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# Influence of material properties on near dry-EDM process: The discussion of research for titanium grade 2 and Inconel 625 alloy

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**Abstract.** Dry EDM machining with external workpiece cooling is one of the possible modifications of dry EDM process, which enables to reduce the negative impact of EDM machining on the environment and on the machine tool operator. At the same time, it is possible to obtain relatively good machining accuracy and surface quality. Due to the problems with the effective heat dissipation from the machining gap, the application of dry-EDM is still limited to micromachining. In this paper the comparison and discussion of dry-EDM technological factors for two hard to machine materials: Inconel 625 and Titanium Grade 2 have been presented. The tests were carried out in carbon dioxide as a dielectric supplied to the machining gap through the channel in the workpiece electrode. To improve the process effectivity additional workpiece cooling were also applied, however the presence of fluid in machining area makes the process near dry-EDM. The input machining parameters were pulse time, machining voltage, current amplitude and inlet gas pressure. The main aim of this work was to show the significance of the type of machined material on the material removal rate, and surface layer (i.e. roughness, morphology and microhardness). The results analysis will be discussed considering differences in physical properties of machined materials.

## Introduction

Nickel and chromium-based superalloys such as Inconel 625 and titanium Grade 2 are widely used in all the branches of industry, such as aviation, space industry, automotive and power generation industry. Inconel alloys account for more than half of the materials used to manufacture the hot sections of turbojet engines [1]. Inconel alloys are used similarly to titanium alloys for the manufacture of turbine blades of high-temperature turbo-machine engine components [2]. Titanium alloys are also used very extensively in the medical industry, particularly because of their biocompatibility, which is very important for implant materials. Due to the physical and mechanical properties of these materials, conventional machining of these materials is very difficult and, moreover, often cost-intensive due to high material losses during machining (material costs) and tool wear [3,4]. Machining methods which may be used for mentioned materials are unconventional machining methods such as electrochemical, electro-discharge or ultrasonic machining [5,6].

The physical phenomena occurring during material removal in EDM are very complex [2,7]. When the potential is applied to both electrodes (workpiece and tool electrode), a pulsed DC is generated between these electrodes. At the time when the gap width is adequate and the breakdown field strength is exceeded, the dielectric breakdown phenomena by gases occurs and electrons are emitted from the working electrode. Accelerated in the electric field electrons collide with the atoms of the gas leading to atoms' ionization, which results in formation an ionization fronts from anode and cathode. When the fronts are connected, then a flow of high current in a small bridge occurs. It results in forming plasma channel with gas-interface. The rapid thermal processes lead to melting, boiling and evaporating of the workpiece surface and the tool electrode. As a result, a discharge channel consisting of an inner plasma channel and a transition area into the gas phase. The discharge channel close implosively, after the pulse is down and its volume increases continuously with the high internal pressure development, which enables the removal of some of the molten metal from the crater. Dielectric is poured over the molten metal in the craters, causing rapid cooling of the electrode material, so that micro-cracks can also form within the craters formed. The main function of the dielectric fluid is to cool, solidify the molten workpiece material and remove it from the machining zone [8,11].

