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Investigation of Workpiece and Tool Surface Quality in Electro Discharge Machining of Al 5083 Alloy Produced by Powder Metallurgy

Ahmet Tolunay IŞIK[1], Ramazan ÇAKIROĞLU[2*]

[1] *Karabük Üniversitesi, Lisansüstü Eğitim Enstitüsü, Karabük, Türkiye*
[2] *Gazi Üniversitesi, Teknik Bilimler MYO, Ankara, Türkiye*

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ABSTRACT

Aluminum alloys are widely preferred in various fields such as aerospace, ship and automotive due to their lightness and relevant production cost. In this study, electro discharge technique was used in the processing of aluminum 5083 alloy (Al5083) produced by powder metallurgy method. The surface quality resulting from the experiments was investigated in terms of Ra, Rz and Rsm. Experimental studies were carried out according to Taguchi L9 orthogonal experimental design, using three different levels of discharge current, pulse on time and pulse off time parameters. As the discharge current increased, Ra and Rz increased, Rsm first decreased and then increased. As the pulse on time increased, Ra and Rz first increased and then decreased, and Rsm increased. When the pulse off time increased, Ra and Rz decreased and Rsm increased. As a result of the analysis of variance (ANOVA) performed to determine the effect rates of the variable parameters on the surface quality, the order of importance of the parameters was found to be discharge current, pulse off time and pulse on time. The effect of discharge current, which is the most effective parameter according to ANOVA, on Ra, Rz and Rsm was calculated as respectively 70.87%, 70.41% and 36.34%. Microscopic images taken from the tool (copper) and workpiece surface show that the craters and peaks formed by the spark effect are formed on both material surfaces.

Toz Metalürjisi ile Üretilmiş Al 5083 Alaşımının Elektro Erozyon ile İşlenmesinde İş Parçası ve Takım Yüzey Yapısının İncelenmesi

MAKALE BİLGİSİ

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ÖZET

Alüminyum alaşımları hafifliği ve uygun üretim maliyetiyle havacılık, gemi ve otomotiv gibi çeşitli alanlarda yaygın olarak tercih edilmektedir. Bu çalışmada toz metalurji yöntemi ile üretilen alüminyum 5083 alaşımının (Al5083) işlenmesinde elektro erozyon tekniği kullanılmıştır. Yapılan deneyler sonucu oluşan yüzey kalitesi Ra, Rz ve Rsm cinsinden incelenmiştir. Deneysel çalışmalar, üç farklı seviyede boşalım akımı, vurum süresi ve vurum aralığı parametreleri kullanılarak Taguchi L9 ortogonal deney tasarımına göre yapılmıştır. Boşalım akımı arttıkça Ra ve Rz artmış, Rsm önce azalmış sonra artmıştır. Vurum süresi arttıkça Ra ve Rz önce artmış sonra azalmış, Rsm ise artmıştır. Vurum aralığı arttığında ise Ra ve Rz azalırken, Rsm değerleri artmıştır. İşleme parametrelerinin yüzey kalitesi üzerindeki etki oranlarının belirlenmesi amacı ile yapılan varyans analizi (ANOVA) sonucu parametrelerin önem sırası boşalım akımı, vurum aralığı ve vurum süresi şeklinde bulunmuştur. ANOVA'ya göre en etkili parametre olan boşalım akımının Ra, Rz ve Rsm'ye etkisi sırasıyla %70.87, %70.41 ve %36.34 olarak hesaplanmıştır. Takım (bakır) ve iş parçası yüzeyinden alınan mikroskopik görüntüler kıvılcım etkisi ile oluşan krater ve tepelerin her iki malzeme yüzeyinde de oluştuğunu göstermektedir.

1. INTRODUCTION (GİRİŞ)

Aluminium alloys are a common type of material used in various fields with high corrosion resistance, high fatigue strength, high thermal and electrical conductivity [1,2]. Aluminium alloys, which can be produced at low cost using the powder metallurgy method, are frequently preferred in

**** Corresponding author, e-mail:*** *rcakiroglu@gazi.edu.tr*
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many industries instead of traditional metal materials due to their lightness [3]. However, due to the high ductility and thermal conductivity of the aluminium alloy, burrs occur on the machined surface by conventional methods and wear due to cutting tool adhesion during machining [4]. Electro discharge machining (EDM) technology which is one of the advanced manufacturing methods, is widely used to produce complex shapes without the need for a second finishing process between the conductors, regardless of the hardness of the material [5,6]. Using this technique, aluminium alloy can be easily machined without tool wear when the variable parameters are adjusted appropriately. The tool used in EDM is low cost as it can be selected from easily formable conductive materials [7,8].

EDM technique realise the machining process with the effect of high discharge current and short-term electric sparks in a controlled time interval between two electrically conductive metals. During the machining process, the workpiece and tool material melts or evaporates a little with the effect of the high temperature occurring in the machining area. The insulating liquid used as a dielectric is used both for cooling and to remove the molten materials called debris formed during processing in the processing area [9].

The selection and use of process parameters in EDM technique with a complex processing mechanism is mostly determined by experience [10]. Thus, the manufacturing process will be carried out efficiently and quickly when the processing parameters are optimized. In research into this area, discharge current (Ip), pulse on time (Ton), pulse off time (Toff), reference voltage and dielectric pressure are indicated as the most effective variable parameters on important performance results such as material removal rate (MRR), tool wear rate (TWR) and average surface roughness (Ra) [11,12]. The white layer, craters and peaks that appear on the machined surface after EDM are surface damages during thermal machining [13,14]. Studies on the evaluation of performance results in the machining of aluminium alloys by electro discharge (EDM) can be listed as follows.

