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Optimization of Overcut in EDM of Mirrax Steel Using Copper Alloyed Electrodes

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ABSTRACT

In this study, the optimization of overcut in electrical discharge machining (EDM) processes, with a focus on the effects of various process parameters on machining performance, particularly when challenging materials such as Mirrax steel are investigated. A Taguchi-based experimental design was employed to systematically analyze three distinct copper-based alloy electrodes; CuCoNiBe, $CuNi_2SiCr$, and $CuCr_1Zr$ under varying discharge currents (6 A, 12 A, 25 A), pulse on-times (50 µs, 100 µs, 200 µs), and pulse off-times (200 µs, 400 µs, 800 µs). It was found that overcut is significantly influenced by the electrode type, discharge current, and pulse duration, with the CuCoNiBe electrode exhibiting the highest overcut values. Analysis of Variance (ANOVA) was conducted to confirm the significant contributions of these parameters to overcut variability. This research contributes to a deeper understanding of the interplay between EDM parameters, in advanced manufacturing applications.

Bakır Alaşımlı Elektrotlar Kullanılarak Mirrax Çeliğinin EEİ'sinde Yanal Açıklık Optimizasyonu

MAKALE BİLGİSİ

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ÖZET

Bu çalışma, Mirrax çeliği gibi işlenmesi zor malzemelerin, işleme parametrelerinin işlebilirlik performansı üzerindeki etkilerine odaklanılarak, Elektrik Erozyon ile İşleme (EEİ) süreçlerinde yanal açıklık optimizasyonu araştırılmıştır. Üç farklı bakır alaşımı elektrotun (CuCoNiBe, $CuNi_2SiCr$ ve $CuCr_1Zr$) değişen boşalım akımları (6 A, 12 A, 25 A), vurum süreleri süreleri (50 µs, 100 µs, 200 µs) ve bekleme süreleri (200 µs, 400 µs, 800 µs) altında sistematik olarak analiz etmek için Taguchi tabanlı bir deneysel tasarım kullanılmıştır. Yanal açıklığın elektrot tipi, boşalım akımı ve vurum süresinden önemli ölçüde etkilendiği ve CuCoNiBe elektrotun en yüksek yanal açıklık değerlerini gösterdiği bulunmuştur. Bu parametrelerin yanal açıklık üzerindeki etkilerini belirlemek için Varyans Analizi (ANOVA) kullanılmıştır. Bu çalışma, gelişmiş imalat uygulamalarında EDM parametreleri arasındaki etkileşimin daha iyi anlaşılmasına katkı sağlamaktadır.

1. INTRODUCTION (GİRİŞ)

One essential non-conventional machining method for creating intricate and exact geometries in hard, electrically conductive materials is still EDM. It is widely used in sectors including aerospace, automotive, and medical devices, where traditional machining frequently finds it impossible to treat materials that are challenging to mill or to achieve the necessary precision [1,2]. Controlled electrical discharges are produced by EDM between an electrode and a workpiece that is immersed in a dielectric fluid. Material gets melted and vaporized as a result, and the dielectric fluid then removes it [3-5]. Although there are significant drawbacks to EDM, most notably overcut, or the removal of material that is larger than required. Overcut has a direct impact on the final machined part's performance, surface polish, and dimensional correctness [6-8].

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Overcut is influenced by several process parameters, including the discharge current, pulse duration (on-time), pulse off-time, and electrode material [9,10]. The amount of energy applied during each spark is mostly determined by the discharge current; higher currents result in bigger material removal rates but also raise the risk of overcut. The length of each discharge is determined by pulse on-time, which also affects the size of the heat-affected zone (HAZ) via influencing heat transmission to the workpiece. Longer off-times can result in more stable machining conditions, but at the expense of decreased productivity. Pulse off-time, on the other hand, affects the cooling between discharges. Because different materials have varied levels of wear resistance, thermal conductivity, and erosion behavior, electrode material also has a big impact on overcut [10-14].

