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Selected Aspects of Surface Integrity of Inconel 625 Alloy after Dry-EDM in Carbon Dioxide

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Abstract. The dry-EDM process is environmentally neutral and enables to obtain good machining accuracy and relatively good surface quality. On the other hand, the application of dry-EDM is limited due to problems with the effective dissipation of heat from the machining zone and instability of material removal. The machining of Inconel 625 alloy was carried out in the carbon dioxide as a dielectric supplied to the machining gap through the channel in the working electrode, in the milling kinematics. In one of the investigated variants, the workpiece was submerged additionally in the deionized water during machining. The main aim of this research was to determine an influence of EDM milling in carbon dioxide with and without external workpiece cooling on the workpiece technological surface integrity i.e. roughness, morphology and microhardness. The pulse time, current amplitude and gas pressure were selected as investigated parameters. Obtained results indicate significant differences in surface layer properties for both investigated machining variants.

Introduction

Electro-Discharge machining (EDM) is one of the most commonly used in all the branches of industry, non-conventional machining methods, where the material is melted, evaporated and removed as a result of electrical discharges occurring between the working electrode and the workpiece in the working electrode gap, which is filled with dielectric. Because of the thermal character of EDM it is possible to machine each material which is an electroconductive (in some cases also semi-conductors can be machined) regardless its mechanical or chemical characteristics. EDM process enables to shape very small elements with high precision, good surface quality and acceptable accuracy, it is also possible to get even very thin - walled (high aspect-ratio) elements with complicated shapes. Changes in the technological properties of the surface layer which occur as a result of the spark erosion effect are strictly related to the used EDM machining process parameters. There are few factors which affect the EDM process such as current intensity, voltage, pulse on and off time, dielectric type, material of working electrode and EDM generator type. The literature [1] emphasizes the key influence of the type of used dielectric on the properties of the surface layer. This is related to the physical properties of the dielectric, which determine the possibility of electrical discharges, the ability to extinguish the arc and cooling and solidification of evaporated or melted material, removal of erosion products from the treatment zone, as well as heat dissipation from the workpiece and electrode [2]. It should be also pointed that the thermal and electrical character of EDM implies the need to pay special attention to the thermal and electrical properties of the machined materials. Workpiece thermal and electrical properties determine the efficiency of the machined material melting, evaporation and cooling.

It is possible to divide dielectrics that are used in EDM into three groups: hydrocarbon-based dielectric liquids, water-based dielectric liquids and gaseous dielectrics. In the variant of EDM in gas, the gas (e.g. air, oxygen or nitrogen) is used as dielectric and the melted material is removed from machining gap by the high-pressure gas flow through thin-walled pipe electrode. The role of gas is to cool, solidify and prevent molten material from welding to the electrode and workpiece. In addition,

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gas-jet stabilize the plasma channel between sequent discharges and allows to recovery of dielectric strength in the machining gap. As omitting gas air, nitrogen, oxygen and a mixture of argon and air can be applied. Conventional EDM treatment in a liquid dielectric is a strictly thermal process, while in the EDM treatment in the reactive gas oxidation occurs – which testify about the thermo-chemical nature of the treatment [3]. In comparison to treatment in liquid one can state following advantages of EDM treatment in a gas [2, 4, 5, 6]: (1) reduced negative impact on the natural environment (no harmful products of dielectric decomposition reach the atmosphere), (2) due to the lower energy density, more uniform working electrode linear wear, (3) smaller inter-electrode gap, better machining accuracy, (4) relatively good surface quality (thin thermal influence layer), (5) higher machining efficiency, which is determined by the process stability (for some machining conditions the plasma channel can develop more easily). However, despite of a number of advantages of the EDM process in the gas, there is still a significant problem with the effective heat removal from the machining zone and material surface, the appropriate selection of process parameters, and thus achieving the appropriate stability and efficiency of the treatment. Therefore, EDM in gas is still not used in industrial conditions.