Kalyon, investigated the effects of discharge current (6-25 A), pulse on time (50-200 μs) and pulse off time (50-200 μs) parameters on the material removal rate, tool wear rate and average surface roughness results in electro discharge machining of aluminium 6082 alloy. In the Taguchi optimization for the best average roughness value, the author stated that optimum conditions were created at the lowest parameter values (6A,50μs,200μs), so that the washing effect of the dielectric was sufficient and the machining speed could be decrease by shortening the pulse interval [15]. Safiei et al. examined the effects of discharge current (12, 36 A), pulse on time (20, 180 μs), pulse off time (10, 80 μs), reference voltage (40, 60 V) and jump speed (5, 20 mm/sn) parameters on Ra and MRR in machining aluminium 5083 alloy with EDM. The authors stated that with the increase of the pulse on time, which is the most effective parameter, cause a worse surface roughness with the irregular spark rate will increase [16]. Ali et al. investigated the effects of copper, copper-tungsten, graphite and brass tools on the MRR, TWR and Ra in the parameters range of discharge current (2-30 A), pulse on time (100-400 μs), pulse off time (1-9 μs) and reference voltage (21-30 V) during EDM of aluminium LM6 alloy. The authors mentioned that the thermal conductivity and melting point of the tool material affect the performance results [17]. Kakkar et al. examined discharge current (7,9,11 A), reference voltage (30,40,50 V) and pulse on time (50,100,150 μs) variable parameters on the MRR, TWR and Ra in machining Al-SiC metal matrix composite with EDM. The authors reported that MRR increased, TWR and Ra adversely affected with increasing discharge current, pulse on time and reference voltage [18]. Sadagopan and Mouliprasanth investigated the effects of biodiesel, transformer oil and kerosene dielectrics on the TWR and Ra results in the parameters range of discharge current, pulse on time, pulse off time during EDM of aluminium 6063 alloy. The authors reported that dielectrics with low viscosity (4-6 cst) and high flash point (100-170 °C) had better shown MRR, TWR, and Ra [19]. In addition, Guu and Hou studied the effects of discharge current (0.5, 1, 1.5 A) and pulse on time (3.2, 4.8, 6.4 μs) parameters on the machined surface quality (Ra≈0.3-0.075 μm) in machining Fe-Mn-Al alloy with EDM. The negative effects of the discharge energy increases with discharge current and pulse on time, on the surface quality, such as the formation of deep craters, large micro-hole and damage area [20]. Çakıroğlu and Günay used for fatigue prediction of Rz, Rsm and Vickers hardness results which are affected by discharge current (3-12 A), pulse on time (3-8 µs) and pulse off time (5-7 µs) parameters in the turning of AISI L2 cold work tool steel with EDM. The authors reported that Rz and Rsm increased with discharge current and pulse on time, while Rz decreased at the highest value of pulse on time. Also, the authors in these study suggested obtaining low Rz and high Rsm results in order to improve the fatigue life in their study [21].

In the literature, it has been observed that studies mostly focused on the evaluation of the average surface roughness (Ra) in the machining of aluminium alloys with the EDM method. However, it is important to examine other roughness criteria as the Ra value is not fully sufficient to control the functionality of parts manufactured by machining. In this study, electro discharge machining experiments were carried out on Al5083 alloy produced by powder metallurgy method at different variable parameters. The quality of the machined surfaces was evaluated in terms of roughness criteria average surface roughness (Ra) which gives a general description of height changes, average surface roughness depth (Rz) which gives information about rarely high peaks and deep valleys that cannot be detected in the Ra parameter and average peak width (Rsm) which gives general information about the width of the hills and valleys that cannot be detected in height parameters such as Ra and Rz.

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

2.1. Experimental Setup (Deney Düzeneği)

The main purpose of this study is to determine the effects of variable parameters on surface roughness values (Ra, Rz and Rsm) in the processing of pure Al5083 alloy produced by powder metallurgy method with EDM. In the experimental study, Furkan brand "K1 Z-NC EDM" die-sinking type electro erosion bench located in Gazi University Technical Sciences Vocational School campus was used. The electro erosion bench and the images taken during the experiment and the test equipment are given in Figure 1.

