www.czasopisma.pan.pl PAN www.journals.pan.pl

ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 2023
Issue 2/2023

106 – 111

10.24425/afe.2023.144301

15/2

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Effects of EDM on the Chemical Composition and Microstructure of the Surface Layer of Alnico Alloys

D. Bańkowski *, P. Młynarczyk, B. Szwed
Kielce University of Technology, Poland
* Corresponding author. E-mail address: damianbankowski1@gmail.com

Received 19.11.2022; accepted in revised form 22.02.2023; available online 26.05.2023

Abstract

This article deals with the effects of electrical discharge machining (EDM) on the chemical composition and microstructure of cast Alnico alloys, i.e., iron-based alloys composed of aluminum, nickel and cobalt. The experiments focused on determining the chemical composition of the surface layer before and after the EDM process. The microstructure of the material altered by the EDM was also examined. The study included measurement of the thickness of the white layer characteristic of EDM. It is evident that low values of the surface roughness parameters can be obtained by correctly selecting the EDM process parameters. The average surface roughness reported in the experiments was 1 µm. The surface roughness measurements were conducted with a Talysurf CCI lite non-contact profiler. The metrological results also indicate that lower surface roughness can be obtained at small discharge energies.

Keywords: Electrical discharge machining (EDM), Alnico, Chemical composition, Roughness, Surface quality

1. Introduction

Alnico is a group of iron-based alloys of aluminum (Al), nickel (Ni), and cobalt (Co), which may also contain copper and titanium. Being ferromagnetic materials characterized by high coercivity, i.e. high resistance to demagnetization, Alnico alloys are suitable for permanent magnets [1]. Alnico magnets are known to retain their magnetism at high temperatures, even up to 525°C [2, 3].

Alnico magnets have been mass-produced for merely 50 years. They vary depending on the manufacturing process. There are 29 varieties in total, with 17 produced by casting, 10 by sintering, and 2 by combing the two methods [4].

Some types of Alnico magnets are isotropic (with the same properties in all directions), and these can be efficiently magnetized in all directions. Other types, e.g., Alnico 5 and Alnico 8, are anisotropic (with different properties in different directions) and these have a preferred direction of magnetization, which implies that one direction is better than all the others. Anisotropic Alnico alloys magnetized in one direction make stronger magnets than isotropic Alnico alloys [4].

Alnico alloys used as strong permanent magnets have numerous industrial and consumer applications. They are common, for instance, in electric motors, magnetrons, sensors, microphones, electric guitar pickups, or even cow stomach magnets [3, 5]. These days, however, Alnico magnets are being systematically replaced by stronger rare earth magnets [3, 6]. Since Alnico alloys are brittle materials, they are prone to cracking and fracture. They are thus very difficult to machine. Traditional machining operations may cause Alnico alloys to chip, crack or break [3]. Figure 1 shows examples of defects observed in the machining of Alnico alloys. As proposed in this article, Alnico alloys should be shaped using electrical discharge machining (EDM).

Fig. 1. Typical defects observed in the machining of Alnico alloys

EDM is a metal fabrication method based on electrical discharges. During the process, there is no contact between the tool and the workpiece, acting as the cathode and the anode, respectively [4]. However, the process requires immersing the two electrodes in a dielectric fluid. Erosion of the material is a result of rapidly recurring current discharges [7-9]. The role of the tool is to replicate in negative the desired shape [4].

EDM differs from conventional machining in that there is no physical contact between the tool and the work. The distance of the tool electrode to the workpiece surface may range from 0.01 mm to 0.8 mm, depending on the machining conditions. The EDM process is characterized by the formation of a plasma channel, followed by the formation and expansion of a gas bubble around it. Another characteristic feature of EDM is the resolidification of some of the melted material on the workpiece surface, the so-called white layer.

The temperature of 14,000 K reached during the process is responsible for the local melting and partial evaporation of the workpiece material. The surface quality is highly dependent on how much debris is generated and removed during a single discharge [7-9]. The higher the discharge energies, the higher the machining efficiency and, consequently, the higher the surface roughness [10, 11]. In other words, larger craters are produced at higher voltage and current values. The morphological features of EDM machined surfaces are dependent on various factors, especially the pulse-on and pulse-off times, the material of the tool electrode, the type of dielectric fluid, and its flow direction [12, 13].