Arun Kumar et al. explored the application of the MFAPM-EDM process on Aluminum 6061 alloy, with a specific focus on overcut. They varied several process parameters, including discharge current, powder concentration, pulse duration, and magnetic field strength, employing a Box-Behnken design approach for analysis. Their findings indicated that a semi-empirical model offered improved accuracy in predicting overcut [15]. Similarly, Anshuman Das et al. investigated how various process variables, such as current, gap, voltage, pulse on time, and pulse off time, influenced overcut. Their experimental design utilized the Response Surface Methodology (RSM) with a Box-Behnken layout. The results revealed that both current and pulse on duration had a significant impact on overcut, while pulse off duration and gap also played roles in its minimization [16]. In another study, S. Rajamanickam and J. Prasanna examined the EDM of Ti-6Al-4V using a brass tube electrode, applying multi-objective optimization to assess material removal rate, tool wear rate, and overcut. Their experiments were designed using RSM-CCD and the "Technique for Order of Preference by Similarity to Ideal Solution" method, yielding results of 3.6996 mm^3/sec for material removal rate, 0.0625 mm/sec for tool wear rate, and 0.33 mm for overcut [17]. Reza Teimouri and Hamid Baseri investigated the effects of a rotational electrode and a rotating magnetic field on electrode wear rate (EWR) and overcut. Their results showed that while the electrode wear rate increased with discharge energy, pyrolytic carbon helped to reduce EWR in high-energy regimes. They noted that increasing both the electrode and magnetic field speeds heightened the electrode wear rate by efficiently removing debris from the machining gaps, which otherwise restricted pyrolytic carbon formation. As the energy regime shifted from low to high, overcut tended to increase due to larger discharge craters, while elevated electrode and magnetic field speeds trapped debris, leading to higher overcut. The application of the magnetic field generated a Lorentz force that exacerbated lead overcut [18]. Munmun Bhaumik and Kalipada Maity examined how cryotreated double tempered electrodes affected radial overcut (ROC) during the electro-discharge machining of AISI 304. They evaluated process performance using ROC parameters alongside tungsten carbide electrodes and performed regression analysis to correlate responses with process parameters. Their microstructural analysis revealed that conventional EDM produced the least radial overcut compared to powder-mixed EDM, and that cryotreated double tempered electrodes significantly reduced ROC in comparison to untreated electrodes [19]. Zhao et. al. conducted experiments on electro-discharge machining, analyzing parameters like peak current and pulse duration. An empirical formula for overcut was established using the least square method, demonstrating reasonable agreement between calculated results and further experimental results [20].

The optimization of overcut in EDM is essential for enhancing machining accuracy and overall performance, especially when working with difficult-to-machine materials like Mirrax steel. Various optimization techniques have emerged as effective tools for systematically analyzing and improving EDM processes. Among these, the Taguchi method is widely recognized for its ability to minimize overcut while ensuring robust performance across different machining conditions [21]. By employing orthogonal arrays, the Taguchi method allows for the simultaneous evaluation of multiple process parameters such as discharge current, pulse on-time, and pulse off-time while minimizing the number of experimental trials needed [22-24]. This statistical approach focuses on maximizing the signal-to-noise (S/N) ratio, thereby emphasizing consistent performance under varying operational conditions. Complementing the Taguchi method, ANOVA) serves to identify the significance of individual factors and their interactions on overcut, providing insights into how adjustments to machining parameters can lead to enhanced precision [25,26].

Three copper-based alloy electrodes; CuCoNiBe, $CuNi_2SiCr$, and $CuCr_1Zr$ are used in this investigation. Each was selected based on unique electrical and thermal conductivity characteristics that affect determining if it performs in EDM. In order to investigate the impact of discharge currents on overcut, tests are conducted with currents of 6 A, 12 A, and 25 A. Generally speaking, greater currents increase the pace of material removal but also increase the risk of overcut because of overheated material. The impact of spark duration on the workpiece is analyzed using pulse on durations of 50 µs, 100 µs, and 200 µs, while the cooling period between discharges is studied using pulse-off times of 200 µs, 400 µs, and 800 µs. The purpose of this set of parameters is to determine the ideal circumstances for reducing overcut in EDM.

