Int. J. Adv. Eng. Pure Sci., Special Issue-1 e11-e16
DOI: 10.7240/jeps.450866

RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Effect of Machining on Workpiece Surface Characteristics in Electric Discharge Drilling (EDD)

Elektro Erozyon ile Delik Delmede İşlemenin İşparçası Yüzey Karakteristiklerine Etkisi

Oğuz ERDEM [1], Can ÇOĞUN [2], İbrahim USLAN [3]

[1] *Kırşehir Ahi Evran University, Department of Mechanical Engineering, 40100, Kırşehir, Turkey*

[2] *Çankaya University, Department of Mechatronics Engineering, 06790, Ankara, Turkey*

[3] *Gazi University, Department of Mechanical Engineering, 06560, Ankara, Turkey*

Abstract

In electric discharge drilling (EDD), rapid local heating and cooling of the workpiece surface by means of electric discharges results in surface layers (recast, heat affected and base material). In this study, the main workpiece surface texture measures, namely the recast layer thickness (RLT) and average surface roughness (R_a) characteristics were investigated for varying machining parameters (discharge current and pulse on time). The conducted experiments revealed the strong dependence of surface characteristics on machining parameters.

Keywords: Electric discharge drilling, Recast layer thickness, Average surface roughness, Ti6Al4V, Inconel 718, AISI4140

Öz

Elektro erozyon ile delik delmede (EEDD), işparçası yüzeyinin elektriksel boşalmalar yoluyla hızlı bir şekilde bölgesel olarak ısıtılması ve soğutulması, yüzey katmanlarına (tekrardan katılaşmış, ısıl etkilenmiş ve ana malzeme) neden olur. Bu çalışmada, ana işparçası yüzey dokusu, yani tekrardan katılaşmış katman kalınlığı (RLT) ve ortalama yüzey pürüzlülüğü (Ra) özellikleri, farklı işleme parametreleri için (boşalım akımı ve vurum süresi) araştırılmıştır. Yapılan deneyler, yüzey özelliklerinin işleme parametrelerine kuvvetle bağımlılığını ortaya koymuştur.

Anahtar Kelimeler: Elekro erozyon ile delik delme, Tekrardan katılaşmış katman kalınlığı, Ortalama yüzey pürüzlülüğü, Ti6Al4V, Inconel 718, AISI4140

I. INTRODUCTION

In today's technology, electric discharge machining (EDM) is one of the non-traditional manufacturing methods used in production of hard to machine materials and difficult geometries [1, 2]. EDM is based on the principle of very small volume material erosion from the workpiece surface by means of electrical discharges between the conductive electrode and the workpiece immersed into dielectric liquid. The electrode (tool) is prepared according to the cavity to be formed in the workpiece [3]. The electric discharge drilling (EDD) is generally used for drilling starting holes for wire-EDM applications and turbine blade cooling holes. A continuously rotating hollow metal electrode flushed by a dielectric fluid removes material by electric discharges [4-6].

Recently, it has become highly difficult to machine new engineering materials with traditional manufacturing methods that have been greatly improved in thermal, chemical and mechanical properties like Ti6Al4V (Ti64) and Inconel 718 (In718) alloys widely used in automotive, aviation and aerospace applications owing to their low density and high strength properties [4, 7-9].

In EDM, material removal from the workpiece is accomplished by melting and evaporation phenomena. A solidified region (recast layer) is formed on the workpiece and electrode surfaces due to rapid cooling of molten materials. As a result, changes in terms of chemical composition and hardness are observed at these regions. Besides, there is a thermally affected

Sorumlu yazar/Corresponding Author: Oğuz ERDEM, Tel: +90(386) 2803825, e-posta: oguz.erdem@ahievran.edu.tr
Gönderilme/Submitted: 04.08.2018, **Düzenleme/Revised:** 08.11.2018, **Kabul/Accepted:** 29.01.2019

multi-layered zone beneath these surfaces. Recast layer of workpiece has very high hardness and brittle nature. Furthermore, the recast layer, where residual stresses are observed, contains micro-fractures and micro-craters [10, 11]. Another mechanism effective on characteristics of the recast layer is the carbon accumulation which increases the hardness of the workpiece surface [12, 13].