Research into EDM has included determining the effects of discharge energy on the volume [14], area [15], diameter [16] or depth of craters [17]. Studies of microwire electrical discharge machining show that crater dimensions, e.g., the average diameter or the maximum depth can be predicted on the basis of spark energy [18]. The findings by Masuzawa et al. suggest that lower surface roughness (Ra), i.e., smaller craters, can be produced by applying low open-circuit voltage [19]. As reported by Guu in [20], higher values of the parameter Ra are a result of higher discharge currents and longer pulse-on times. Research into the relationships between the discharge energy and the geometrical surface characteristics shows that the crater dimensions are also dependent on the tool material, the workpiece material, and the type of dielectric fluid [4, 21]. There seem to be no studies dealing with the influence of EDM on the chemical composition of Alnico alloys.

EDM is a manufacturing process providing one of the highest accuracies; this technology can be used to produce components delicate and intricate in shape at high cutting speeds. The major drawback of this method, related to the process physics, is that it works well with electrically conductive materials. EDM is suitable for machining very hard materials, e.g., hardened steels and sintered carbides [21-24]. EDM is known to be more effective than conventional processes [25-28].

The aim of this study was to find out whether the material from the tool electrode would be transferred to the workpiece during machining. It was also essential to determine whether the EDM process would increase the content of copper at the surface of the Alnico alloy. Changes in the chemical composition of the surface layer may be responsible for changes in the properties of the material. The information is particularly important when the modified surface needs to be coated. Changes in the chemical composition imply changes in the magnetic capacity and/or coercivity (resistance to demagnetization), both being of significance in the case of permanent magnets. The study also included measurements of the surface quality in the craters.

2. Materials and methods

The experiments aimed to determine how EDM affected the composition and structure of Alnico alloys at the surface. The machining process was performed using a BP93L EDM machine. A power of 3 kW and a maximum spark current of 35 A were used to shape the material. The dielectric fluid − kerosene − was filtered and recirculated with a feed pump to ensure the efficiency of the machining process. Additional rotary movements of the tool and the workpiece were achieved using a special system illustrated in Figure 2. The solution provided good control of the electrodes (changes in the direction and speed of cutting), effective removal of the eroded material, and uniform surface finish.

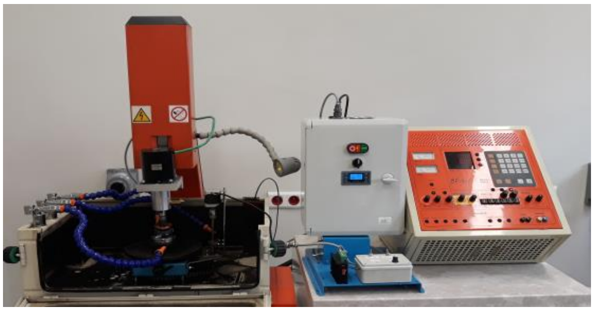

Fig. 2. A system providing additional rotary movements of the tool and the workpiece

The surface analysis was carried out using a JEOL 7100F field emission scanning electron microscope equipped with an Oxford Instruments X-max EDS (energy dispersive spectrometer) detector and a BSE (back-scattered electron) detector, operating at a magnification of 10−1,000,000 x and an accelerating voltage of 100 V−30 kV. The examinations were conducted at a resolution of 1.2 nm or 3 nm with the voltage being 30 kV and 1 kV, respectively. The other parameters were: current intensity − 1 nA and tool to work distance − 10 mm. The data were analyzed using the AZtec software.

The 3D surface roughness parameters were determined using a Taylor-Hobson Talysurf CCI Lite non-contact 3D profiler [29, 30]. Finally, a Nikon Eclipse MA200 optical microscope fitted with NIS

4.20-Elements Viewer imaging software was used for the microstructural examinations.

3. Results and Discussion

The material under analysis was a cast Alnico alloy – Figure 3. The investigations involved determining its composition by means of a JEOL JSM-7100F field emission scanning electron microscope.

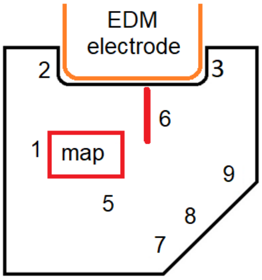

Fig. 3. Points and regions of SEM analysis

Figure 4 shows the structure of the material in area 5 with points where the chemical composition was measured.