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

The "FURKAN EDM M25 A" type electro-erosion machine from Karabük University Technology Faculty's Manufacturing Engineering Laboratory was utilized in the experiments. Electroerosion is one of the classic machine tools. It is commonly used for treating workpieces with complex geometry. It is a vital machine, particularly in the mold-making industry. The electro-erosion machine can process all electrically conductive materials. Figure 1 shows the electro-erosion machine used for the experimental experiments.

Figure 1. Electro erosion machine (FURKAN EDM M25 A) (Elektro erozyon tezgahı (FURKAN EDM M25 A)

CuCoNiBe, $CuNi_2SiCr$ and $CuCr_1Zr$ copper alloy electrodes were employed. The electrode dimensions employed in the experiment were Ø15x10 mm. Figure 2 depicts electrode samples, with mechanical and physical parameters reported in Tables 1.

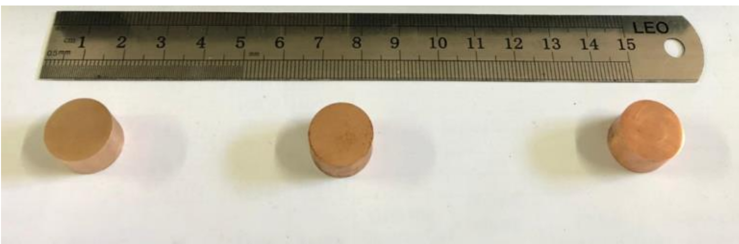

Figure 2. Electrodes (from right to left; $CuNi_2SiCr$, CuCoNiBe, $CuCr_1Zr$) (Elektrotlar (sağdan sola; $CuNi_2SiCr$, CuCoNiBe, $CuCr_1Zr$))

Table 1. Mechanical and physical properties of electrodes (Elektrotların mekanik ve fiziksel özellikleri)

	Unit	CuCoNiBe	$CuNi_2SiCr$	$CuCr_1Zr$
Hardness	HB	230-260	190-230	135-170
Tensile Strength	N/mm²	700-900	600-800	400-500
Yield Strength	N/mm²	600-700	500-600	320-410
Elastic Modulus (20°C)	GPa	130	140	122
Electrical Conductivity	MS/mm	25-30	22-27	45
Thermal Expansion Coefficient (273-573 K)	10^{-6}/K	17	17	17
Thermal Conductivity (20°C)	W/m·K	200-230	190-230	320
Density	g/cm³	8.75	8.8	8.9

In the EDM experiments, Mirrax plastic mold steel was utilized as the workpiece material. The dimensions of the workpiece were 30x25x20 mm. The chemical composition of the workpiece is presented in Table 2. EDM operates in an insulating environment, achieved through the use of dielectric fluids that possess no electrical conductivity. During the EDM process, the dielectric fluid plays a critical role by establishing a plasma channel at a certain point, facilitating the discharge of sparks between the workpiece and the electrode. Additionally, it assists in removing the eroded material from the machining area, acts as a coolant, and prevents oxidation on the workpiece surface. In this study, kerosene was used as the dielectric fluid, and it was applied using the lateral spray method during the experiments. The overcut values of machined workpieces were measured using the BestScope BS-3020T stereo microscope instrument.

Table 2. Chemical composition of the workpiece (İş parçasının kimyasal bileşimi)

Element	C	Cr	V	Si	Mo	Mn	Ni
% Weight	0.25	13.3	0.35	0.35	0.35	0.55	1.35

The experiments were designed according to Taguchi's L_{27} orthogonal array methodology, utilizing three distinct process parameters. These parameters included discharge current (I), pulse on time (T_{on}), and pulse off time (T_{off}). The workpiece processing time was maintained as a constant duration of 30 minutes across all experimental conditions. Discharge currents of 6 A, 12 A, and 25 A were employed, while arc durations of 50 µs, 100 µs, and 200 µs were selected. Pulse off times of 200 µs, 400 µs, and 800 µs were also utilized. The factors and levels applied in the experiments are detailed in Table 3.