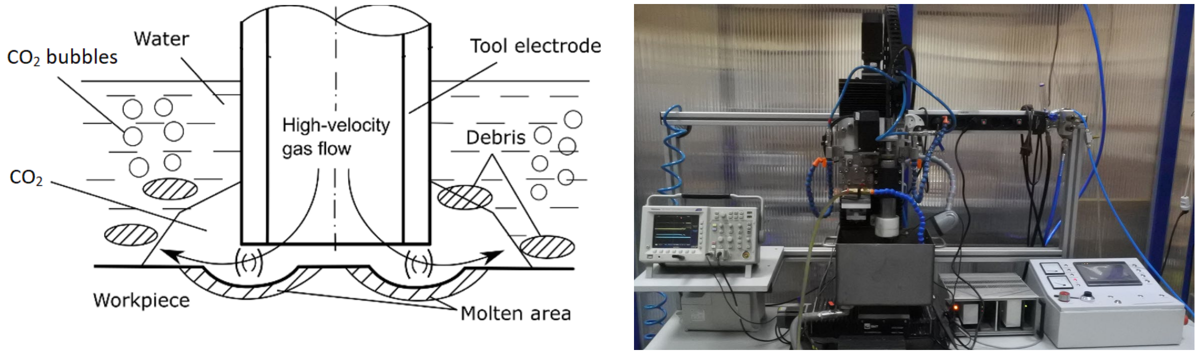
The undoubted advantage of EDM is the dimensional and form accuracy that can be achieved during the process, even when machined feature size is below 100 µm. During stable machining the machining accuracy might be in range of the machining gap width. Disadvantages include the low machining productivity, high working electrode wear, as well as thermal stresses that occur in the surface layer after machining [12]. There are advantages of EDM such as possibility to machine any material which is electrical conductor (stainless stills, carbides, titanium and nickel alloys, etc., materials which are characterized by high hardness) it is also possible to obtain thin-walled elements, with complicated geometry and at the same time with very good accuracy (even close to 2 µm). However, one of the biggest drawback of EDM is the negative environmental impact when machining in liquid dielectrics, especially when the most commonly used hydrocarbon dielectrics are applied. One possible solution in the entrepreneurship where there is no possibility to use other machining technology than EDM, to reduce the negative influence on the environment and the machine-tool operator might be the usage one of alternative, environmentally neutral dielectrics. These include gaseous dielectrics such as air, oxygen, nitrogen, argon or carbon dioxide [13].

Due to the fact that during dry-EDM process it is still a problem with effective removal of heat from the machining gap, as well as workpiece material surface, adequate selection of process input parameters, dry-EDM is still limited to micromachining and is not used in industrial applications [14]. What is more one of the factors which has major impact on dry-EDM process it the workpiece material. Roth et al. [15] shows in his work, the influence of process stability and dry-EDM efficiency, not only because of the material's' physical properties, but mainly due to the properties which have a direct impact on the nature of the discharges produced during machining.

In this paper the results of dry-EDM milling of Inconel 625 and titanium Grade 2 in the carbon dioxide with the additional external workpiece cooling (sample immersed in the de-ionized water environment) were presented. The goal of this research was to determine the influence of material properties on dry-EDM process, considering gap working voltage, current intensity, pulse on-time, pulse off time and gas pressure. It is also worthy to mention that research of dry-EDM with carbon dioxide as dielectric medium is rarely described in the literature.

## Materials and Methods

The near-dry EDM milling was conducted on the research test stand equipped with electro-discharge generator MATRIX MPS – 7163 160V/3A at the Cracow University of Technology [14]. The tool was tubular copper working electrode with an outer diameter of 1 mm. The carbon dioxide as the medium was supplied with pressure to the machining gap through thin - walled pipe electrode, while the workpiece was submerged in the de-ionised water (Fig. 1). Inconel 625 alloy and titanium Grade 2 were machined in the milling kinematics, with the parameters described in Table 1. The polarity during machining Inconel 625 was - working electrode (+), workpiece (-); during machining titanium Grade 2 - working electrode (-), workpiece (+). The electrode polarity was established on the basis of the preliminary tests, where the machining stability and working electrode wear were verified for machining both Inconel 625 alloy and titanium Grade 2. The difference between used electrodes polarity between Inconel alloy and titanium Grade 2 is caused by the characteristic of used EDM generator type, as well as differences in the materials properties. For the samples 7A and 7B, the average values from three repetitions of the machining are presented in Table 1.



a) b)

*Fig 1. a) Scheme of dry-EDM in the deionized water environment [14,16], b) test stand.*

*Table 1. Samples description with machining parameters, working tool: tubular copper electrode Ø1 mm, gas: carbon dioxide, external coolant type: deionised water (G= 0.01 µS), voltage: U=100 V*

| **Inconel 625 (A)** | **titanium Grade 2 (B)** | **Pulse on-time [µs]** | **Voltage [V]** | **Current intensity [A]** | **Gas pressure [bar]** |
|---|---|---|---|---|---|
| 1A | 1B | 100 | 100 | 2.70 | 6 |
| 2A | 2B | 500 | 100 | 2.70 | 6 |
| 3A | 3B | 300 | 100 | 0.90 | 6 |
| 4A | 4B | 300 | 100 | 4.50 | 6 |
| 5A | 5B | 300 | 100 | 2.70 | 2 |
| 6A | 6B | 300 | 100 | 2.70 | 10 |
| 7A (3 repetition) | 7B (3 repetition) | 300 | 100 | 2.70 | 6 |