In EDM, the recast layer properties vary depend on various parameters like discharge current (I_d), pulse on time (t_{on}), pulse off time (t_{off}), type and characteristics of the dielectric liquid, addition of powder into dielectric liquid, application mode of the dielectric to the machining medium, electrode material and its' manufacturing method, physical properties of the workpiece [13]. In Cogun et al. study [12], B_4C powder added copper and pure copper electrodes, produced by powder metallurgy, were used as the electrodes whereas SAE1040 steel were used as workpiece. They reported increasing workpiece recast layer thickness (RLT) with increasing I_d and t_{on}. The RLT was measured as 3.4 ± 1.5 µm for pure copper powder electrode at I_d=3 A and t_{on}=25 µs whereas 9.0 ± 2.1 µm at I_d=6 A and t_{on}=50 µs settings. It has been reported that the recast layer, defined as 'Zone A', contains perlite lamellae (ferrite and cementite).

In Hasçalık et al. study [14], Ti64 workpieces were EDMed with electrolytic copper electrodes in kerosene dielectric. Experiments were carried out for depth of 5 mm with the machining parameters of level 1 (I_d=3 A, t_{on}=25 µs) and level 2 (I_d=12 A, t_{on}=50 µs). The RLT of Ti64 machined at Level 1 was found as 7 µm whereas it is about 12 µm for Level 2 settings. In Zhang et al. study [15], the recast layer formed in water-in-oil (W/O) dielectric were examined by comparing them with those of formed in kerosene and de-ionized water. The recast layer formed in W/O yielded larger RLT and SR values than that of the other dielectrics.

Some attempts have been made to establish mathematical relationships between the EDM machining parameters and the recast layer characteristics. Ramasawmy et al. study [16] presented the effect of the EDM machining parameters (I_d and t_{on}) on average white layer thickness (AWLT) by empirical equations in terms of 3D surface texture amplitude and spatial surface texture parameters (Sds). They have reported the better prediction of AWLT in use of Sds. They revealed that the I_d had a dominant effect on dimension of the craters than the t_{on} and dimensions of the molten workpiece pool, and eventually the AWLT, can be described by the magnitude of the surface tension.

In Li et al. study [3], white layer thickness (WLT) was modelled and analyzed in terms of different machining parameters (I_d=3-6-9 A, t_{on}=32-64-96 µs and t_{off}=64-96-128 µs) by using the response surface methodology (RSM) and analysis of variance (ANOVA) in die-sinking EDM. They stated that the predicted values agreed well with the experimental findings. They reported that the lower I_d=3 A (the most important factor affecting WLT) and t_{on}=32 µs and longer t_{off}=128 µs minimized the WLT. In Banu et al. study [17], empirical models were developed for the estimation of material removal rate (MRR) and recast layer hardness in micro-EDM. Polarity, flushing, gap voltage, and tool electrode rotational speed were identified in the model. A 370-rpm rotational speed and at 80-V gap voltage were found as the optimum parameters for maximum MRR and minimum recast layer hardness.

The goal of this study is to experimentally investigate of the effects of machining parameters on RLT and surface roughness (SR) of EDD process for AISI4140 die steel, Ti64 and In718 alloy workpieces.

II. EXPERIMENTAL METHOD

A FURKAN EDM M25A die sinking machine was transformed to a EDD machine by making series of modifications. The pulse generator was an isopulse type with 3 kVA capacity and 80 V open circuit voltage. The experimental setup consists of; i) dielectric tank, ii) dielectric heating and temperature control and iii) electrode rotation systems (Figure 1). Self-made dielectric tank system was designed to provide homogenous distribution of added powders into the dielectric. Flush mixing of dielectric was provided by means of 20 mm diameter copper pipe placed at the bottom of the tank with evenly spaced holes (Figure 2). The powder added dielectric (PAD) was sucked from the bottom level of the tank by means of a gear pump. One of the two branches of the pump exit was directed to the copper pipe for PAD flush mixing whereas the other was directed to the ceramic piston pump (Figure 1) for pressurization of the dielectric to be sent to tube electrode center hole to flush the debris away from the machining gap. The dielectric heating was provided by electrical resistances and on-line temperature control was done by means of a thermocouple with +/ – 1 ºC accuracy. The rotation of the tube electrode (max. speed=1000 rpm) was provided by an electric motor.