Table 3. Parameters and levels (Parametreler ve seviyeler)

Factors	Level	1	2	3
Electrode	A	CuCoNiBe	$CuNi_2SiCr$	$CuCr_1Zr$
***I* (A)**	B	6	12	25
T_{on} (µs)	C	50	100	200
T_{off} (µs)	D	200	400	800

3. EXPERIMENT AND OPTIMIZATION RESULTS (DENEY VE OPTİMİZASYON SONUÇLARI)

Table 4 presents the experimental results and highlights the significant influence of various input parameters electrode type, I, T_{on}, and T_{off} on the overcut achieved during the electroerosion machining process. The electrode type plays a crucial role, with the CuCoNiBe electrode exhibiting the widest range of overcut values, reaching a maximum of 905 µm. This suggests that while this electrode can effectively remove material, it may also lead to higher levels of overcut under certain conditions. In contrast, the $CuNi_2SiCr$ and $CuCr_1Zr$ electrodes demonstrate relatively moderate overcut values, indicating that these materials may offer better control and precision when used in the electroerosion process, particularly at lower discharge currents and shorter pulse durations.

I, T_{on}, and T_{off} are critical parameters that further shape the overcut outcomes, as detailed in Table 4. Higher discharge currents, specifically at 25 A, consistently correlate with increased overcut values, indicating that excessive energy input can lead to significant thermal effects, thereby expanding the machining zone. Additionally, longer T_{on} and T_{off} exacerbate the overcut, as observed in trials with maximum values of 800 µs for T_{on}. These findings underscore the importance of optimizing these parameters to minimize overcut while ensuring effective material removal. By carefully balancing these input factors, it is possible to enhance machining precision and achieve more desirable results in electroerosion applications.

Table 4. Experimental results

Sq.	Variables	Electrode	I (A)	T_{on} (µs)	T_{off} (µs)	Overcut (µm)
1	$A_1B_1C_1D_1$	CuCoNiBe	6	50	200	203
2	$A_1B_1C_2D_2$			100	400	266
3	$A_1B_1C_3D_3$			200	800	250
4	$A_1B_2C_1D_2$		12	50	400	284
5	$A_1B_2C_2D_3$			100	800	345
6	$A_1B_2C_3D_1$			200	200	204
7	$A_1B_3C_1D_3$		25	50	800	350
8	$A_1B_3C_2D_1$			100	200	200
9	$A_1B_3C_3D_2$			200	400	905
10	$A_2B_1C_1D_1$	$CuNi_2SiCr$	6	50	200	293
11	$A_2B_1C_2D_2$			100	400	270
12	$A_2B_1C_3D_3$			200	800	325
13	$A_2B_2C_1D_2$		12	50	400	210
14	$A_2B_2C_2D_3$			100	800	400
15	$A_2B_2C_3D_1$			200	200	598
16	$A_2B_3C_1D_3$		25	50	800	455
17	$A_2B_3C_2D_1$			100	200	525
18	$A_2B_3C_3D_2$			200	400	603
19	$A_3B_1C_1D_1$	$CuCr_1Zr$	6	50	200	340
20	$A_3B_1C_2D_2$			100	400	338
21	$A_3B_1C_3D_3$			200	800	358
22	$A_3B_2C_1D_2$		12	50	400	427
23	$A_3B_2C_2D_3$			100	800	351
24	$A_3B_2C_3D_1$			200	200	533
25	$A_3B_3C_1D_3$		25	50	800	392
26	$A_3B_3C_2D_1$			100	200	612
27	$A_3B_3C_3D_2$			200	400	590