In the literature, one can find examples of using EDM in gas in various kinematic variants and modifications of the process itself (so-called process hybridization). One of the hybridization describes Yang et al. [7], who indicate the use of EDM in milling kinematics in deionized water using oxygen as a dielectric (in this configuration one can state that is quasi dry-EDM process). Thanks to the continuous supply of oxygen to the machining zone and the fast-moving working electrode, very high machining efficiency have been achieved and at the same time the oxidation of the surface increased. Joshi et al. [8] introduced the pulsed magnetic field during dry-EDM. It allowed to achieve a 130% increase in the machining efficiency with negligible working electrode wear (in relation to EDM treatment in the gas without assistance). Liqing and Yingjie [9] due to use of a mixture of oxygen and other gases (argon, nitrogen and air) and the use of cryogenic cooling of the workpiece with liquid nitrogen achieved an increase in machining efficiency and a reduction in surface roughness.

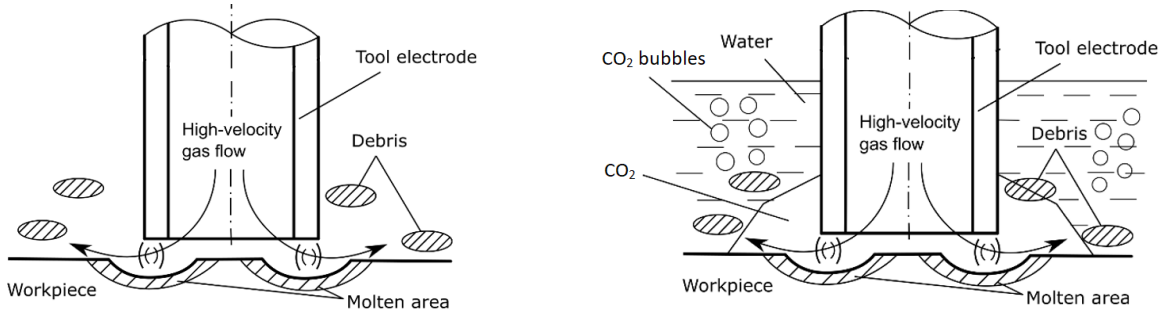
In the paper the results of dry-EDM milling of Inconel 625 in the carbon dioxide and in the second variant in the carbon dioxide with the sample immersed in the de-ionized water environment were presented. The goal of these research was to determine an influence of gap voltage, current intensity, pulse on-time and pulse off-time on the material surface integrity (i.e. roughness, heat affected zone, morphology and microhardness).

Materials and Methods

The EDM milling was conducted on the research test stand equipped with electro-discharge generator at the Cracow University of Technology. The tests were carried out with the application of tubular copper electrode with an outer diameter of 1 mm. The carbon dioxide as a dielectric was supplied to the machining gap through the channel in the working electrode in two following configurations (Fig. 1):

- variant A: the carbon dioxide as the medium was supplied with pressure to the machining gap through thin - walled pipe electrode,
- variant B: the carbon dioxide was supplied to the gap in similar way as in A, however the workpiece was submerged in the de-ionised water.

In both cases, the Inconel 625 alloy was machined and in each EDM milling operation 10 layers of material were removed, alternating in two directions (the working electrode was lowered by 25 μm each layer). Such a strategy allowed to stabilized machining conditions. For each variant 9 samples were machined with different pulse on-time, voltage, current and gas pressure (Tab. 1) and following constant machining conditions: polarity - working electrode (+), workpiece (-); pulse duty CO_2 factor: 0,5. The values presented in the Table 1 for samples 1A and 1B are the average values from three repetitions of the machining.



a) Dry-EDM (variant A)

b) Dry EDM in the deionized water environment (variant B)

Figure 1 Scheme of the two dry-EDM variants [10]

