDM process. The experimental design accounted for six critical process parameters, each varied at three distinct levels: pulse-on time (A), servo voltage (Aj), pulse-off time (B), discharge frequency (FF), short-pulse duration (Tac), and wire speed (Ws). A complete overview of the parameter settings is presented in Tab. 1. Dielectric conductivity was rigorously controlled at a constant level of 5 - 10 µS throughout all trials, ensuring a stable discharge environment and minimizing process variability. Continuous monitoring and real-time adjustments were performed to maintain optimal machining conditions and ensure experimental repeatability and accuracy.

Tab. 1: Parameters used in experiment

Name of the parameter	Symbol	Unit
Pulse width	A	µs
Time between two pulses	B	µs
Frequency	FF	%
Short pulse time	Tac	µs
Servo voltage	Aj	V
Wire speed	Ws	m/min

Tab. 2 displays constant parameters during the experiment and their values.

Tab. 2: Parameters used in experiment

Name of the parameter	Symbol	Unit	Value
Wire tension	Wb	N	1
Voltage	V	V	-80
Injection pressure	Inj	bar	4
Short pulse time	IAL	A	8

Considering six independent control factors, each evaluated at three discrete levels, a full factorial experimental design would require an impractically large number of experimental trials. Such an approach would be both time- and resource-intensive, leading to substantial operational costs. To optimize the experimental process, the Taguchi method was employed as an alternative design strategy. This method, which assumes the independence of input variables, enables a more efficient configuration by utilizing the L27 orthogonal array. The L27 matrix significantly reduces the total number of experiments required while maintaining the ability to evaluate the main effects and selected interactions among the factors. Experimental trials were performed on a ROBOFIL 310 wire EDM machine from Charmilles Technologies, known for its high precision and stability in experimental applications. A detailed overview of the experimental setup based on the L27 array is presented in Table 3. The design was systematically developed in line with the Taguchi methodology to maximize experimental efficiency and measurement accuracy. The orthogonality of the L27 array enhances the statistical validity of the analysis, allowing for a clear interpretation of the influence exerted by each control factor on the observed responses. In experimental setup, special attention was devoted to the clamping of the workpiece, which was a sample made of sintered carbide type K. Experimental setup can be seen in the Fig 1.

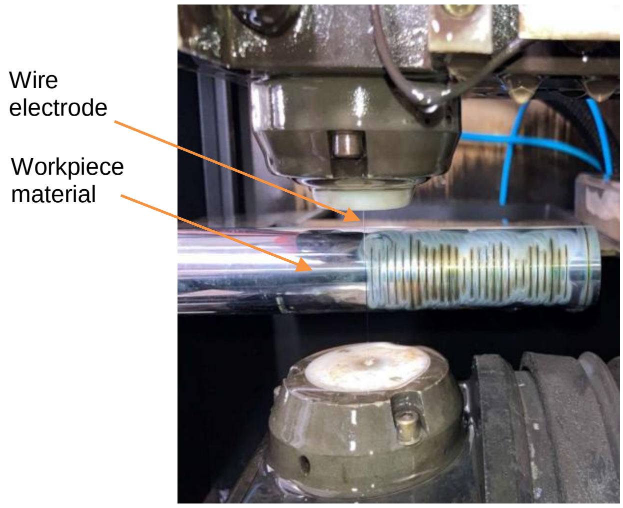

Fig. 1. Experimental setup in screening experiment

The machining process was monitored using an oscilloscope (Keysight EDUX 1002A) (Fig 2.) in order to determine the point at which the process reaches a stable state. The oscilloscope trace captured key electrical characteristics, including the spark signal, the interval between two consecutive pulses, and the ionization time. Among these, the inter-pulse interval is of primary importance for process monitoring, as the process is considered stable when this interval approaches the pre-set reference value. The ionization time can be observed on the waveform before the start of the pulse. The value of this time depends on the condition of the dielectric. If the dielectric is contaminated with material that has been removed from the workpiece, or if it contains other impurities, this time is short, and the discharge will not have sufficient energy. Conversely, if the conditions at the cutting site are favorable i.e., if the dielectric has the lowest possible conductivity the conditions for discharge will be favorable, and the discharge will have the desired energy. Therefore, it is important to monitor the local quality of the dielectric, and measuring the voltage waveform using an oscilloscope appears to be a good method for observing the local quality of the dielectric. As a result, the sample used for the screening experiment exhibits varying depths of wire penetration, reflecting the transitional behavior of the process before achieving stability. The purpose of the screening experiment was to verify that all selected parameter levels are capable of operating within a stable machining window.