In the experiments, AISI4140 steel [2], Ti64 [3] and In718 [4] were used as workpiece materials (Table 1). Workpieces were ED drilled by single-hole rotating copper electrodes with 2 mm outer diameter. The drilling process was carried out for 20 mm depth at the ground interfaces of two overlapping workpiece surfaces by using a simple clamp (Figure 2). A ceramic guide was used to correctly align the rotating electrode at 1000 rpm speed. The halves of the drilled workpieces are shown in Figure 3. The separated halves facilitated easy surface roughness measurements and microstructure inspections. Tap water dielectric (without any powder addition) was flushed at 140 bar through the center hole of the electrode. The machining settings used in the experiments are given in Table 2.

The average surface roughness (R_a) values of the machined holes were found by taking the arithmetic average of three measurements (at hole inlet, the middle and the exit sections) by using Surcorder SE1200 type portable surface roughness measurement device. Optical microscope (Olympus BX43F) and Jeol JSM-6360LV scanning electron microscope (SEM) were used to determine the RLT of the ED drilled samples after applying surface cleaning treatments (rough cleaning of the surface, sanding, etching and polishing).

Before the surface inspections, acid etching operations were performed to samples for better observation. AISI4140 specimens were acid etched by 2% nitric acid + 98% ethanol solution for 1 minute [18], Ti64 samples by 0.5 mol HCl + 0.5 mol H2SO4 solution for 60 minutes [19] and the In718 samples, by using 50% HCl + 50% methanol solution for 60 minutes [20]. After etching operations, all samples were washed with plenty of ethyl alcohol.

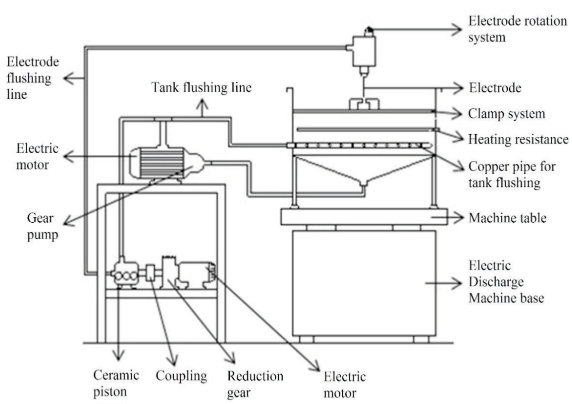

Figure 1. Schematic representation of the experimental setup

Table 1. The properties of workpieces

Properties – Unit	AISI4140	Ti64	In718
Density – (kg/m^3)	7700	4430	8190
Melting temperature – (K)	1684	1933	1617
Specific heat capacity – (J/kg.K)	473	526.3	435
Thermal conductivity – (W/m.K)	42.7	6.7	11.2
Electric conductivity – (ohm-cm)	222 x 10^{-9}	1.78 x 10^{-4}	1.21 x 10^{-4}

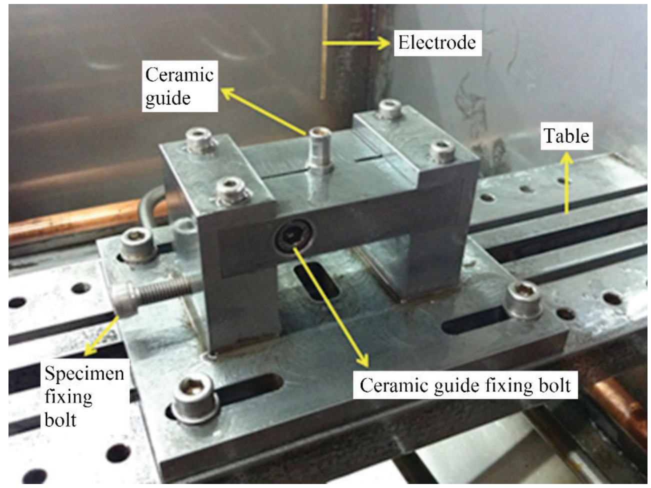

Figure 2. The clamp system (specimen mounting)