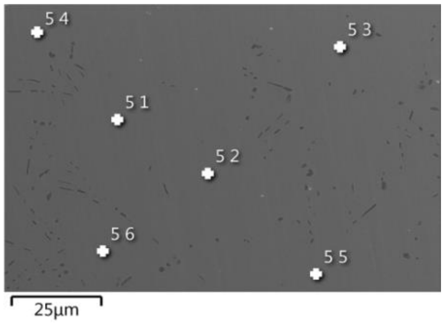

Fig. 4. Image of the material in area 5

Figure 5 shows an EDS spectrum of the material for point 5 indicated in Figure 3.

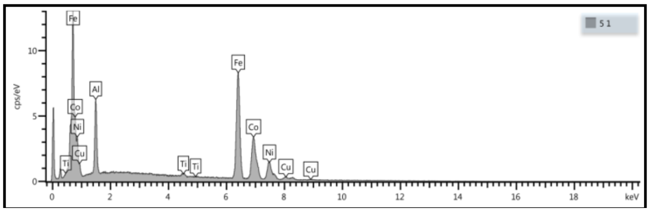

Fig. 5. X-ray spectrum of the material at point 5

Table 1 provides the average chemical composition of the material determined at the points marked in Figure 2.

For points 2 and 3, the sulfur (Si) content was also determined. The element was reported to reach 4.6 and 0.6%, respectively. This confirmed that sulfides occurred locally.

Then, an element map was produced for area of interest number 1 to determine the spatial distribution (concentrations) of elements in the Alnico alloy. The properties of the material may be adversely affected if the elements are not distributed evenly. Figure 6 shows an elemental map obtained for the area marked as 'map' in Figure 3.

Table 1.
Average chemical composition (atomic weight %) of the material studied (analysis at different points)

No	Al	S	Ti	Fe	Co	Ni	Cu	O
2	12.9	4.6	5.6	42.0	20.2	11.5	3.2	0.0
3	14.3	0.6	1.1	45.8	22.1	12.5	3.6	0.0
5	14.6	0.0	0.6	46.0	22.5	12.8	3.5	0.0
6	14.7	0.0	2.1	45.0	21.9	12.5	3.8	0.0
7	17.0	0.0	0.6	31.4	11.7	6.9	1.6	30.8
8	16.4	0.0	0.5	30.9	14.5	7.1	2.2	28.4
9	13.3	0.0	0.4	34.3	14.4	7.0	2.3	28.3

17

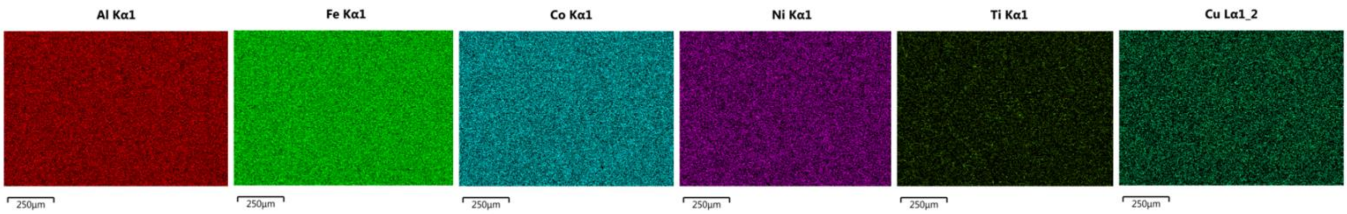

Fig. 6. Distribution of elements in the area of interest (Fig.3)

From the results provided in Figure 6, it is evident that the elements found, i.e., iron, aluminum, cobalt, nickel, titanium and copper, are distributed uniformly in this area.

The next stage of the experiments aimed to determine whether the use of a copper electrode in the electrical discharge machining process had any effect on the chemical composition of the workpiece. Observations of the workpiece microstructure were conducted in the area of interest at points 2 and 3, as indicated in Figure 3. The chemical composition of the material was also measured along line 6 shown in Figure 3.

According to the design of experiment, the chemical composition of the material studied was determined by means of line scan analysis. The measurements were conducted before and after the EDM process at points indicated in Figure 7.