Table 1 Samples description with machining parameters

Sample number with additional external cooling (variant A)	Sample number without additional external cooling (variant B)	Pulse on-time [µs]	Voltage [V]	Current intensity [A]	Gas pressure [bar]
2A	2B	100	100	2.70	6
3A	3B	500	100	2.70	6
4A	4B	300	100	0.90	6
5A	5B	300	100	4.50	6
6A	6B	300	100	2.70	2
7A	7B	300	100	2.70	10
1A (3 repetition)	1B (3 repetition)	300	100	2.70	6

Presented below analysis was focuses on selected aspect of surface integrity and consists of: surface roughness (parameters Rq, Rz, Rsk, Rku), SEM photographs and microhardness comparison for samples machined with two mentioned before variants. The surface roughness was measured with the Taylor Hobson profilometer (because of the sample size, measuring length was 4 mm). The microhardness tests were performed with Vickers method on INNOVATEST microhardness tester at the load of 0.001 N. The hardness measurements were taken at three heights starting from the 50 µm from the machined surface to a value of 150 µm where the last measurements were taken. At each level the measurement was repeated three times.

Discussion of the results

Considering the results presented in Table 2, Figs. 2 and 3, one can state, that machining in variant B cause significantly improve of surface roughness parameters. However, considering nature of the investigated process one can state that it is hard to identify the relation between roughness parameters in dry-EDM which is caused by the stochastically distribution of discharge craters. In selected cases, the values of Ra and Rz are almost twice smaller than for variant A (i.e. sample 3A vs 3B, 4A vs 4B, 6A vs 6B). One can also state, that surface roughness changes with change of investigated parameters, however in case of pulse time and current amplitude roughens increases with t_i and I increases for both investigated variant, while change of CO_2 inlet pressure cause roughness increase only in variant B. The mean square deviation of the roughness profile Rq for the individual milling was also identified.

The value of Rsk gives information about the symmetry of the profile distribution in relation to mean plane. The lower the Rsk value, the flatter the surface and the more rounded the peaks what is which is beneficial during part exploitation (i.e. good lubrication purposes). It is worth mentioning the advantages of workpiece cooling, because in the variant B value of Rsk decreases with increasing

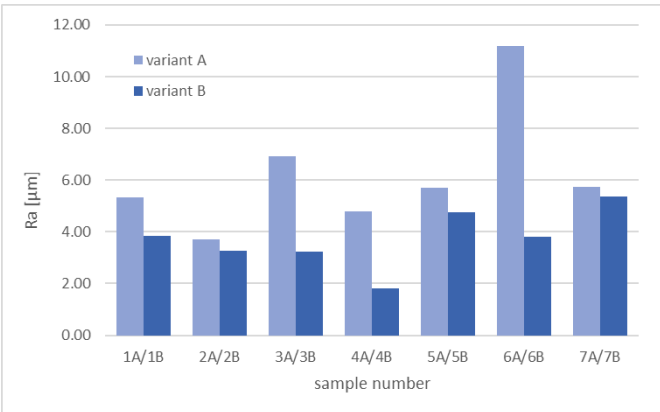
pulse time and current intensity, however an increase in the pressure of the gas supplied to the machining zone causes an increase in the value of Rsk for variant A and B.

The value of Rku (kurtosis) is a measure of the sharpness of profile peaks. When the distribution of profile peaks and valleys are normal Rku=3 µm, while for profiles with sharp peaks Rku can be higher than 20 µm. Considering obtained results one can state, that in majority cases Rku is close to 3 µm, so the profile height distribution is close to normal. The exception is sample 6B, where Rku=7.6 µm.