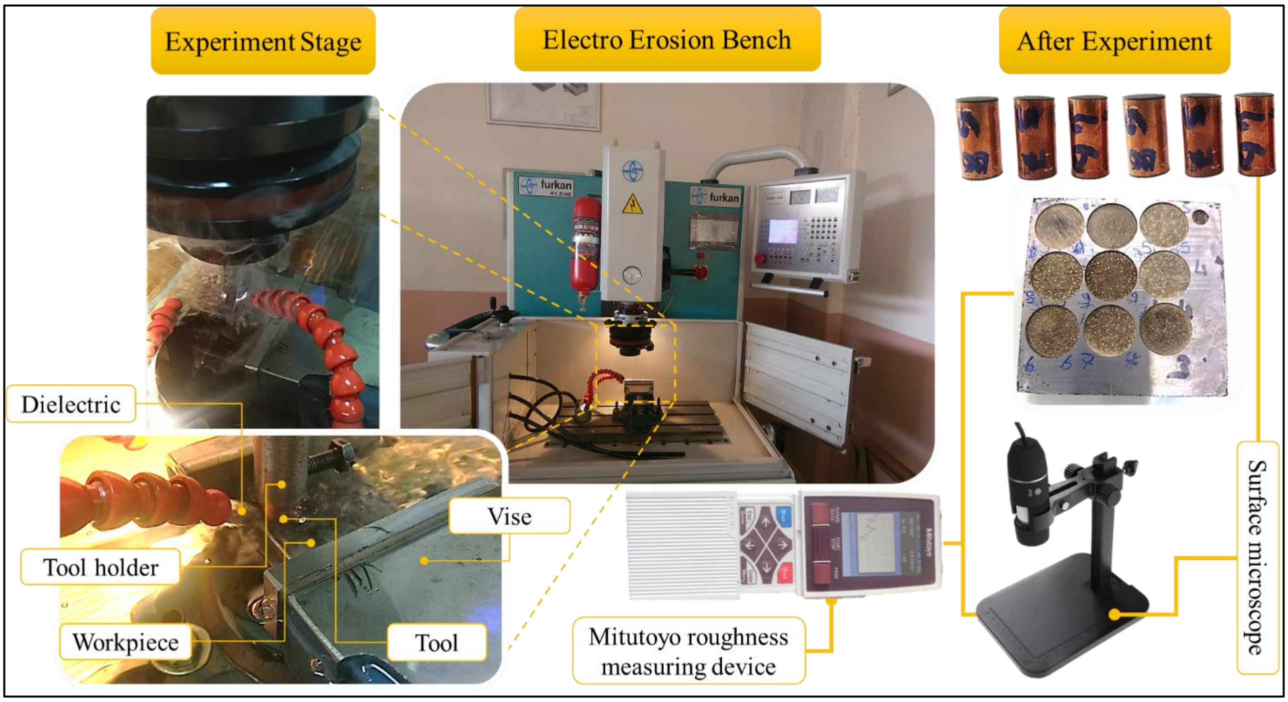

Figure 1. Die-sinking type Z-NC EDM and experimental equipment (Dalma tipi Z-NC elektro erozyon tezgahı ve deneysel ekipmanlar)

2.2. Workpiece, Tool and Dielectric Properties (İşparçası, Takım ve Dielektrik Özellikleri)

Aluminum alloy Al5083 with 10 mm thickness and 60x60 mm dimensions was used as the workpiece material. Al5083 material was produced using powder metallurgy method. In the production method, ground aluminium alloy powders with an average diameter of 45 µm were compressed in a 30x30 mm hot work tool steel powder metal mold at 700 MPa pressure at 500 °C.

The chemical composition of the workpiece material Al5083 is given in Table 1 and its technical characteristics are given in Table 2. Al5083 alloy has properties suitable for use in the aerospace and automotive industries.

Table 1. Chemical composition of Al 5083 alloy (Al5083 alaşımının kimyasal kompozisyonu)

Elements	*Si*	*Fe*	*Cu*	*Mn*	*Mg*	*Zn*	*Ti*	*Cr*	*Other*	*Al*
wt. [%]	0.4	0.4	0.1	0.4-1.0	4.0-4.9	0.25	0.15	0.05-0.25	max. 0.15	92.4-95.6

Table 2. Technical characteristics of Al 5083 alloy (Al5083 alaşımının teknik özellikleri)

Properties	**Value (Max.-Min.)**
Yield Strength (MPa)	125-145
Tensile Strength (MPa)	275-350
Elongation (%)	22
Hardness (Vickers)	87
Density (g/cm^3)	2.66
Electrical Resistance (Ω.cm)	0.00000598
Melting Temperature (°C)	590.6-638
Thermal Conductivity (W/mK)	117
Specific Heat (J/g°C)	0.900

Electrolytic copper material with a diameter of 15 mm and a length of 30 mm was used as the tool (electrode) material. The tool electrode was cut with the help of a wire saw, and the burrs formed after the process were cleaned by sanding. The advantage of copper material in EDM is stated as high electrical conductivity and carbon sequestration ability. During EDM, carbon-based dielectric ionizes and carbon atoms deposition on the tool (anode) material and form a protective layer against wear. The technical characteristics of the tool material are given in Table 3.

Table 3. Technical characteristics of electrolytic copper material (Elektrolitik bakır malzemenin teknik özellikleri)

Properties	**Value (Max.-Min.)**
Hardness (Vickers)	90
Density (g/cm^3)	8.89
Electrical Resistance (Ω.cm)	0.00000172
Melting Temperature (°C)	1083
Thermal Conductivity (W/mK)	391.05
Specific Heat (J/g°C)	3.894

Colorless, odorless, high flash point (102 °C), high corrosion resistance, high chip carrying ability and low viscosity (1,910 mm^2/s) standard EDM fluid was used as a dielectric which is used for cleaning the debris from the machining area and as a coolant. During the experiment, the dielectric was sent to the processing zone continuously in the form of lateral washing with a pressure of 30 kPa.

2.3. Experiment Design and Selection of Parameters (Deney Tasarımı ve Parametrelerin Seçimi)

Determination of variable parameters for determining performance results is an important step in experimental design. When the literature is examined, it is seen that there are many variables that affect the performance of the EDM. Discharge current, pulse on time and pulse off time which are used as the most common and most effective were used as variable parameters in the experiments. As a result of the preliminary experiments carried out to minimize tool wear, the pulse on time parameters at the highest discharge current were determined. The experimental design was created according to the Taguchi L_9 orthogonal array, and at three different levels of three different variable parameters. Variable and fixed parameters are given in Table 4.