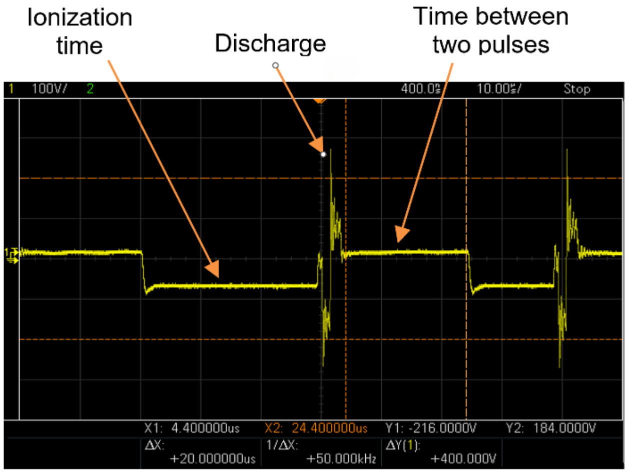

Fig. 2. The oscilloscope trace (the time between two pulses is set to 20 µs in this case, which corresponds to the annotated time segment on the waveform – ΔX = 20µs).

The screening experiment confirmed the appropriateness of the selected process parameter settings. After each machining operation, a precisely 3-meter-long section of the wire electrode was detached, cleaned, and subsequently weighed. A 3-meter length was chosen because the material loss over a 1-meter segment would have been too small to measure accurately. The weighing was performed using a scale with a resolution of 0.001 grams. The measured mass losses are presented in Table 3. Each electrode was weighed three times, and the resulting values were used to calculate the signal-to-noise (S/N) ratio (1), which served as the input for the ANOVA analysis.

$$\mathrm{S/N} = -10\, log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \qquad (1)$$

In this study, the "Smaller is Better" signal-to-noise (S/N) ratio model was employed for the analysis of electrode wear, even though wear is generally regarded as an undesirable phenomenon in conventional machining processes. However, in the context of rough cutting using Wire Electrical Discharge Machining (WEDM), increased electrode wear may indicate a higher energy input into the cutting zone, which is advantageous when the primary objective is to maximize the material removal rate. Given that the focus of the process was exclusively on productivity without consideration of surface integrity or dimensional accuracy it was assumed that greater electrode wear corresponds to higher cutting efficiency.

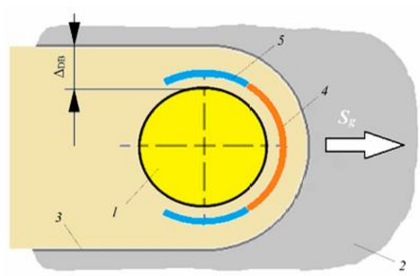

Fig. 3. Electrode wear at roughing, where (1) is a electrode, (2) workpiece, (3) machined surface, (4) front wear, (5) lateral wear [Grigoriev 2020]

All cutting operations were observed to remain stable throughout the experimental runs, confirming that the increased wear did not negatively impact process stability. Accordingly, the application of the "Smaller is Better" criterion enabled the identification of parameter settings associated with the highest S/N ratio, representing the most favorable conditions in terms of energy transfer and material removal performance. In the WEDM process, two types of electrode wear can be observed during rough cutting, depending on their location: frontal wear and lateral wear. During finishing operations, frontal wear does not occur; only lateral wear is present (Fig. 3).

3 RESULTS

The experimental part of this study was evaluated using statistical methods. Initially, the signal-to-noise (S/N) ratio was calculated for all 27 experimental trials, serving as a preliminary indicator of data quality and consistency. Subsequently, an analysis of variance (ANOVA) was conducted to assess whether individual process parameters had a statistically significant effect on wire wear. The ANOVA results enabled the identification of the most influential factors affecting kerf width, thereby providing essential insights for optimizing the cutting process. This statistical evaluation not only validated the experimental design but also established a solid foundation for interpreting the outcomes. Through this comprehensive and methodologically sound approach, the study ensured that the conclusions drawn were both statistically valid and practically relevant. Before applying ANOVA, it is necessary to verify whether the measured values (or their S/N ratios) follow a normal distribution. In this case, the Ryan-Joiner normality test was used (Fig. 4).