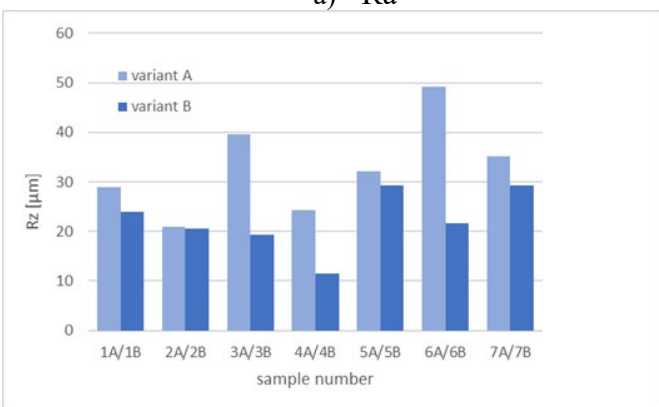
It is worthy to mention, that roughness values for experiments 3A/3B and 6A/6B differ significantly from the other samples. These tests were conducted with the same voltage and current intensity but for extreme value of pulse on-time (max. t_i=500 µs for samples 3A/3B) and gas pressure (min. p=2 bar for samples 6A/6B).

Table 2 Surface roughness parameters (mean values based on 3 measurements) after EDM in two variants

Sample number (var. A/var B)	Ra [µm]		Rz [µm]		Rq [µm]		Rsk [µm]		Rku [µm]	
	A	B	A	B	A	B	A	B	A	B
2A/2B	3.72	3.25	21.00	20.53	4.64	4.29	-0.01	0.72	3.03	3.75
3A/3B	6.92	3.25	39.53	19.23	8.77	4.09	0.36	-0.06	3.07	3.06
4A/4B	4.80	1.82	24.27	11.43	5.86	2.31	0.63	0.48	2.79	3.04
5A/5B	5.71	4.77	32.07	29.20	7.12	6.09	0.45	-0.04	3.14	3.20
6A/6B	11.19	3.82	49.27	21.57	13.37	4.72	0.05	0.10	3.53	7.67
7A/7B	5.73	5.36	35.10	29.30	7.26	6.51	0.48	0.20	3.23	2.82
1A/1B	5.34	3.83	28.88	23.99	6.58	4.90	0.44	0.07	3.07	3.18