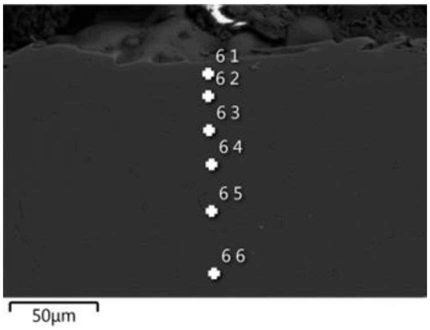

Fig. 7. Measurement points to analyze the chemical composition of the Alnico alloy

Table 2 shows the data obtained through the line scan analysis to determine the chemical composition in area 6.

Table 2.
Chemical composition (atomic weight %) of the alloy measured in area 6

Point	Al	Ti	Fe	Co	Ni	Cu
6 1	15.3	0.7	45.2	22.2	12.6	4.0
6 2	14.8	0.7	45.2	22.2	13.1	4.0
6 3	14.8	0.5	46.1	22.0	12.8	3.8
6 4	14.8	0.7	45.9	22.2	12.8	3.6
6 5	13.7	9.4	41.4	20.1	11.6	3.8
6 6	14.6	0.6	46.1	22.6	12.5	3.6
average	14.7	2.1	45.0	21.9	12.5	3.8

Measurements of the surface texture were carried out for two different conditions of EDM, i.e., at low and high energy densities. The low energy density condition was when the current intensity I was 5 A, the pulse-on time t_{on} was 50 µs, and the pulse-off time t_{off} was 90 µs. The high energy density condition, on the other hand, was at I = 15 A, t_{on} = 350 µs, and t_{off} = 10 µs. The morphology of the EDM machined surfaces was determined by means of an optical profiler. The results are illustrated in Figs. 8 and 9.

From Figure 8, it is evident that low discharge energies, i.e., low current and short pulse-on time, produce surfaces with numerous but shallow craters. The surface roughness parameter Ra reached 1.5 µm. However, machining at high current intensity and long pulse-on time resulted in surfaces characterized by large, deep craters, which were very few in number. The area of a single crater was large. In this case, the surface roughness Ra was much higher, reaching 13.3 µm.

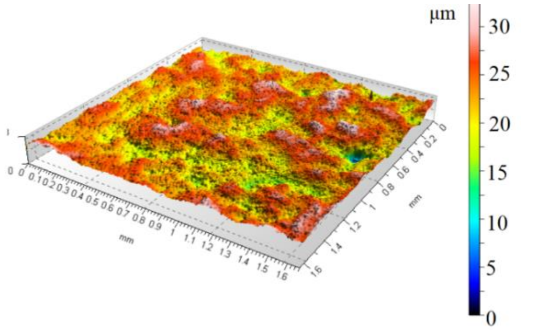

Fig. 8. Isometric view of the surface after EDM at low energy density resulting in low surface roughness

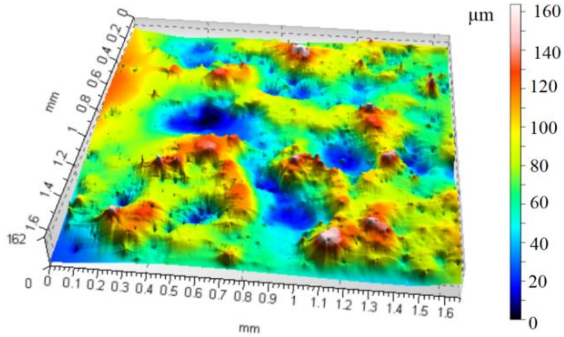

Fig. 9. Isometric view of the surface after EDM at high energy density resulting in large craters

The surfaces obtained for two different EDM conditions were observed using a scanning electron microscope. Figure 10 shows a surface machined at low energy density (I = 5 A, ton = 50 µs, toff = 90 µs). Figure 11 displays a photomicrograph of a surface produced at high energy density (I = 15 A, ton= 350 µs, toff= 10 µs)