Table 4. Variable and fixed machining conditions (Değişken ve sabit işleme koşulları)

Parameters	**Levels**			**Unit**
	1	**2**	**3**	
Variable Parameters				
Discharge current (Ip)	6	9	15	A
Pulse on time (Ton)	75	150	300	µs
Pulse off time (Toff)	50	100	150	µs
Fixed Parameters				
Dielectric pressure	30			kPa
Open circuit voltage	130			V
Reference voltage (gap)	60			V
Discharge time	1			sec
Back off	1,2			mm
Machining depth	1			mm
Power supply (DC)	250-233			V

2.4. Determination of Performance Results and Statistical Analysis of Results (Performans Sonuçlarının Belirlenmesi ve İstatistiksel Analizi)

After the manufacturing stage in the industry, the surface quality and roughness of the final product is an important criterion in terms of quality control. In this study,

- Average surface roughness (Ra), the arithmetic mean of the absolute value of deviations from the mean line (Z(x)) along the sample length (lr) (Equation 1).

$$Ra = \frac{1}{lr}\int_0^{lr}|Z(x)|\,dx \tag{1}$$

- Average surface roughness depth (Rz), the sum of the highest peak and the deepest valley in a sample length is defined as Rz_i. Rz is obtained by averaging the Rz_i values calculated along the evaluation length (Equation 2).

$$Rz = \frac{1}{n}\sum_{i=1}^{n} Rz_i \tag{2}$$

- Average peak width (Rsm), average of Xs values calculated over the evaluation length. Xs, the width of the highest and deepest points that intersect the mean line on the x-axis defined within the sample length (Equation 3) [22].

$$Rsm = \frac{1}{n}\sum_{i=1}^{n} Xs_i \tag{3}$$

were determined as performance results in terms of contribution to the literature and industry. Mitutoyo brand Surftest SJ-210 model roughness device was used to measure the surface roughness values. Measurements were taken from three different places of each test sample and the average was calculated. The surface roughness device was used at λc:0.8 nm and λs:2.5 µm measurement conditions. In addition, images were taken with a digital camera to evaluate the surface topography of the powder metallurgy samples and the tool (electrode) after processing.

Statistical analysis was carried out by analysing the mean values of the variable parameters and the effect plots of the signal to noise ratios. In the Taguchi method, a method of approach is used to calculate the deviation between the experimental results and the optimum value. In order to minimize the Ra and Rz results from the surface roughness results, the "small is better" approach (Equation 4) was used in the Taguchi methodology. In order to maximize the Rsm result, due to its effect on fatigue the "large is better" approach was used in the Taguchi methodology (Equation 5), thus the signal-to-noise (S/N) ratios of the result data were determined. ANOVA (analysis of variance) was used to calculate the contribution rates and percentages of variable parameters to the performance results [23].

<u>Small is better:</u>

$$\text{Signal to noise ratio}, \eta = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{4}$$

Large is better:

$$\text{Signal to noise ratio}, \eta = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n} 1/y_i^2\right) \quad (5)$$

3. EXPERIMENT RESULTS AND DISCUSSION (DENEY SONUÇLARI VE TARTIŞMA)

In this study, the effect of variable parameters on the surface roughness of aluminium 5083 alloy by EDM was investigated. The roughness results and signal/noise ratios obtained as a result of the experiments are given in Table 5.

Table 5. Experiment results and S/N ratios (Deney sonuçları ve S/G oranları)

Exp. No	Ip [A]	Ton [µm]	Toff [µs]	Ra [µm]	S/N ratio (Ra)	Rz [µm]	S/N ratio (Rz)	Rsm [µm]	S/N ratio (Rsm)
1.	6	75	50	10.980	-20.8120	63.575	-36.0657	488.575	53.7786
2.	6	150	100	9.309	-19.3781	60.683	-35.6613	367.967	51.3162
3.	6	300	150	6.546	-16.3195	44.252	-32.9186	411.833	52.2944
4.	9	75	100	11.421	-21.1541	65.190	-36.2837	328.167	50.3219
5.	9	150	150	11.870	-21.4890	67.397	-36.5728	323.000	50.1841
6.	9	300	50	13.717	-22.7452	82.485	-38.3274	396.450	51.9638
7.	15	75	150	12.619	-22.0205	76.038	-37.6206	350.600	50.8962
8.	15	150	50	18.205	-25.2038	108.708	-40.7252	462.725	53.3065
9.	15	300	100	17.128	-24.6741	101.266	-40.1092	544.700	54.7231

The effects of variable parameters on Ra, Rz and Rsm can be seen in the graphs created in Minitab 19 program using Equation 4 and Equation 5 (Figure 2-4). The highest value of the calculated signal/noise ratio shows the most effective experiment or the most effective variable parameter values for surface roughness. When the main effect graphs are examined, according to the "small is better" approach, the best Ra 6 A Ip, 300 µs Ton and 150 µs Toff processing condition, the best Rz 6 A Ip, 75 µs Ton and 150 µs Toff processing condition; According to the "large is better" approach, the best Rsm can be obtained at 15 A Ip, 300 µs Ton and 50 µs Toff machining condition.

In Figure 2, it is seen that Ra improves with decreasing discharge current, increasing pulse on time and pulse off time. The negative effect of the discharge current on the average surface roughness is known [24–26]. Pulse on time as expands the diameter of the plasma channel during machining as also increases the surface roughness by increasing the discharge energy. High discharge energy causes more melting and evaporation of the workpiece material [27]. With increasing plasma channel diameter and greater melt density, the cleaned material in the pulse off time often creates peaks at less elevation. This can be seen as a reducing factor in the average surface roughness.