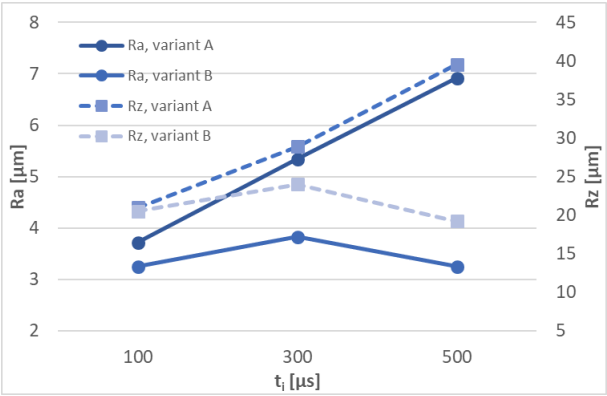


a) Ra

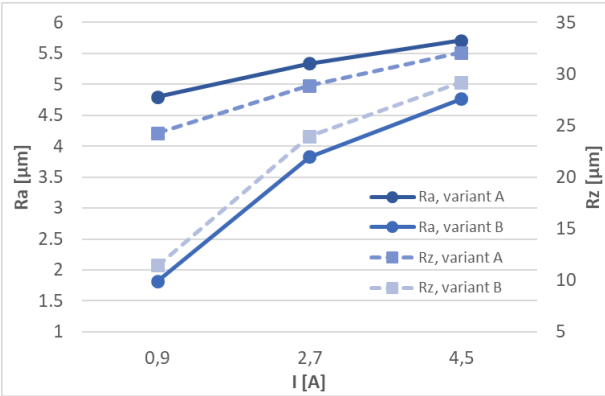


b) Rz

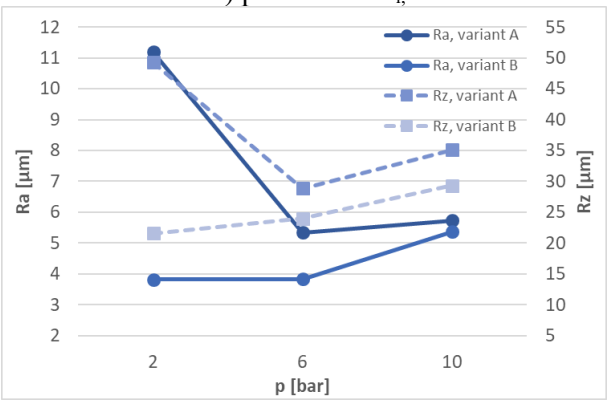
Figure 2 Comparison of surface roughness parameters for both investigated variants: a) Ra and b) Rz



a) pulse time - t_i,



b) current intensity - I



c) gas presurre - p

Standard deviations of Ra and Rz for samples machined with research plan central parameters (t_i=300 µs, I=2,70 A, p= 6 bar):

- 1A: σRa= 1,65 µm; σRz=7,12 µm,
- 1B: σRa= 0,55 µm; σRz=3,44 µm.

Figure 3 Comparison of the influence of different process parameters: t_i,, I and p on the surface roughness petameters Ra and Rz for investigated variants (relation based on the mean values according to Table 2)

The preliminary and qualitative analysis of changes in surface layer morphology SEM photographs of surface cross-section was considered. According to Figs. 4, 5, and 6 one can formulate the following conclusions:

- in both variants increase of pulse time current amplitude cause increase of thickness of white layer as well as more microcracks occur. Increase of t_i and I also increasing surface irregularities and makes discharge craters deeper, however such effect is more noticeable when machining is carried out in variant A (Fig. 4 and 5),
- the surface layer morphology depends also on gas pressure, especially when machining without workpiece cooling. In variant A increase of p cause decrease of thickness of white layer, discharge craters become shallower and less amount of melted material (particles) is visible on surface (Fig. 6). It is worth to mentioning that there were not such significant differences in case of machining in variant B.

Further analysis of heat affected zone properties is necessary, especially to explain the differences in the amount and thickness of solidified material on the machined surface.

The last investigated factor was surface microhardness, calculated as the average of the three measurements (Fig. 7). As a reference microhardness of raw material was also measured (its mean value was 229 HV). When analyzing the values of microhardness machined in variant A, one can state that in most cases it is lower than microhardness of raw material as well as microhardness of surface obtained during machining in variant B. The decrease of hardness in relation to raw material may result from changes in the chemical composition of surface layer. It is connected with phenomena occurring during melting and solidification of the electrode material, as well as the oxidation process. It leads to changes of composition in the surface layer and affects physical and chemical properties of material. However, to detail the change in microhardness further in-depth analysis is necessary, especially with regard to changes in the depth of the material.