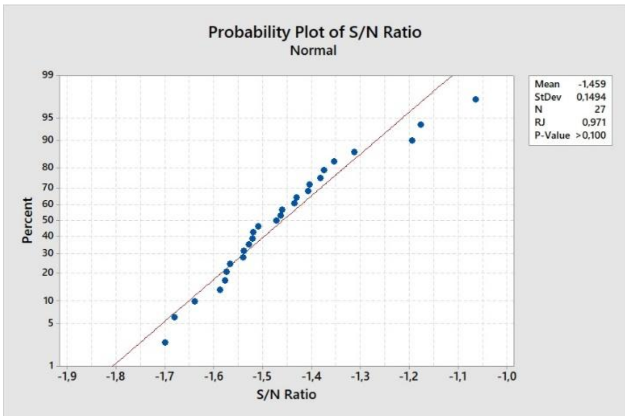

Fig. 4. Normality test for S/N ratio

To verify the assumption of normality, a probability plot of the S/N ratio was constructed. The data points closely follow the reference line, suggesting that the distribution of the values is approximately normal. Furthermore, the Ryan–Joiner (RJ) statistic reached a value of 0.971, which is very close to 1 and indicates a strong fit to a normal distribution. The p-value obtained from the normality test was greater than 0.100, meaning that the null hypothesis of normality cannot be rejected at the commonly used significance levels. These results confirm that the S/N ratio data used in this study can be considered normally distributed, thereby justifying the application of statistical methods that assume normality.

Tab. 3: Experimental setup by Taguchi methodology

The results of the ANOVA indicate that among the six studied factors, pulse-on time (Ws) and frequency (FF) had a statistically significant effect on the S/N ratio, with p-values of 0.001 and 0.004, respectively. Additionally, pulse duration (A) also showed a significant influence with a

p-value of 0.030.

Tab. 4: ANOVA results

Source	*DF*	*Contribution*	*F-value*	*P-value*
A	2	13,17%	4,58	0,03
B	2	0,8%	0,28	0,761
Aj	2	5,93%	2,06	0,164
Ws	2	33,02%	11,48	0,001
TAC	2	2,57%	0,89	0,432
FF	2	24,38%	8,47	0,004
Error	14	20,14%		
Total	26	100%		

These three factors can therefore be considered the most influential in the context of this experiment. In contrast, the factors B, Aj, and TAC showed no statistically significant effect ($p > 0.05$), suggesting a negligible impact on the response variable under the tested conditions. The error term accounted for approximately 20% of the total variation, indicating a reasonably good model fit given the complexity of the process. These findings support the conclusion that optimizing the significant parameters particularly pulse-on time and frequency can lead to improved process performance during rough cutting by WEDM.

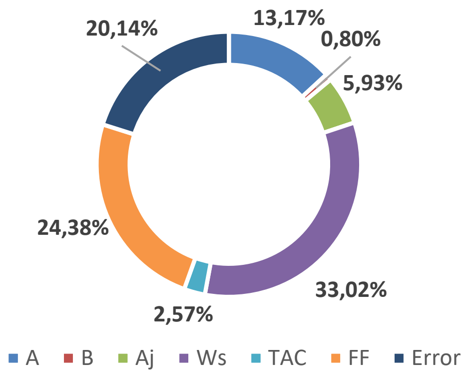

Fig. 5. The proportion of the influence of input parameters on electrode wear

The graph (Fig. 5) clearly shows the percentage influence of the individual input parameters, calculated from the signal-to-noise ratio.