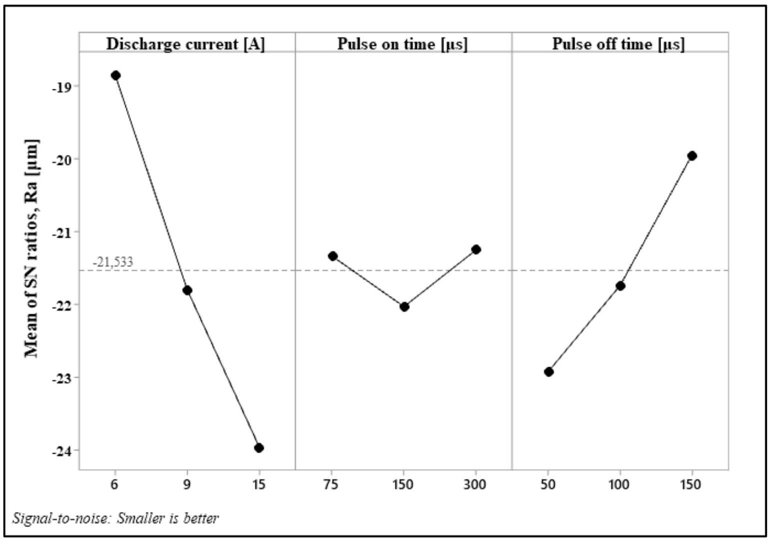

Figure 2. S/N ratio plot for average surface roughness (Ra) (Ortalama yüzey pürüzlülüğü (Ra) için S/N oranları grafiği)

In Figure 3, it is seen that Rz improves with decreasing discharge current and pulse on time and increasing pulse off time. The effect of the discharge current on Rz should be greater than for other roughness results. The discharge current is the most effective variable on the depth of surface roughness due to the increase in the intensity of the spark [28]. In contrast to the average surface roughness in the figure, a lower Rz result was obtained at the lower value of the pulse on time. In addition, an increase in Rz is observed at high pulse on time compared to 150 µs level. The Rz result is a performance result calculated by averaging the highest peaks. The density of low-level peaks does not affect this result.

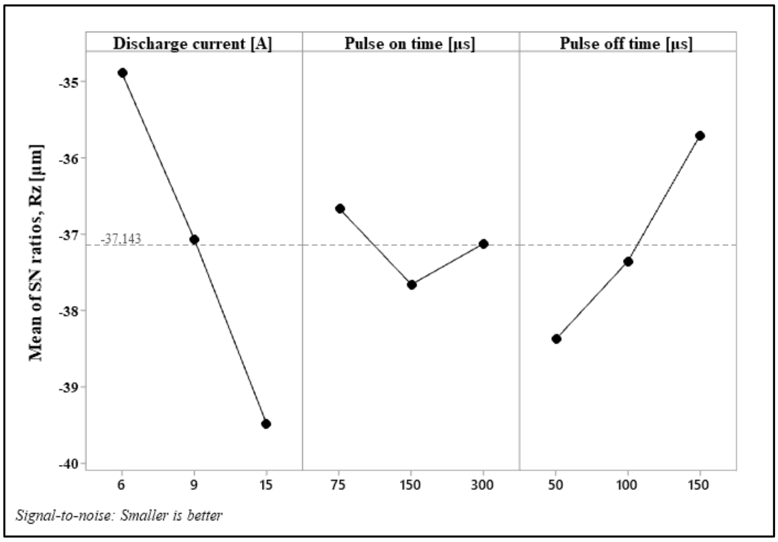

Figure 3. S/N ratio plot for average surface roughness depth (Rz) (Ortalama yüzey pürüzlülüğü yüksekliği (Rz) için S/N oranları grafiği)

In Figure 4, it is seen that Rsm increases with decreasing pulse off time and increasing pulse on time. Rsm obtained in the experimental study is calculated as the mean width of the highest peaks and troughs [21]. It cleans the debris from the dielectric processing zone in the pulse off time. The increased pulse off time takes out more of the recast melt during cleaning. This situation creates new peaks and craters and has a reducing effect on Rsm. However, in the literature, it is mentioned that the surface roughness worsens as a result of poor cleaning of the spillage when the pulse off time is not sufficient [29]. The low discharge current in the experimental study reduces the discharge energy and erodes less surface, thus increasing the average width of craters and peaks. The increased discharge energy with high discharge current increases the amount of molten material and causes the formation of larger craters, thus increasing the Rsm.

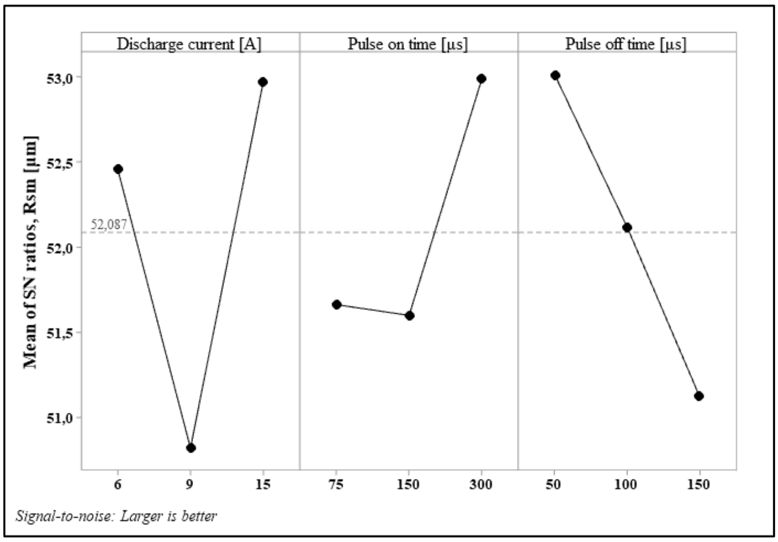

Figure 4. S/N ratio plot for average peak width (Rsm) (Ortalama tepe genişliği (Rsm) için S/N oranları grafiği)

Analysis of variance was used to determine statistically significant variable parameters and their contribution to surface roughness. ANOVA results for surface roughness of variable parameters are presented in Table 6. In the table is given as P effect of the processing conditions ($P \leq 0.05$ as boundary condition), DF degrees of freedom, SS sum of squares and MS mean of squares [30]. The F-value indicates a value in the confidence interval for the contribution of the processing conditions to the model for the result to be modelled for prediction. At larger F value, it can be interpreted that the machining condition causes a large change on the performance result.