Figure 3 provides a comprehensive overview of the overcut measurement results derived from a systematic experimental sequence involving three different electrode materials: CuCoNiBe, $CuNi_2SiCr$, and $CuCr_1Zr$. In Figure 3.a) ($A_1B_1C_1D_1$), using the CuCoNiBe electrode with a discharge current of 6 A, a pulse on time of 50 µs, and a pulse off time of 200 µs, the overcut is recorded at 203 µm, establishing a baseline for comparison. Subsequent configurations, such as in Figure 3.b) ($A_2B_1C_3D_3$), which retains the same electrode and current but varies the pulse parameters, demonstrate changes in overcut, with the measurement recorded at 325 µm when the pulse on time is increased to 200 µs and the pulse off time to 800 µs. In Figure 3.c) ($A_3B_1C_1D_1$), the results for the $CuCr_1Zr$ electrode at 6 A and 50 µs pulse on time yield an overcut of 340 µm, indicating a significant influence of material properties on machining outcomes. Finally, in Figure

3.d) ($A_3B_3C_3D_2$) highlights the $CuCr_1Zr$ electrode with a discharge current of 25 A and longer pulse durations, resulting in a notable overcut of 590 μm.

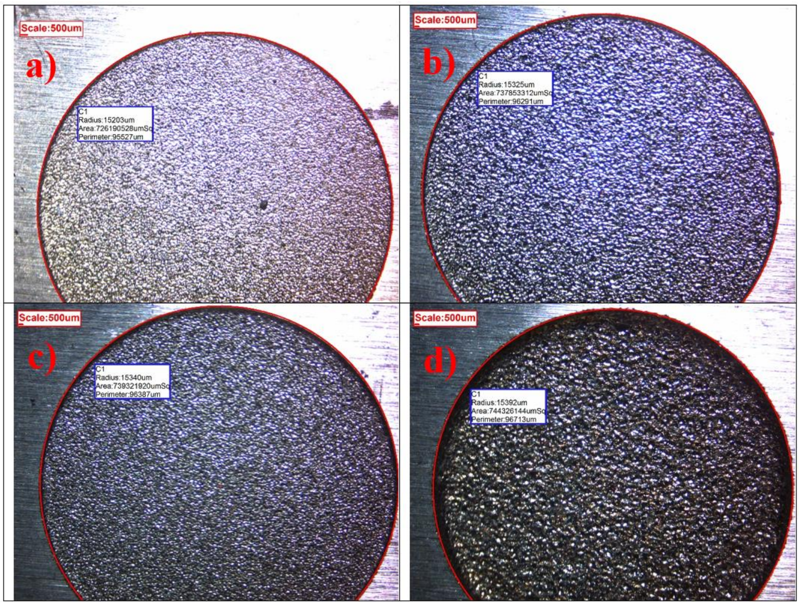

Figure 3. Overcut measurement results a) $A_1B_1C_1D_1$ b) $A_2B_1C_3D_3$ c) $A_3B_1C_1D_1$ d) $A_3B_3C_1D_3$

The graphs in Figure 4 were developed using the experimental results obtained from Table 4. Surface graphs provide for a more detailed evaluation of the parameters' influence on the overcut. Figure 4a demonstrates a clear trend of increasing overcut with higher discharge current, particularly at lower pulse on times. This is attributed to the fact that elevated current levels lead to greater material removal, resulting in a larger overcut. The graph underscores the importance of optimizing both discharge current and pulse on time to achieve a balanced trade-off between material removal and overcut. This finding highlights the inherent complexity of the electro erosion process and the necessity for precise parameter selection [27-29].

Figure 4b depicts the relationship between overcut, I, and T_{off} in EDM processes. It shows a significant increase in overcut as the discharge current increases, with higher currents (up to 25 A) leading to a larger overcut. This is consistent with the greater energy per discharge at higher current levels, which enhances material removal. Additionally, pulse-off time exerts a nonlinear influence on overcut. While moderate overcut values are observed at lower T_{off} values (200 μs), the overcut peaks at approximately 800 μs, suggesting that a longer T_{off} allows for improved cooling and debris removal. Beyond this point, the effect of T_{off} on overcut diminishes, indicating diminishing returns. Overall, the graph highlights the intricate relationship between discharge current and pulse off time, both of which are critical to controlling overcut in EDM applications [30,31].