Number of exp.	A	B	Aj	Ws	TAC	FF	Weight 1	Weight 2	Weight 3	AVG value	S/N ratio
1	0,4	16	30	5	0,2	50	1,177	1,178	1,171	1,175	-1,40325
2	0,4	16	30	5	0,3	75	1,201	1,197	1,203	1,200	-1,58606
3	0,4	16	30	5	0,4	100	1,127	1,132	1,132	1,130	-1,06415
4	0,4	20	40	10	0,2	50	1,193	1,198	1,202	1,198	-1,56676
5	0,4	20	40	10	0,3	75	1,197	1,192	1,188	1,192	-1,52800
6	0,4	20	40	10	0,4	100	1,183	1,186	1,181	1,183	-1,46216
7	0,4	24	50	15	0,2	50	1,212	1,218	1,218	1,216	-1,69869
8	0,4	24	50	15	0,3	75	1,214	1,216	1,210	1,213	-1,67962
9	0,4	24	50	15	0,4	100	1,199	1,202	1,195	1,199	-1,57399
10	0,5	16	40	15	0,2	75	1,191	1,196	1,194	1,194	-1,53767
11	0,5	16	40	15	0,3	100	1,187	1,183	1,184	1,185	-1,47193
12	0,5	16	40	15	0,4	50	1,196	1,202	1,199	1,199	-1,57640
13	0,5	20	50	5	0,2	75	1,166	1,168	1,172	1,169	-1,35383
14	0,5	20	50	5	0,3	100	1,168	1,163	1,158	1,163	-1,31165
15	0,5	20	50	5	0,4	50	1,211	1,205	1,207	1,208	-1,63896
16	0,5	24	30	10	0,2	75	1,191	1,187	1,191	1,190	-1,50852
17	0,5	24	30	10	0,3	100	1,182	1,179	1,176	1,179	-1,43029
18	0,5	24	30	10	0,4	50	1,192	1,194	1,196	1,194	-1,54009
19	0,6	16	50	10	0,2	100	1,170	1,173	1,171	1,171	-1,37361
20	0,6	16	50	10	0,3	50	1,194	1,192	1,188	1,191	-1,52068
21	0,6	16	50	10	0,4	75	1,177	1,181	1,181	1,180	-1,43520
22	0,6	20	30	15	0,2	100	1,178	1,177	1,172	1,176	-1,40571
23	0,6	20	30	15	0,3	50	1,193	1,188	1,192	1,191	-1,51825
24	0,6	20	30	15	0,4	75	1,181	1,184	1,184	1,183	-1,45970
25	0,6	24	40	5	0,2	100	1,142	1,147	1,146	1,145	-1,17613
26	0,6	24	40	5	0,3	50	1,173	1,168	1,176	1,172	-1,38106
27	0,6	24	40	5	0,4	75	1,149	1,143	1,150	1,147	-1,19382

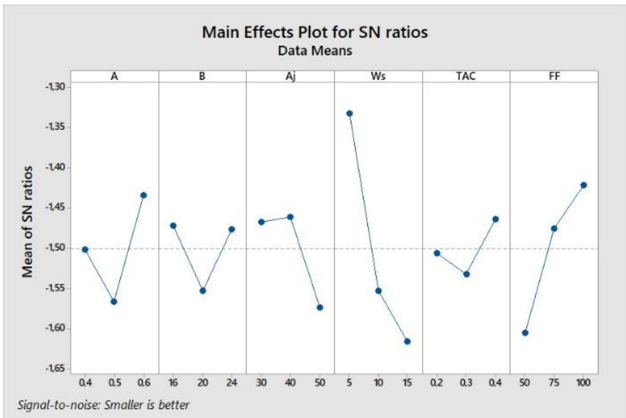

Fig. 6. The Main effects plot for S/N ratio

Fig. 6 presents the main effects plot for the signal-to-noise (S/N) ratio, based on the "Smaller is Better" criterion. This plot offers a visual comparison of the influence of individual factors on the response variable. The steeper the slope of a given factor, the greater its effect on the S/N ratio across its levels.

The results clearly indicate that the factor Ws (wire speed) has the most significant impact, as it shows the largest variation between levels. In contrast, factors B, Aj, and TAC display relatively flat profiles, suggesting a negligible influence on wire wear. Factors A and FF exhibit a moderate effect. This plot also facilitates the identification of optimal factor levels those associated with the lowest mean S/N ratio are considered preferable under the "Smaller is Better" assumption.