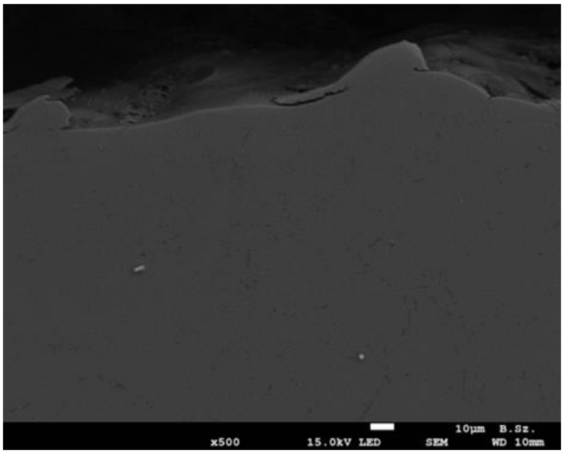

Fig. 10. SEM micrograph of the area adjacent to the cutting zone; EDM at low energy density

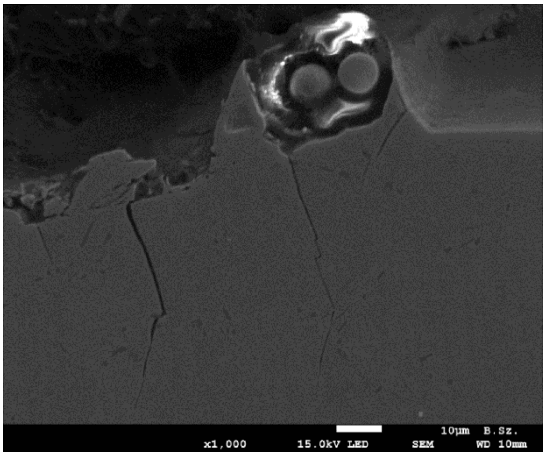

Fig. 11. SEM micrograph of the area adjacent to the cutting zone; EDM at high energy density.

From Figures 10 and 11, it can be concluded that high energies used during EDM were responsible for cracks. Figure 11 also shows drops of material that melted but did not have time to evaporate from the cutting zone. The surface in the photomicrograph in Figure 11 is definitely more enhanced than that depicted in Figure 10. This confirms that if the EDM process is performed at lower power consumption, lower surface roughness is obtained.

The metallographic specimens were etched using Nital; as a result, the white layer was revealed. Figure 12 displays a metallographic specimen used to analyze the effects of the EDM process.

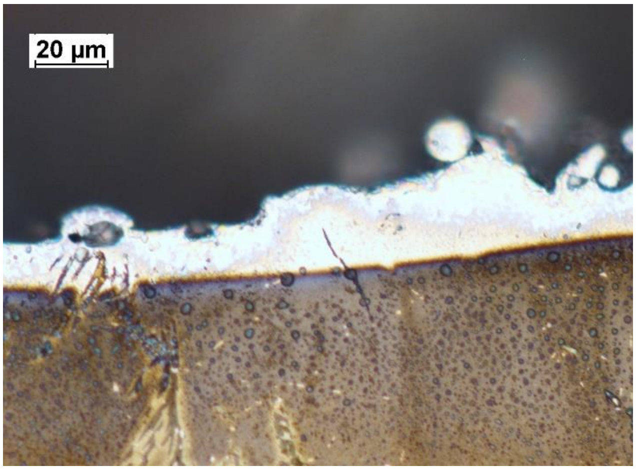

Fig. 12. Structure of the EDM machined Alnico alloy revealed through metallographic examination

The examination results indicate that after EDM, the thickness of the white layer ranged between 10 and 30 µm.

4. Conclusions

The findings concerning the effects of EDM on the chemical composition and microstructure of Alnico alloys can be summarized as follows.

- The chemical composition of the alloy was measured at different points in the area of interest. The distribution of elements was uniform. The average values of the elements present were: Al 13.9% at, Ti 2.9% at, Fe 44.1% at. 21.4% at, Ni 12.2% at, and Cu 3.5% at.
- The line scans and elemental maps confirm that the distribution of elements in the material was uniform; patchy concentrations of elements were not observed.
- Reflections (bright areas) were reported along the edges of areas 7, 8, and 9; the chemical composition data indicated strong oxidation when the content of oxygen was higher than 50% at.
- Slight precipitation of sulfides occurred due to the presence of oxygen (when higher than 50% at).
- High energies during the EDM process caused fracturing of the Alnico alloy at the surface.
- EDM performed at low energies resulted in low surface roughness (even lower than 1 µm).
- The white layer being a result of the EDM process had a thickness of about 10 to 30 µm.