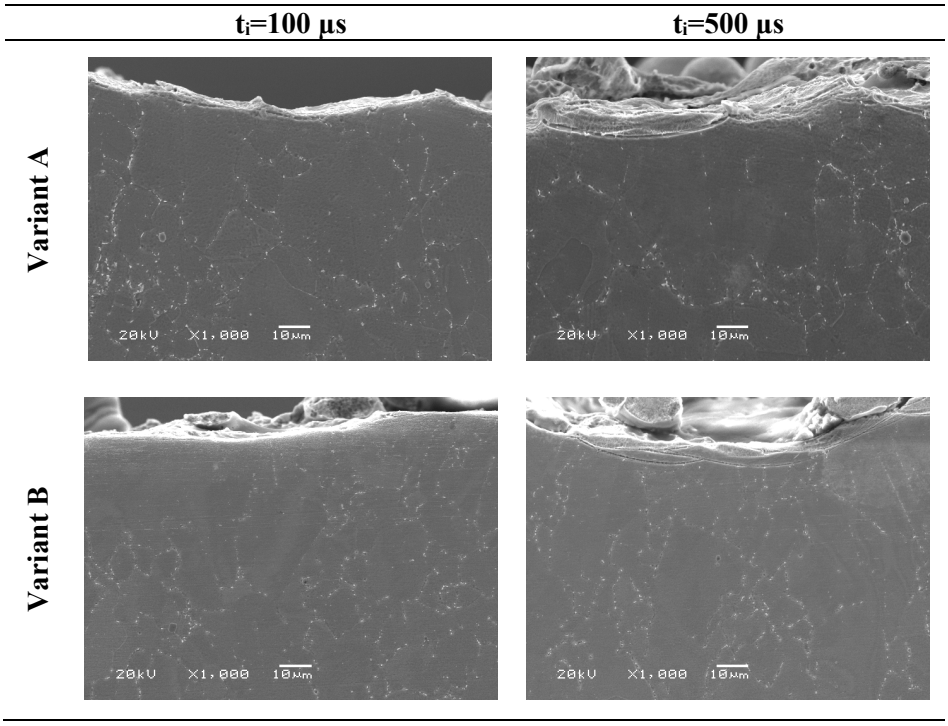


Figure 4 Comparison of the SEM photos after EDM process with pulse time t_i=100 µs and t_i=500 µs in two variants with the following machining parameters: U=100 V, I=2.7 A, p=6 bar.

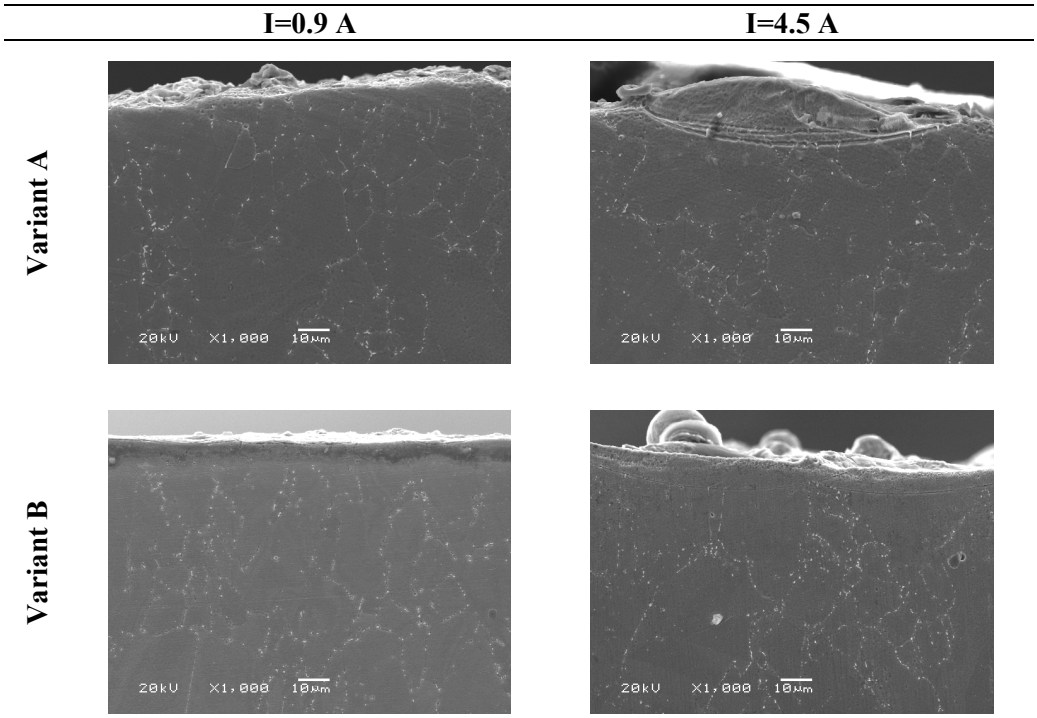


Figure 5 Comparison of the SEM photos after EDM process with current I=0.9 A and I=4.5 A in two variants with the following machining parameters: t_i= 300 µs, U=100 V, p=6 bar