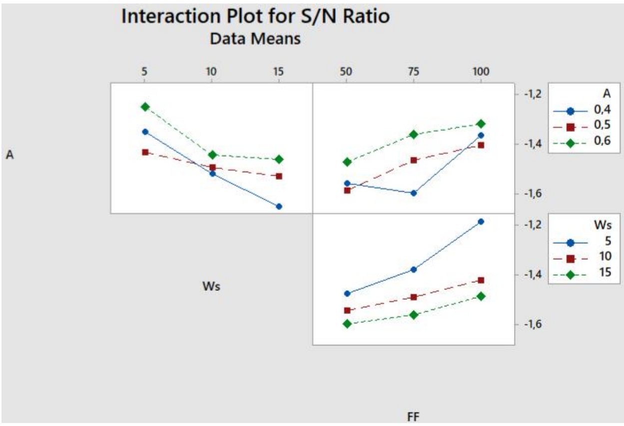

Fig. 7. Interaction plot for S/N Ratio

Fig. 7 presents the interaction plot for the three statistically significant factors A, Ws, and FF as determined by the ANOVA. The purpose of this plot is to evaluate whether the effect of one factor depends on the level of another, which is indicated by non-parallel or intersecting lines. In the A vs. Ws plot, a moderate interaction is observed particularly for A = 0.4, where the S/N ratio decreases sharply with increasing Ws. For the other levels of factor A, the differences are less pronounced but still noticeable. The A vs. FF plot also reveals a weak but present interaction, as the lines do not run entirely parallel. The most notable interaction appears between Ws and FF, where the slopes differ significantly, and the lines diverge at higher levels of FF. This suggests that the effect of Ws on the response is not consistent across FF levels.

These findings emphasize the importance of considering not only the main effects of individual factors but also their combined influence when optimizing the process.

Fig.8. Microscopic image of a new electrode (mag 215,1x).

Fig. 8 shows a new coated electrode. The electrode featured a pure copper (Cu) core, coated with a multi-layer GAMA Cu_5Zn_8 alloy. The electrode was electrolytically coated. The electrode was examined under a microscope after each experimental trial. Three images were captured at different locations along the electrode. This approach was chosen to document the largest possible portion of the electrode and to capture both frontal and lateral wear. Due to the rough cutting operation, both frontal and lateral wear were present on every electrode. An example of lateral wear is shown in Fig. 8.

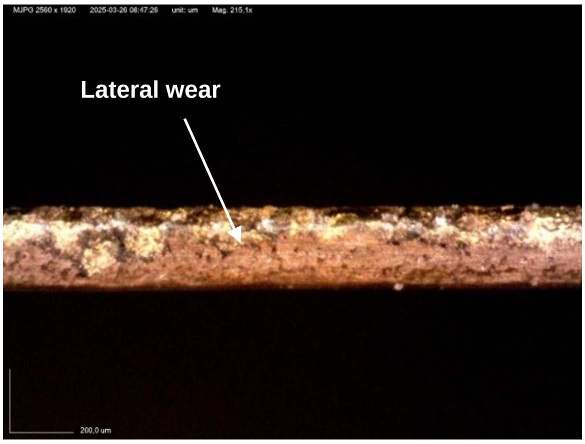

Fig. 9. Microscopic image of a wear electrode (mag 215,1x).

Frontal wear can be observed in Fig. 9.

Fig. 10. Microscopic image of an electrode exhibiting predominant frontal wear (mag 215,1x).

This image was taken from experiment 25, where the one of the highest electrode wear was recorded based on the gravimetric method (i.e., the greatest loss in electrode mass).

4 SUMMARY

This study comprehensively examined the influence of selected generator parameters on the wear behavior of a coated wire electrode during rough cutting operations in the Wire Electrical Discharge Machining (WEDM) process. A structured experimental approach based on the Taguchi method with an L27 orthogonal array was utilized to efficiently evaluate six key process parameters. The analysis, which employed signal-to-noise (S/N) ratios in conjunction with ANOVA, enabled the identification of the most statistically significant factors contributing to electrode wear.