Acknowledgements

The research reported herein was supported by a grant from the National Centre for Research and Development through the Lider XI Programme. Grant title: "Improvements in the technology of machining the surfaces of spherical rings of magneto mirrors through the use of electro-erosion machining (EDM)". Grant number: LIDER/59/0246/L-11/19/NCBR/2020.

References

[1] Alnico magnets. Retrived April 22, 2022, from https://magnesy.pl/magnesy-alnico.

[2] Alnico. Retrived April 22, 2022, from https://pl.wikipedia.org/wiki/Alnico.

[3] Bańkowski. D., Młynarczyk. P., Spadło. S., Sójka. R., Klamczyński, K. (2022). Tomographic testing of alnico alloys. Metal. In the 31st International Conference on Metallurgy and Materials, 18 – 19 May, 2022 (pp. 675-681), Brno, Czech Republic. https://doi.org/10.37904/metal.2022.4507.

[4] Bańkowski, D. & Młynarczyk, P. (2022). Influence of EDM process parameters on the surface finish of alnico alloys. *Materials.* 15(20), 7277, 1-13. https://doi.org/10.3390/ma15207277.

[5] Retrived April 22, 2022, from https://pl.alegsaonline.com/art/2916

[6] Maroufian, S.S. & Pillay, P. (2019). Design and analysis of a novel PM-assisted synchronous reluctance machine topology

with AlNiCo magnets. *IEEE Transactions on Industry Applications*. 55(5), 4733-4742. DOI: 10.1109/TIA.2019.2925784

[7] Świercz, R. & Oniszczuk-Świercz, D. (2019). Investigation of the influence of reduced graphene oxide flakes in the dielectric on surface characteristics and material removal rate in EDM. *Materials*. 12(6), 943, 1-19. https://doi.org/10.3390/ma12060943.

[8] Bartkowiak, T., Mendak, M., Mrozek. K., Wieczorowski, M. Analysis of surface microgeometry created by electric discharge machining. *Materials*. 1996-1944. 13(17), 3830, 1-28. https://doi.org/10.3390/ma13173830.

[9] Świercz, R., Oniszczuk-Świercz, D. (2017). Influence of electrical discharge pulse energy on the surface integrity of tool steel 1.2713. In 26th International Conference on Metallurgy and Materials, 24-26 May 2017 (pp. 1450-1455), Ostrava: Tanger.

[10] Han, F., Jiang, J. & Yu, D. (2007). Influence of discharge current on machined surfaces by thermoanalysis in finish cut of WEDM. *International Journal of Machine Tools Manufacture*. 47(7), 1187-1196. DOI: 10.1016/j.ijmachtools.2006.08.024.

[11] Hyde, J.M., Cadet, L., Montgomery. J. & Brown. C.A. (2014). Multi-scale areal topographic analysis of surfaces created by micro-EDM and functional correlations with discharge energy. *Surface Topography Metrology and Properties.* 2(4), 045001, 1-9. DOI: 10.1088/2051-672X/2/4/045001.

[12] Świercz, R., Oniszczuk-Świercz, D., Chmielewski, T. (2019). Multi-response optimization of electrical discharge machining using the desirability function. *Micromachines*. 10(1), 72, 1-25. https://doi.org/10.3390/mi10010072.

[13] Jarosz, K., Nieslony, P., Loschner, P. (2019). Investigation of the effect of process parameters on surface roughness in EDM machining of ORVAR (R) supreme die steel. In Advances in Manufacturing Engineering and Materials. ICMEM 2018, 18-22, June 2018 (pp: 333-340). Novy Smokovec, Slovakia. DOI:10.1007/978-3-319-99353-9_36.

[14] Tosun, N. & Pihtili, H. (2003). The effect of cutting parameters on wire crater sizes in wire EDM. *International Journal of Advanced Manufacturing Technology*. 21, 857-865. https://doi.org/10.1007/s00170-002-1404-1.

[15] Ozkavak, H.V., Sofu, M.M., Duman, B. & Bacak, S. (2021). Estimating surface roughness for different EDM processing parameters on Inconel 718 using GEP and ANN. *CIRP Journal of Manufacturing Science and Technology*. 33, 306-314. https://doi.org/10.1016/j.cirpj.2021.04.007.