Figure 4c illustrates the interaction between overcut, pulse on time T_{on}, and T_{off} in EDM processes. The graph shows that as T_{on} increases from 50 μs to around 200 μs, the overcut rises, reaching its peak within this range, indicating that longer pulse durations enable more material removal. However, further increases in T_{on} beyond this range result in diminishing returns, as the overcut begins to plateau. Similarly, increasing T_{off} from 200 μs to approximately 800 μs leads to a peak in overcut, as longer off times promote improved debris clearance and cooling. The nonlinear relationship observed for both T_{on} and T_{off} indicates that careful optimization of these parameters is essential for maximizing efficiency in EDM machining [32-34].

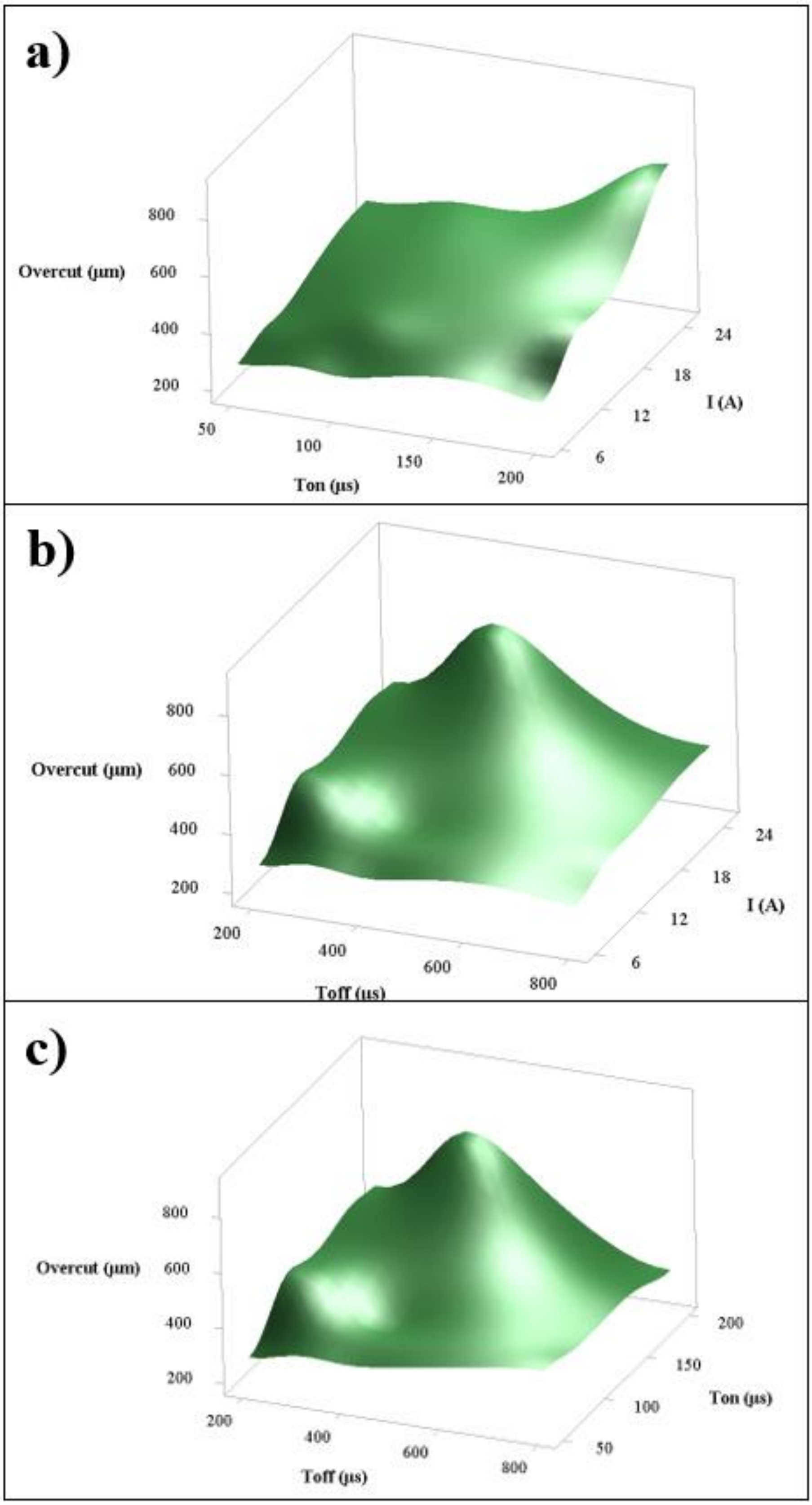

Figure 4. Effect of parameters on overcut (Parametrelerin yanal açıklık üzerindeki etkileri)

The smaller-the-better criterion is utilized to calculate the Signal-to-Noise (S/N) ratios, which allows for the assessment of the impact of each factor, including electrode type, discharge current, pulse on time, and pulse off time. The average S/N ratios are computed for each factor level, enabling the identification of optimal conditions that minimize