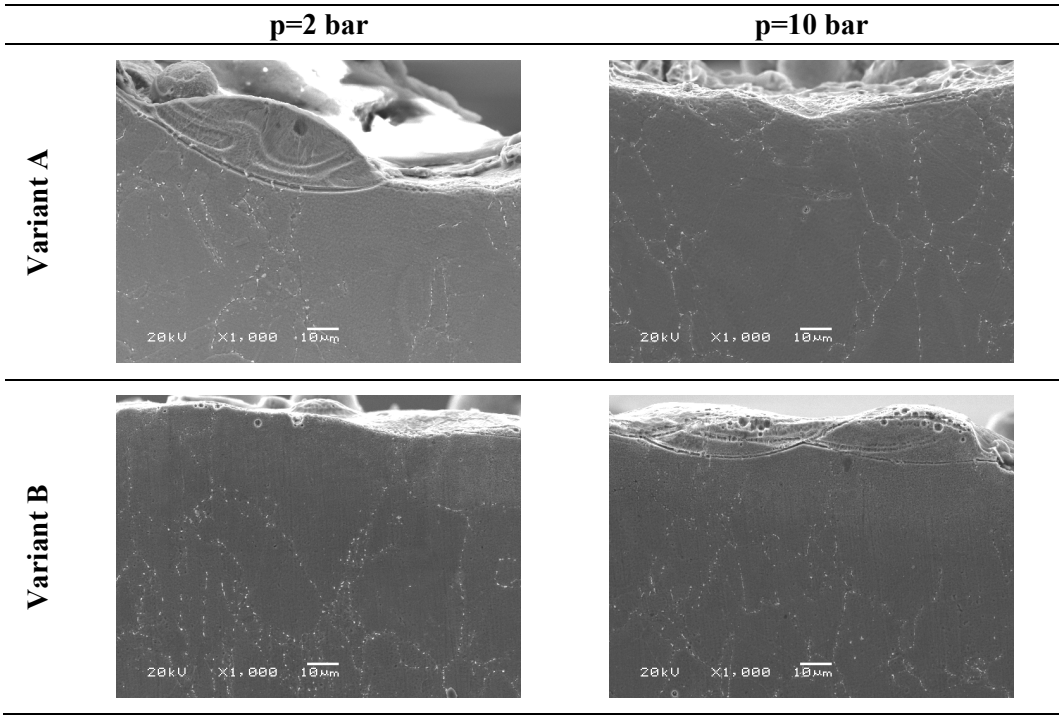


Figure 6 Comparison of the SEM photos after EDM process with pressure p=2 bar and p=10 bar in two variants with the following machining parameters: t_i= 300 μs, U=100 V, I=2.7 A

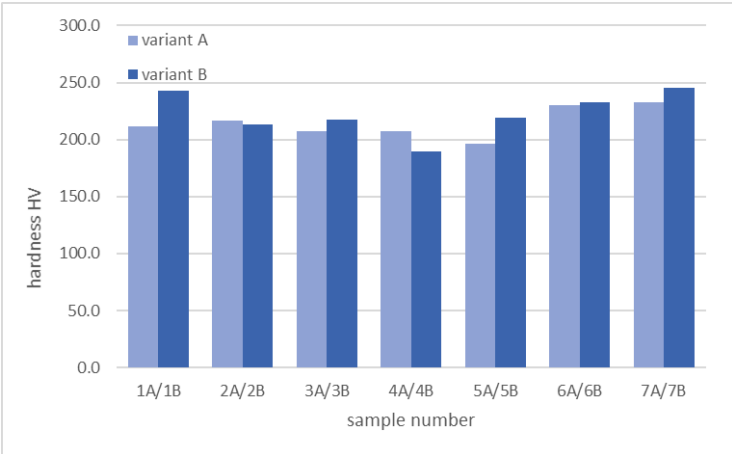


Figure 7 Results of microhardness measurements in two variants, average values from repetitions at three levels, RAW material hardness 229 HV

Summary

One of the most important advantages of dry-EDM process is that it is environmentally friendly, meaning that during the machining process decomposition of the harmful dielectric's components, as it happens during machining with e.g. carbon-based dielectric liquids, does not occur. Unfortunately, dry-EDM process is still not commonly used in industrial applications. It is caused by the complex physical-chemical nature of the process, problems with effective heat dissipation from the machining zone, as well as adjusting proper process parameters, allowing to achieve the appropriate reliability of material removal.