In the analysis of the F-value in Table 6, the most important parameter affecting Ra, Rz and Rsm is the discharge current. In the P-value analysis, it is seen that Ip has a significant effect for Ra and Rz, while other variable parameters have no significant effect on the result data (Ra, Rz, Rsm).

Table 6. ANOVA results for surface roughness (Yüzey pürüzlülüğü için ANOVA sonuçları)

Source	DF	SS	MS	F-Value	P-Value	PCR (%)
			Ra			
Ip	2	74.354	37.177	19.95	0.048	70.87
Ton	2	3.182	1.591	0.85	0.539	3.03
Toff	2	23.647	11.823	6.35	0.136	22.54
Error	2	3.726	1.863			3.55
Total	8	104.91				100.00
			Rz			
Ip	2	2334.11	1167.06	56.86	0.017	70.41
Ton	2	182.04	91.02	4.43	0.184	5.49
Toff	2	757.73	378.86	18.46	0.051	22.86
Error	2	41.05	20.53			1.24
Total	8	3314.93				100.00
			Rsm			
Ip	2	17014	8507	1.71	0.369	36.34
Ton	2	8263	4131	0.83	0.546	17.65
Toff	2	11599	5799	1.17	0.462	24.78
Error	2	9942	4971			21.24
Total	8	46817				100.00

The ratio (%) contribution of the variable parameters (PCR) on Ra, Rz and Rsm is shown graphically in Figure 5 as a result of the analysis of variance. When the graphs are examined, Ip 70.87%, Ton 3.03% and Toff 22.54% has effect on Ra, Ip 70.41%, Ton 5.49%, Toff 22.86% has effect on Rz, Ip 36.34%, Ton 17.65%, Toff 24.78% has effect on Rsm. The mean effect on the experimental study was determined as 59.21% for Ip, 8.72% for Ton and 23.39% for Toff.

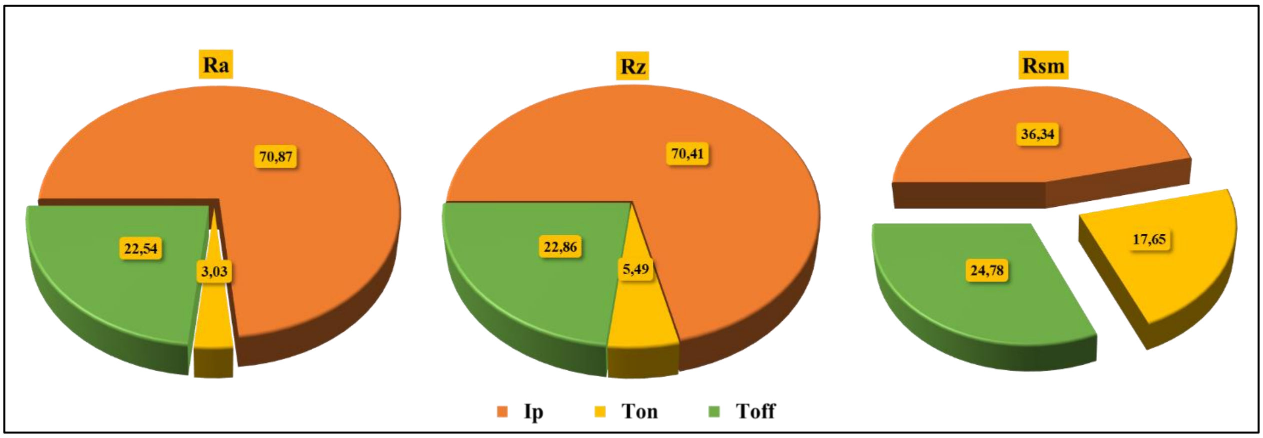

Figure 5. Percent effect plot of variable parameters on Ra, Rz and Rsm (Değişken parametrelerin Ra, Rz ve Rsm üzerine yüzde etki grafiği)

After the experiments, the images taken from the machined surface of the workpiece material are separated in detail in Figure 6 according to the processing conditions. Figure 6 shows traces of burning and recast material, micro-hole or crater-like structures formed on the workpiece surface [31]. These structures are encountered in the recast layer (white layer) , which is a typical result of the electro-erosion process [32]. The recast layer is a hard-brittle structure, the thickness of which varies according to the melting point of the electrode, discharge energy and pulse off time [33]. This layer consists of dielectric material and electrode (tool or workpiece) material that cannot be ejected in the pulse off time, which rapidly cools and solidifies [34]. As seen in Figure 6, the crater width increases as the pulse on time increases due to the expansion in the plasma channel. With the effect of the experimental design, it is seen that this expansion increases with the increase in the pulse off time in the 6A, 9A and 15 A discharge current experiments.