Described below analysis was focused on comparison of selected aspects of surface integrity of Inconel 625 alloy and titanium Grade 2 after dry-EDM in the milling kinematics with external workpiece cooling such as: surface roughness parameters (measured with Taylor Hobson profilometer), SEM photographs and microhardness. The detailed research methodology and research devices which were used during this research were described in [14].

## Discussion of the Results

Fig. 2 shows the differences of material removal rate during (MRR) dry-EDM of Inconel 625 and titanium Grade 2 with external workpiece cooling. MRR was determined by the calculation of the workpiece material volume removed and the total milling time in each trial (each time removing 10 layers of material).

It is possible to say that in the most trials, the material removal rate is higher for Inconel 625, or material removal rates for both materials are very close. However, the exceptions are: trials 4B (where the highest current value, I=4.5 A, was used) and 3B (where the lowest current value, I=0.9 A, was used). Trial 3B was interrupted after removal of the one layer of the material, as the total milling time for this layer exceeded the total milling time for the 10 layers of titanium Grade 2 in all other cases. It was stated that milling with these machining parameters used for trail 3B is inefficient. As a result, in all diagrams trial 3B is marked in a separate color (grey).

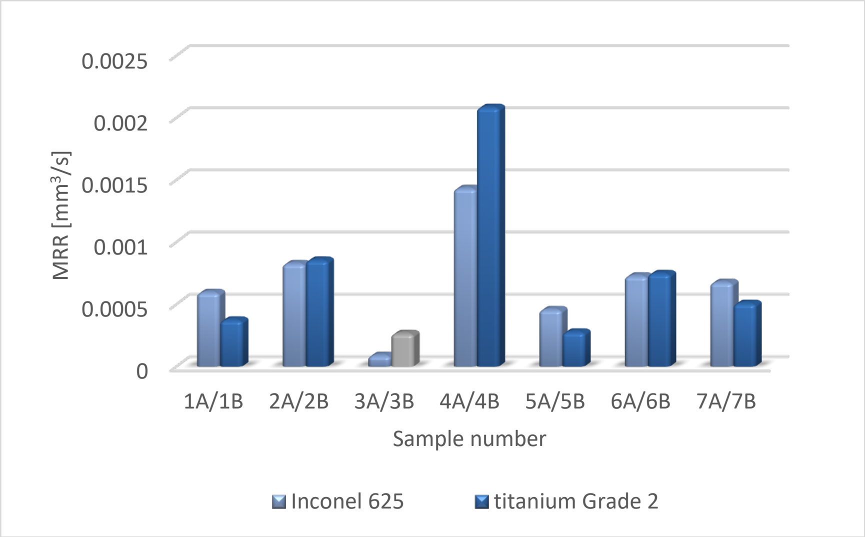


*Fig 2. Comparison of material removal rate during dry-EDM of Inconel 625 and titanium Grade 2 with external workpiece cooling.*

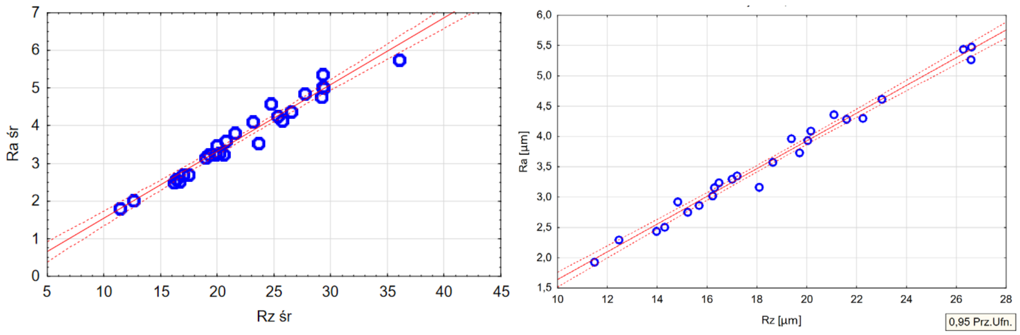
Considering the results presented in Table 2, Fig. 3, Fig. 4, one can state, that the significant differences between the results of roughness parameters of Inconel 625 and titanium Grade 2 may be observed. Much higher values of Ra and Rz parameters were obtained for Inconel 625 comparing to titanium Grade 2, when machining with higher current intensity (I=4.5 A), sample 4A, and with highest pressure (p=10 bar), sample 6A. What is more the influence of input process parameters to Ra and Rz roughness parameters can be observed. In case of the current intensity and gas pressure similar tendencies may be noticed. Strong linear correlation pattern between Ra and Rz parameters was also observed (r=0.980 for Inconel 625 and r=0.992). The examples of roughness profiles are presented in the Fig. 5.