The main aim of the research described in the paper was to determine the influence of chosen process parameters on the material surface integrity. During the research it was stated that:

- machining in variant B (the carbon dioxide supplied with the pressure to the machining gap through thin-walled pipe electrode and the workpiece submerged in the de-ionised water) cause significantly improve of surface roughness parameters in comparison to variant A (the carbon dioxide supplied with pressure to the machining gap through thin-walled pipe electrode)

- in both variants by an increase of pulse time and current amplitude cause increase of thickness of heat affected zone,
- the surface layer morphology depends also on gas pressure, especially when machining without workpiece cooling, with the increase of gas pressure discharge craters become shallower and less amount of material is melted on the surface. Such significant differences were not noticed in variant B,
- in variant A in the most cases microhardness is lower than microhardness of raw material as well as microhardness of surface after machining in variant B. It will be caused by potential changes in the chemical composition of the surface layer.

Considering the complexity of the nature of electrical discharge machining in gaseous dielectrics, the broader and deeper analysis of the influence of mentioned EDM process parameters is required. It has to be noticed, that in variant B gap consists of stochastic mixture of gas and liquid (which influence on gap deviations) and application of carbon dioxide has influence on the nature of spark discharge and material removal process. Therefore, further research should especially focus on these aspects of proposed modification of dry-EDM process and its influence on the heat affected zone properties in details.

References

[1] S. Chakraborty, V. Dey, S. K. Ghosh, A review on the use of dielectric fluids and their effects in electrical discharge machining characteristics, Precis. Eng. 40 (2015) 1–6.

[2] F. T. B. Macedo, M. Wiessner, C. Hollenstein, F. Kuster, K. Wegener, Investigation of the Fundamentals of Tool Electrode Wear in Dry EDM, Procedia CIRP 46 (2016) 55–58.

[3] M. Kunleda, Y. Miyoshi, T. Takaya, N. Nakajima, Y. ZhanBo, M. Yoshida, High Speed 3D Milling by Dry EDM, CIRP Ann. - Manuf. Technol. 52 (2003) 147-150.

[4] M. Kunieda, M. Yoshida, N. Taniguchi, Electrical Discharge Machining in Gas, CIRP Ann. - Manuf. Technol. 46 (1997) 143–146.

[5] P. Govindan, S. S. Joshi, Experimental characterization of material removal in dry electrical discharge drilling, Int. J. Mach. Tools Manuf. 50 (2010) 431–443.

[6] R. Roth, F. Kuster, K. Wegener, Influence of oxidizing gas on the stability of dry electrical discharge machining process, Procedia CIRP 6 (2013) 338–343.

[7] D. Yang, M. Qiu, Y. Han, L. Kong, W. Zhou, Z. Liu, Technology of ablation milling by fast-moving electrode, Int. J. Adv. Manuf. Technol. 96 (2018) 103-109.

[8] S. Joshi, P. Govindan, A. Malshe, K. Rajurkar, Experimental characterization of dry EDM performed in a pulsating magnetic field, CIRP Ann. - Manuf. Technol. 60 (2011) 239–242.

[9] L. Liqing, S. Yingjie, Study of dry EDM with oxygen-mixed and cryogenic cooling approaches, Procedia CIRP 6 (2013) 344–350.

[10] A. Żyra, W. Bizoń, S. Skoczypiec, Primary research on dry electrodischarge machining with additional workpiece cooling, AIP Conference Proceedings 2018.