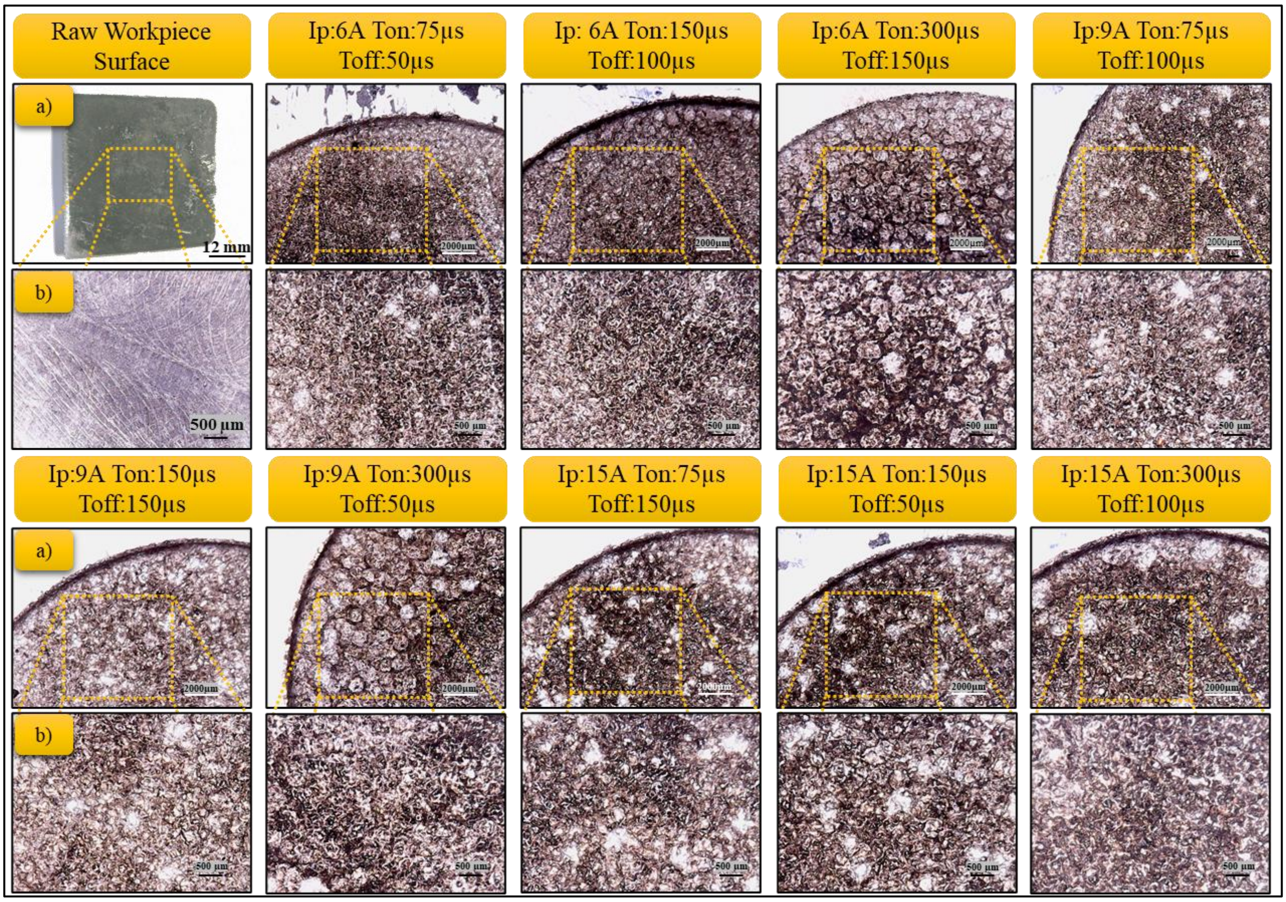

Figure 6. Surface images of workpiece material in a) 2000 µm, b) 500 µm scale (İş parçası malzemesinin yüzey görüntüleri a) 2000 µm ölçeğinde, b) 500 ölçeğinde)

Electro-erosion machining is a two-way advanced manufacturing technique in which the workpiece and tool material are wear. Machining takes place with electrons moving from the workpiece to the tool (electrode) surface and ions moving from the dielectric to the workpiece (cathode) [35]. Thus, it is possible to see craters and microcracks in the electrode material after EDM. After the experiments, the images taken from the machining surface of the tool material (electrode) are separated in detail in Figure 7 according to the machining conditions. When the tool images are examined, the pulse on time and pulse off time cause the craters to expand on the tool electrode surface as well as on the workpiece surface. In addition, the color difference between the unused tool and the used tool can be opened as short circuits and burns caused by spark energy as a result of the carbon from the dielectric penetrating the surface of the positive pole copper electrode during processing [36].