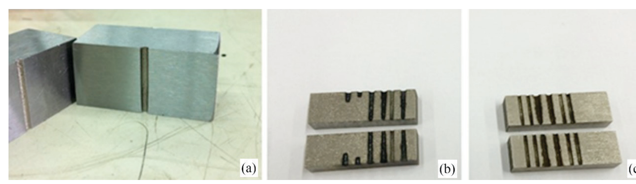

Figure 3. Drilled workpiece halves: a) AISI4140, b) Ti64, c) In718

Table 2. The machining settings used in the experiments

Machining	Machining parameters		
code	Discharge current –I (A)	Pulse on time – t_{on} (μs)	Pulse off time[(1)] – t_{off} (μs)
MC1	3	25	50
MC2	8.2	35	16
MC3	12	35	26

[1] Duration between two successive pulses (pause time)

III. RESULTS AND DISCUSSIONS

As seen from Figure 4b, the molten AISI4140 workpiece material has flowed around the hole wall. So, the determination of RLT accurately was in doubt since it was hard to differentiate recast layer. The same occurrences were also observed in the Ti64 (Figure 5b) and In718 workpieces. So, the flowed layer was removed from the hole walls by surface cleaning and etching processes and the RLT of the specimens were determined through the optical microscope images. The optical examinations clearly revealed the surface layers formed on the AISI4140 surface, namely, recast layer (zone A), heat affected zone (zone B) and base metal (zone C) (Figure 6).

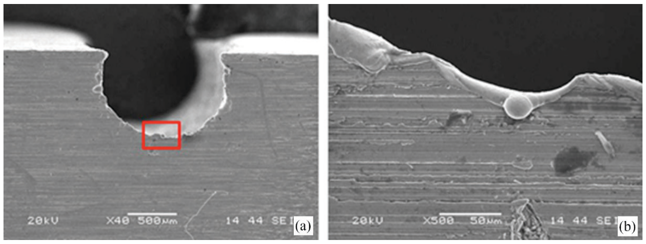

Figure 4. AISI4140: a) a drilled workpiece half, b) magnified view of selected region

In Figure 7-9, the heat affected zone under the recast layer of AISI4140, Ti64 and In718 workpieces for different machining settings are shown clearly.

For the tested settings, RLT values increased with increasing I_d and t_{on} (Table 3). The experimental RLT results obtained in this study are in agreement with the findings in [14], Cogun et al. [12] and Li et al. [3] studies. Figure 10 reveals the increasing R_a values with increasing I_d and t_{on} for the tested workpieces. The lowest R_a values were obtained at MC1 setting (low energy discharges) whereas the highest values were obtained at the MC3 setting (high energy discharges).

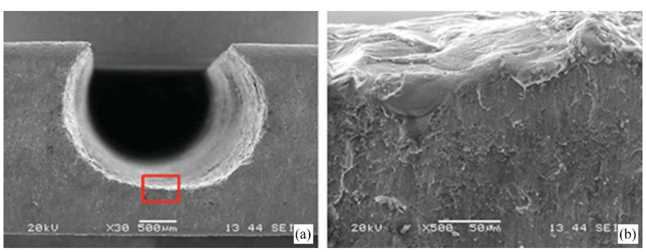

Figure 5. Ti64: a) a drilled workpiece half, b) magnified view of selected region