overcut. Subsequently, ANOVA is performed to determine the significance of each parameter's contribution to the variation in overcut, providing insights into their interactions [35,36]. The overall results emphasize the effectiveness of the Taguchi method in enhancing process efficiency and achieving desirable outcomes in machining operations.

In Figure 5, the main effects plot for the S/N ratios illustrates the relationships among the machining parameters and their impact on overcut within the EDM process, employing the smaller-is-better criterion. The plot indicates a downward trend in the mean S/N ratios as both I and T_{on} increase, suggesting that elevated levels of these parameters contribute to a greater overcut, which is unfavorable in this context. Additionally, the type of electrode demonstrates a negative correlation with the S/N ratios, implying that different electrodes influence overcut variably, with CuCoNiBe electrode exhibiting superior performance in minimizing overcut compared to the other electrodes. Moreover, the T_{off} reveals a slight increase in mean S/N ratios at elevated values, suggesting that extended off times may be advantageous for reducing overcut.

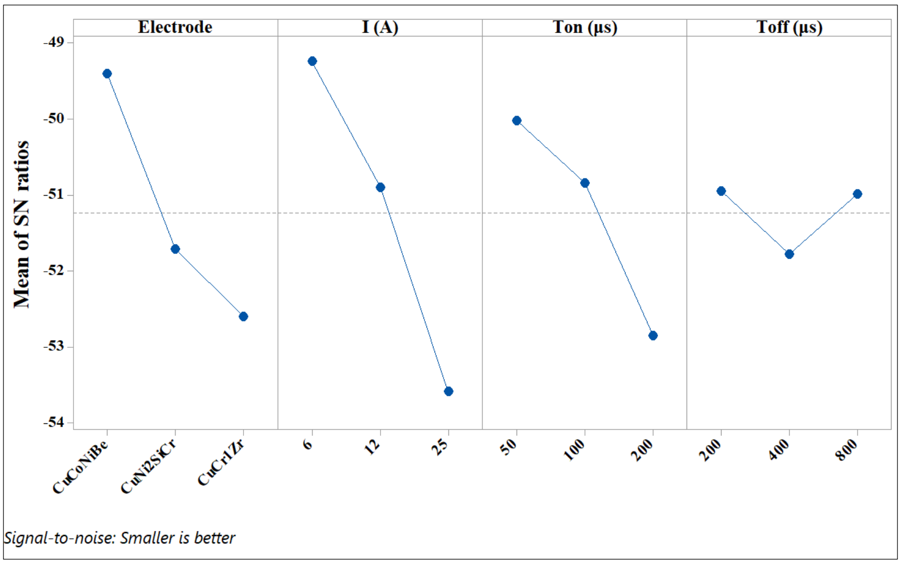

Figure 5. S/N ratios (S/N oranları)