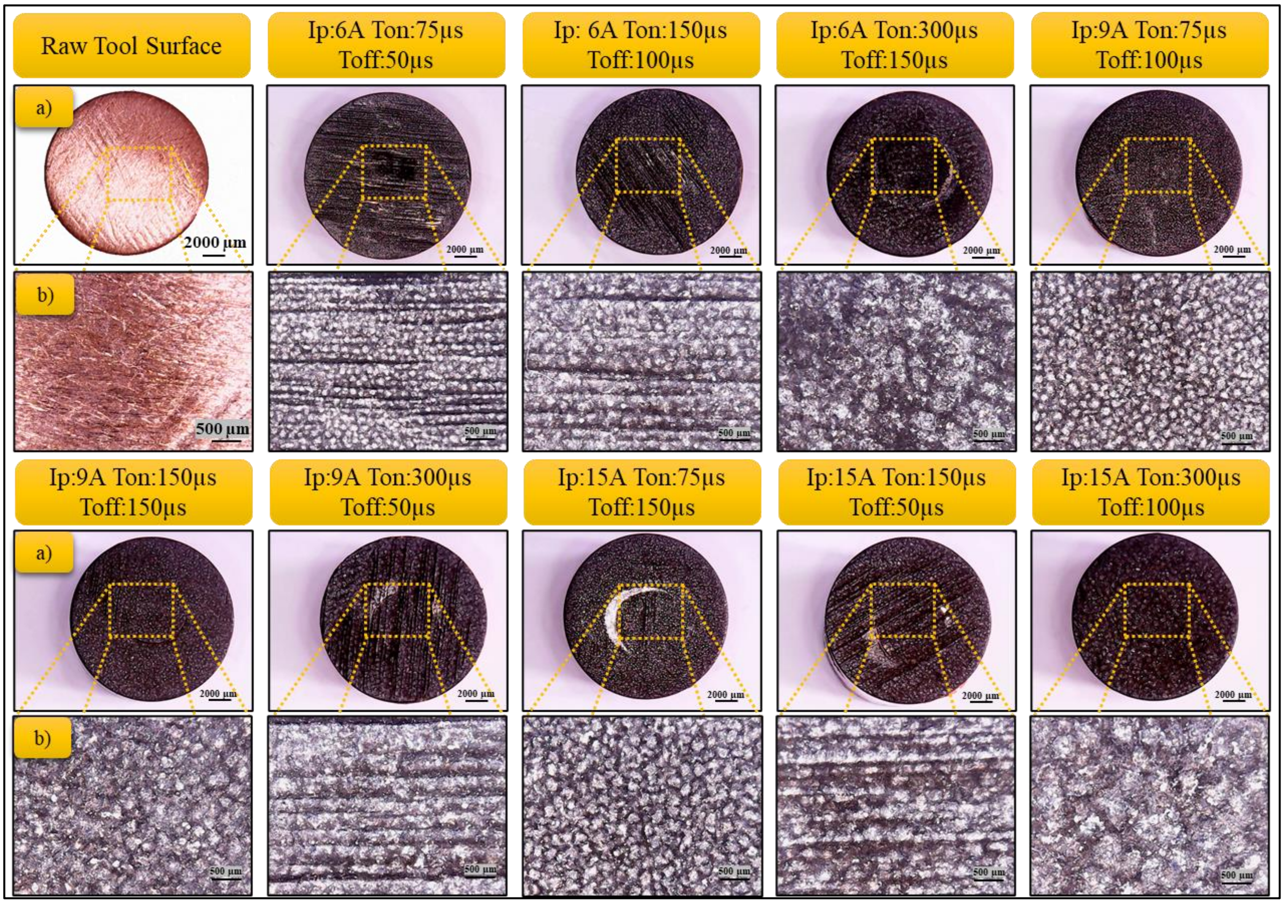

Figure 7. Surface images of tool material in a) 2000 µm scale, b) 500 µm scale (Takım malzemesinin yüzey görüntüleri a) 2000 µm ölçeğinde, b) 500 µm ölçeğinde)

4. CONCLUSIONS (SONUÇLAR)

In this study, the surface roughness of the Al5083 material processed by the die-sinking type electro discharge machining method was investigated. In the study, the effects of variable parameters such as discharge current (Ip), pulse on time (Ton) and pulse off time (Toff) on the obtained Ra, Rz and Rsm surface roughness results were statistically investigated. The effects of the processing parameters on the surface quality were interpreted with the images taken from the machining surface. The results obtained after the experimental study are summarized below as a list.

- The signal to noise ratio for Ra increased by 35.24% in the range from -25.2038 to -16.3195 for Rz increased by 19.86% compared to the variables in the range from -40.7252 to -

32.9186 for Rsm increased by 9.04% compared to the variables in the range from 50.1841 to 54.7231.

- In the experimental study, while the discharge current was the most effective (average 59.21%) parameter on Ra, Rz and Rsm, the mean effect of pulse on time and pulse off time were 8.72% and 23.39%, respectively.
- In the electro discharge machining technique, the workpiece wears out as well as the tool material. Tool material wear increases with increasing discharge current and decreases with increasing pulse on time and pulse off time.
- The surface roughness of the workpiece material increases for Ra and Rz as Ip increases and Toff decreases; first increasing and then decreasing as Ton increases. Rsm first decreased and then increased as Ip increased, increased as the pulse on time increased, and decreased as the pulse off time increased.
- Since Ra and Rz are based on depth values in roughness, the energy of the spark has a bad effect on the surface roughness depth. However, an increase in Ra and Rz was observed in the experimental study at low and high pulse on time. Thus, it was concluded that in the case of a high pulse on time, with increasing plasma channel diameter, denser melt is cleaned in the pulse off time and the height of the peaks and craters decreases.
- High Rsm is a preferred roughness result due to its effect on fatigue. In the experimental study, the pulse off time increased the Rsm by increasing the crater width, and the Rsm decreased as the pulse off time increased. This has been interpreted as the formation of new peaks and craters by further cleaning of the recast melt in the high pulse off time.
- Best Ra at 6 A Ip, 300 µs Ton and 150 µs Toff processing condition, best at Rz 6 A Ip, 75 µs Ton and 150 µs Toff processing condition; the best Rsm can be obtained at 15 A Ip, 300 µs Ton and 50 µs Toff processing condition.

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