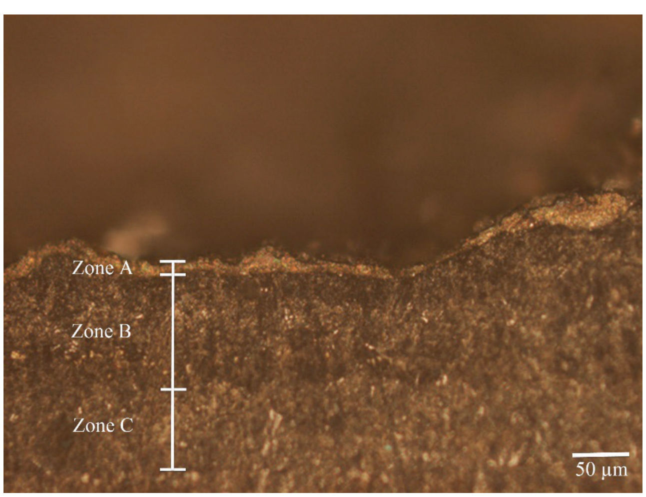

Figure 6. The layers of AISI4140: recast layer (zone A), heat affected zone (zone B), base metal (zone C)

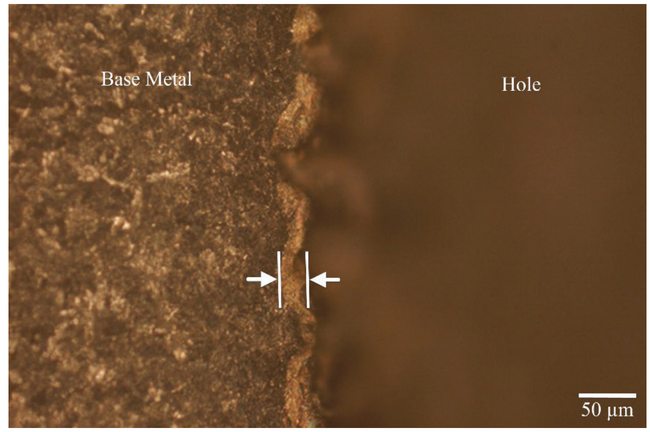

Figure 7. The recast layer seen on the drilled surface of AISI4140 with MC1 machining setting