[16] Gostimirovic, M., Kovac, P. & Sekulic, M. (2012). Influence of discharge energy on machining characteristics in EDM. *Journal of Mechanical Science and Technology*. 26, 173-179. https://doi.org/10.1007/s12206-011-0922-x.

[17] Mohanty, C.P., Mahapatra, S.S. & Singh, M.R. (2017). An intelligent approach to optimize the EDM process parameters using utility concept and QPSO algorithm. *Engineering Science and Technology, an International Journal*. 20(2), 552-562. https://doi.org/10.1016/j.jestch.2016.07.003.

[18] Rajurkar, P., Levy, G., Malshe, A., Sundaram, M.M., McGeough, J., Hu, X., Resnick, R. & DeSilva, A. (2006). Micro and nano machining by electro-physical and chemical processes. *CIRP Annals-Manufacturing Technology*. 55(2), 643-666. DOI:10.1016/j.cirp.2006.10.002.

[19] Masuzawa, T., Yamaguchi, M. & Fujino, M. (2005). Surface finishing of micropins produced by WEDG. *CIRP Annals Manufacturing Technology*. 54(1), 171-174. DOI:10.1016/S0007-8506(07)60076-6.

[20] Guu, Y.H. (2005). AFM surface imaging of AISI D2 tool steel machined by the EDM process. *Applied Surface Science*. 242(3), 245-250. DOI:10.1016/j.apsusc.2004. 08.028.

[21] Paczkowski, T. & Zdrojewski, J. (2016). The mechanism of ecm technology design for curvilinear surfaces. *Procedia CIRP*. 42, 356-361. https://doi.org/10.1016/j.procir. 2016.02.195.

[22] Giridharan, A. & Samuel, G.L. (2015). Modeling and analysis of crater formation during wire electrical discharge turning (WEDT) process. *The International Journal of Advanced Manufacturing Technology*. 77, 1229-1247. https://doi.org/10.1007/s00170-014-6540-x.

[23] Dąbrowski, L. & Paczkowski, T. (2005). Computer simulation of two-dimensional electrolyte flow in electrochemical machining. *Russian Jouranl of Elektrokhimiy*. 41(1), 102-110.

[24] Papazoglou, E.L., Karmiris-Obratanski, P., Karkalos, N.E., & Markopoulos, A.P. (2020). On the use of deformed geometry in EDM modelling: comparative study. *Acta Physica Polonica*. 138(2), 268-271. DOI: 10.12693/APhysPolA.138.268.

[25] Bańkowski, D. & Spadło, S. (2019). The use of abrasive water jet cutting to remove flash from castings. *Archives of Foundry Engineering.* 19(3), 94-98, https://doi.org/10.24425/afe.2019.129617.

[26] Szwed, B., Konieczny, M. (2016). Influence of bonding pressure on the dissimilar joints of titanium and stainless steel with an aluminum interlayer. In International Conference on Metallurgy and Materials METAL 2016, 25-27, May 2016 (pp: 1552-1557). Brno, Czech Republic.

[27] Młynarczyk, P., Krajcarz, D., Bańkowski, D. (2017). The selected properties of the micro electrical discharge alloying process using tungsten electrode on aluminum. *Procedia Engineering*. 192, 603-608. DOI:10.1016/j.proeng.2017.06.104.

[28] Czupryński, A., Poloczek, T. & Urbańczyk, M. (2022). Characterization of a new high abrasion and erosion resistance iron-based alloy for PTA hardfacing. *International Journal of Modern Manufacturing Technologies*. 14(1), 45-54. DOI:10.54684/ijmmt.2022.14.1.45.

[29] Bańkowski, D., Krajcarz, D., & Młynarczyk, P. (2017). Deburring and smoothing the edges using vibro-abrasive machining. *Procedia Engineering*. 192, 28-33. https://doi.org/10.1016/j.proeng.2017.06.005.

[30] Adamczak, S., & Zmarzły, P. (2019). Research of the influence of the 2D and 3D surface roughness parameters of bearing raceways on the vibration level. *Journal of Physics: Conference Series*. 1183(1), 1-10. DOI: 10.1088/1742-6596/1183/1/012001.