In Table 5, the response table for S/N ratios provides a comprehensive overview of the influence of various machining parameters on overcut in the EDM process, utilizing the "smaller is better" criterion. Each parameter, electrode type, I, T_{on}, and T_{off} is evaluated at three different levels. The optimum machining levels for minimizing overcut in the EDM process, as defined by the response table for S/N ratios, are as follows: For electrode type, Level 1 is preferred due to its highest mean S/N ratio of -49.41, indicating superior performance in reducing overcut. In terms of discharge current, Level 1 (6 A) is identified as optimal, with a mean S/N ratio of -49.23, signifying that lower current levels are more effective. Similarly, for pulse on time, Level 1 (50 µs) is recommended, achieving a mean S/N ratio of -50.02, which suggests that shorter pulse durations contribute to reduced overcut. Lastly, Level 1 (200 µs) is the optimal setting for pulse off time, with a mean S/N ratio of -50.95, indicating that shorter off times may enhance performance in minimizing overcut. Thus, the ideal machining parameters for this study consist of electrode type level 1, discharge current level 1 (6 A), pulse on time level 1 (50 µs), and pulse off time level 1 (200 µs).

Table 5. Response table for signal to noise ratios (Sinyal-gürültü oranlarına ilişkin yanıt tablosu)

Level	Electrode	I (A)	T_{on} (µs)	T_{off} (µs)
1	-49.41	-49.23	-50.02	-50.95
2	-51.71	-50.90	-50.84	-51.78
3	-52.59	-53.58	-52.85	-50.99
Delta	3.19	4.35	2.84	0.83
Rank	2	1	3	4

The ANOVA results in Table 6 indicate that the *I* have a statistically significant effect on the transformed response (overcut), with a P-value of 0.009, which is well below the significance threshold of 0.05 [37]. This suggests that variations in current significantly influence the overcut. The electrode type shows a marginally significant effect, with a P-value of 0.051, suggesting it may have some influence on overcut, though not at a strong confidence level. The T_{on} has a P-value of 0.089, indicating a moderate influence that is not statistically significant at the 0.05 level. The pulse off time T_{off}, however, has a P-value of 0.757, meaning it does not significantly affect the overcut. The error term captures the unexplained variation, and the total sum of squares indicates the total variability in the response. Overall, the current is the most significant factor affecting the overcut in this study.

Table 6. ANOVA results (ANOVA sonuçları)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Electrode	**2**	0.64643	0.32321	3.52	0.051
***I* (A)**	**2**	114.795	0.57397	6.25	0.009
T_{on} (µs)	**2**	0.50876	0.25438	2,77	0.089
T_{off} (µs)	**2**	0.05195	0.02598	0.28	0.757
Error	**18**	165.192	0.09177		
Total	**26**	400.701			

4. CONCLUSIONS (SONUÇLAR)

In this study has systematically investigated the influence of various input parameters; electrode type, discharge current, pulse on time, and pulse off time on overcut in EDM applications using the Taguchi L_{27} orthogonal array approach. The ANOVA results highlight that discharge current is the most significant factor affecting overcut, with a strong statistical correlation evidenced by a P-value of 0.009. Additionally, while the electrode type exhibited a marginally significant influence on overcut (P-value of 0.051), the effects of pulse on time and pulse off time were found to be moderate and negligible, respectively. The experimental results indicate that the CuCoNiBe electrode provides a wide range of overcut values, underscoring its effectiveness in material removal but also its potential for greater overcut under specific conditions. Conversely, the $CuNi_2SiCr$ and $CuCr_1Zr$ electrodes demonstrate more stable performance, suggesting they may be preferable for applications demanding higher precision. This study emphasizes the necessity of optimizing discharge current, along with careful selection of electrode materials and machining parameters, to enhance precision and efficiency in EDM processes. Overall, the findings provide valuable insights for future research and practical applications, indicating that adopting an optimal set of parameters can significantly reduce overcut and improve machining outcomes in electroerosion applications.

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