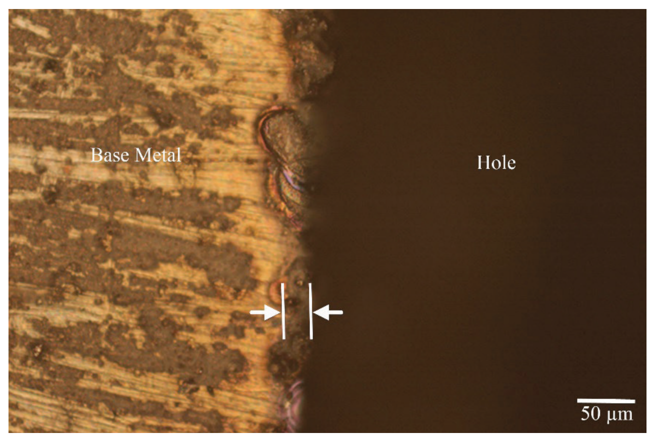

Figure 8. The recast layer on the surface of Ti64 at MC2 machining setting

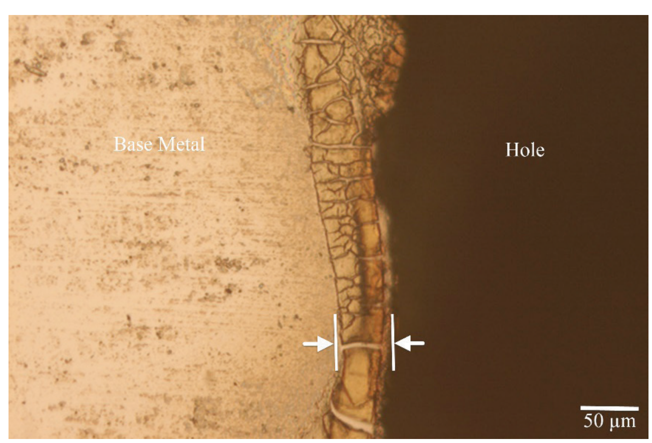

Figure 9. The recast layer on the surface of In718 at MC3 machining setting

Table 3. The RLT values at different machining settings

Workpiece – electrode	Machining settings	RLT (µm)
AISI4140 – Cu	I_d=3A, t_{on}=25µs, t_{off}=50µs	3.7 ± 1.3
	I_d=8.2A, t_{on}=35µs, t_{off}=16µs	4.6 ± 1.4
	I_d=12A, t_{on}=35µs, t_{off}=26µs	6.2 ± 1.3
Ti64 – Cu	I_d=3A, t_{on}=25µs, t_{off}=50µs	5.8 ± 1.5
	I_d=8.2A, t_{on}=35µs, t_{off}=16µs	7.3 ± 1.6
	I_d=12A, t_{on}=35µs, t_{off}=26µs	9.1 ± 2.0
In718 – Cu	I_d=3A, t_{on}=25µs, t_{off}=50µs	4.1 ± 1.6
	I_d=8.2A, t_{on}=35µs, t_{off}=16µs	5.4 ± 1.7
	I_d=12A, t_{on}=35µs, t_{off}=26µs	7.5 ± 1.2

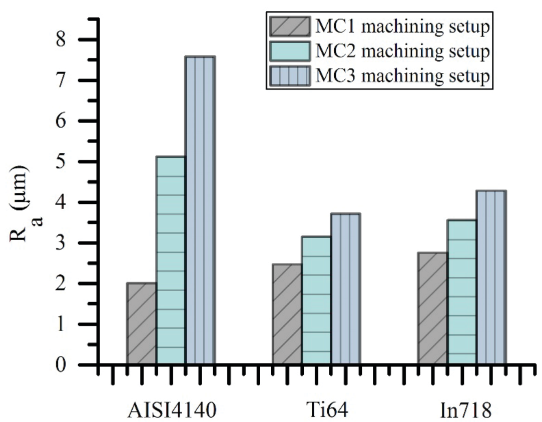

Figure 10. The average surface roughness (R_a) of the drilled workpieces

IV. CONCLUSIONS

In this study, the relationships between the recast layer properties and the machining parameters in electrical discharge drilling (EDD) were investigated and the following conclusions were drawn:

For all tested workpiece materials, increasing discharge current and pulse on time increased the RLT values. The highest RLT values were observed in Ti64 workpieces for all experienced machining settings. This is attributed to low thermal conductivity of the material causing rapid local heating and excessive melting of the material.

The lowest average surface roughness (R_a) value was obtained in AISI4140 workpiece at MC1 machining settings (low energy discharges). The highest R_a values were observed for the highest energy pulses (i.e. MC3 settings). Increasing discharge current and pulse on time resulted in deterioration of the surface texture and higher R_a values. Ti64 and In718 alloys yielded resembling surface roughness characteristics for the same machining settings.

References

[1] Gülcan, O., Uslan, İ., Usta, Y., & Çoğun, C. (2015). Elektro Erozyon ile İşlemede Cu-Cr T/M Elektrot Kullanımının İşleme Performansına Etkisi. *Journal of the Faculty of Engineering and Architecture of Gazi University,* 30(3), 381-394.

[2] Klocke, F., Schneider, S., Ehle, L., Meyer, H., Hensgen, L., and Klink, A. (2016). Investigations on Surface Integrity of Heat Treated 42CrMo4 (AISI 4140) Processed by Sinking EDM. *Procedia CIRP*, 42(2), 580-585.

[3] Li, J., Shi, S., & Zhao, S. (2013). Modeling and Analysis of Micro-hole in Die-sinking EDM Process through Response Surface Method based on the Central Composite Design. *International Journal of Signal Processing, Image Processing and Pattern Recognition,* 6(6), 351-364.

[4] Yılmaz, O., Bozdana, A. T., & Okka, M. A. (2014). An intelligent and automated system for electrical discharge drilling of aerospace alloys: Inconel 718 and Ti-6Al-4V. *Int. J. Adv. Manuf. Technol,* 74(9), 1323-1336.

[5] Bozdana, A. T., & Al-Karkhi, N. K. (2017). Comparative experimental investigation and gap flow simulation in electrical discharge drilling using new electrode geometry. *Mechanical Sciences,* 8(2), 289–298.