The entire process was monitored using an oscilloscope, which provides valuable insights into the cutting operation. The most important parameters displayed by the oscilloscope are the pulse duration (B) and the ionization time. Monitoring parameter B is essential for identifying the point at which the process becomes stable, specifically when B reaches its target value. At the start of cutting, this duration is typically set to a relatively high value, and as the process stabilizes, the control system gradually reduces it to the desired level.

Ionization time, on the other hand, cannot be directly set, as it depends on the local condition of the dielectric fluid. When flushing is effective, the ionization time is generally longer. Conversely, if flushing is insufficient, or if evaporated particles cannot be efficiently removed from the cutting zone due to complex geometries (e.g., angular cutting) or increased workpiece height conductive particles (such as metallic debris from the workpiece or worn wire) accumulate in the dielectric.

These particles shorten the ionization time, since the environment between the electrode and the workpiece becomes partially conductive. As a result, discharges occur more quickly but in a less controlled manner the spark may be initiated prematurely, before the electric field has fully developed and stabilized. In other words, short ionization time indicates that the electric field between the wire and the workpiece does not have sufficient time to stabilize, leading to unreliable spark generation. Conversely, a longer ionization time typically indicates more stable discharge conditions, allowing for improved control over the cutting process.

Among the six investigated parameters, wire speed (Ws), discharge frequency (FF), and pulse-on time (A) exhibited the strongest influence on electrode wear, with statistically significant *p*-values and notable contributions to response variability. In contrast, pulse-off time (B), servo voltage (Aj), and short pulse duration (TAC) did not show statistically relevant effects under the tested conditions, suggesting their limited role in influencing electrode degradation during roughing operations.

The main effects plot clearly highlighted wire speed as the dominant factor, characterized by the steepest change in S/N ratio across its levels. Furthermore, interaction plots revealed important interactions most notably between wire speed and discharge frequency underlining the need to consider the interplay of multiple parameters rather than evaluating them in isolation during process optimization.

In addition to statistical evaluation, microscopic inspection of the wire electrodes after each trial confirmed the presence of both frontal and lateral wear, which are typical in high-energy roughing regimes. These wear patterns were consistent with measured mass loss, thus validating the gravimetric method as a reliable approach for quantifying electrode wear in WEDM.

The findings suggest that careful optimization of electrical parameters, especially wire speed and pulse-on time, can lead to more efficient energy transfer into the cutting zone, resulting in improved material removal rates while maintaining process stability. This contributes to a deeper understanding of the wire wear mechanisms in WEDM and provides a foundation for the development of more robust and productive machining strategies, particularly in applications involving coated wire electrodes and hard-to-machine materials.

Future research will focus on further isolating the effects of electrical discharge parameters by maintaining a constant wire feed rate throughout the experimental trials. This adjustment will allow for a more precise evaluation of the influence of pulse characteristics and voltage settings on electrode wear and overall process performance.

While the Taguchi methodology proved effective for screening key parameters with limited experimental runs, it is important to acknowledge its limitations. The L27 orthogonal array captures only main effects under the assumption of factor independence. More complex, non-linear interactions especially common in high-energy cutting processes like WEDM may remain undetected. Incorporating data-driven modeling approaches such as artificial neural networks (ANN) or support vector machines (SVM) in future work could help capture hidden dependencies and enhance predictive power. When compared with prior studies utilizing uncoated brass or diffused wires [Altuğ 2016, Kumar 2022, Singh 2018], the observed wear values for the multilayer-coated GAMA Cu_5Zn_8 electrode suggest improved thermal resilience and wear resistance, particularly under stable discharge conditions. For instance, Tosun and Cogun [Tosun 2003] demonstrated that increasing discharge current and open-circuit voltage significantly intensifies wire wear in WEDM; however, their work focused on uncoated CuZn37 electrodes without consideration of discharge stability or wear localization. In contrast, the present study introduces oscilloscope-based diagnostics and a coated wire with enhanced thermal properties, which may explain the improved wear behavior despite comparable cutting conditions. Future research should focus on industrial-scale trials using actual part geometries and cutting conditions. Additionally, integrating adaptive control systems—based on real-time feedback from oscilloscope monitoring—could enable dynamic adjustment of parameters, further enhancing machining efficiency and electrode longevity.

5 ACKNOWLEDGMENTS

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