[6] D'Urso, G., Maccarini, G., Quarto, M., Ravasio, C., & Caldara, M. (2016). Micro-electro discharge machining drilling of stainless steel with copper electrode: The influence of process parameters and electrode size. *Advances in Mechanical Engineering,* 8(12), 1-16.

[7] Unses, E., & Cogun, C. (2015). Improvement of Electric Discharge Machining (EDM) Performance of Ti-6Al-4V Alloy with Added Graphite Powder to Dielectric. *Strojniški vestnik – Journal of Mechanical Engineering,* 61(6), 409-418.

[8] Newton, T. R., Melkote, S. N., Watkins, T. R., Trejo, R. M., & Reister, L. (2009). Investigation of the effect of process parameters on the formation and characteristics of recast layer in wire-EDM of Inconel 718. *Materials Science and Engineering A – Structrual Materials Properties,* 5(4), 208-215.

[9] Chen, S. L., Lin, M. H., Huang, G. X., & Wang, C. C. (2014). Research of the recast layer on implant surface modified by micro-current electrical discharge machining using deionized water mixed with titanium powder as dielectric solvent. *Applied Surface Science,* 31(1), 47-53.

[10] Shabgard, M. R., Seyedzavvar, M., & Oliaei, S. (2011). Influence of input parameters on characteristics of EDM process. *Strojni˘ ski vestnik – J. Mech. Eng.,* 57(9), 689-696.

[11] Arooj, S., Shah, M., Sadiq, S., Jaffery, S. H. I., & Khushnood, S. (2014). Effect of Current in the EDM Machining of Aluminum 6061-T6 and its Effect on the Surface Morphology. *Arab. J. Sci. Eng.,* 39(2), 4187-4199.

[12] Cogun, C., Esen, Z., Genc, A., Cogun F., & Akturk, N. (2016). Effect of powder metallurgy Cu-B_4C electrodes on workpiece surface characteristics and machining performance of electric discharge machining. *Proc. IMechE Part B: J. Engineering Manufacture,* 230(12), 2190-2203.

[13] Amineh, S. K., Tehrani, A. F., & Mohammadi, A. (2013). Improving the surface quality in wire electrical discharge machined specimens by removing the recast layer using magnetic abrasive finishing method. *Int. J. Adv. Manuf. Technol,* 66(3), 1793-1803.

[14] Hasçalık, A., & Çaydaş, U. (2007). Electrical discharge machining of titanium alloy (Ti–6Al–4V). *Applied Surface Science,* 5(3), 9007-9016.

[15] Zhang, Y., Liu, Y., Ji, R., & Cai, B. (2011). Study of the recast layer of a surface machined by sinking electrical discharge machining using water-in-oil emulsion as dielectric. *Applied Surface Science,* 25(7), 5989-5997.

[16] Ramasawmy, H., Blunt, L., & Rajurkar, K. P. (2005). Investigation of the relationship between the white layer thickness and 3D surface texture parameters in the die sinking EDM process. *Precision Engineering,* 29(3), 479-490.

[17] Banu, A., Ali, M. Y., & Rahman, M. A. (2014). Micro-electro discharge machining of non-conductive zirconia ceramic: investigation of MRR and recast layer hardness. *Int. J. Adv. Manuf. Technol.,* 75(2), 257-267.

[18] Ruellan, A., Kleber, X., Ville, F., Cavoret, J., & Liatard, B. (2001). Understanding white etching cracks in rolling element bearings: Formation mechanisms and influent tribochemical drivers. *The Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture,* 229(8), 886-901.

[19] Nagaoka, A., Yokoyama, K., & Sakai, J. (2010). Evaluation of hydrogen absorption behaviour during acid etching for surface modification of commercial pure Ti, Ti–6Al–4V and Ni–Ti superelastic alloys. *Corrosion Science,* 52(3), 1130-1138.

[20] Ay, M., Hasçalık, A., & Çaydaş, U. (2012). Yüksek Toleranslı Plazma Arkı İle Kesme Parametrelerinin Araştırılması. *3. Ulusal Talaşlı İmalat Sempozyumu,* Ankara, Türkiye, 04-05 Ekim. Gazi Üniversitesi Teknoloji Fakültesi.