The value of mean square deviation of the roughness profile Rq in most cases is lower for titanium Grade 2. Rsk parameter 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. Much lower values of Rsk parameter were obtained after EDM machining of titanium Grade 2.

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 for Inconel 625, so the profile height distribution is close to normal. Similar, in most cases Rku is close to 3 µm for titanium Grade 2, however it is higher for 4B (I=4.5 A), 6B (p=10 bar) and 7B (research plan center) trial.

*Table 2. Surface roughness parameters of Inconel 625 and titanium Grade 2 (mean values based on 3 measurements) after dry-EDM with additional workpiece cooling.*

| **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** |
| 1A/1B | 3.72 | 3.94 | 21.00 | 20.02 | 4.64 | 5.08 | -0.01 | -0.04 | 3.03 | 3.66 |
| 2A/2B | 6.92 | 3.30 | 39.53 | 16.99 | 8.77 | 4.20 | 0.36 | -0.30 | 3.07 | 3.32 |
| 3A/3B | 4.80 | 2.30 | 24.27 | 12.46 | 5.86 | 2.89 | 0.63 | -0.87 | 2.79 | 3.99 |
| 4A/4B | 5.71 | 2.93 | 32.07 | 14.82 | 7.12 | 3.74 | 0.45 | -0.07 | 3.14 | 4.11 |
| 5A/5B | 11.19 | 4.09 | 49.27 | 20.16 | 13.37 | 5.16 | 0.05 | -0.14 | 3.53 | 3.25 |
| 6A/6B | 5.73 | 2.87 | 35.10 | 15.68 | 7.26 | 4.16 | 0.48 | -0.77 | 3.23 | 6.99 |
| 7A/7B | 5.34 | 4.20 | 28.88 | 21.35 | 6.58 | 5.52 | 0.44 | 0.18 | 3.07 | 5.13 |



a) b)

*Fig. 3. Comparison of correlation coefficient between Ra and Rz parameters for a) Inconel 625 and b) titanium Grade 2.*

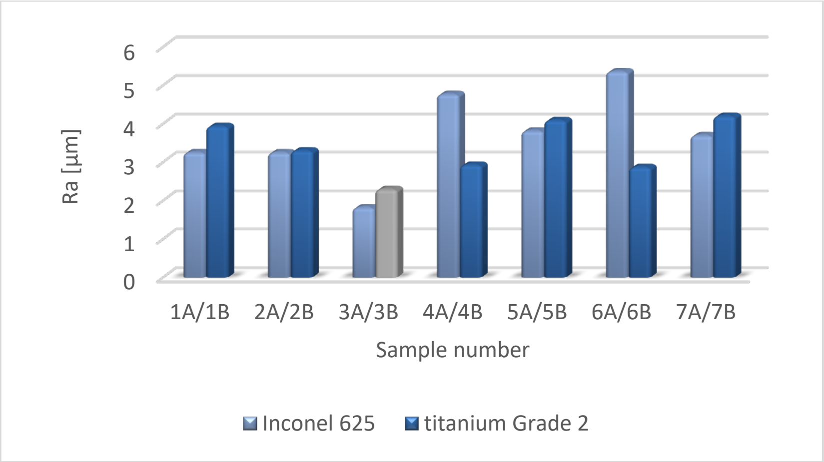
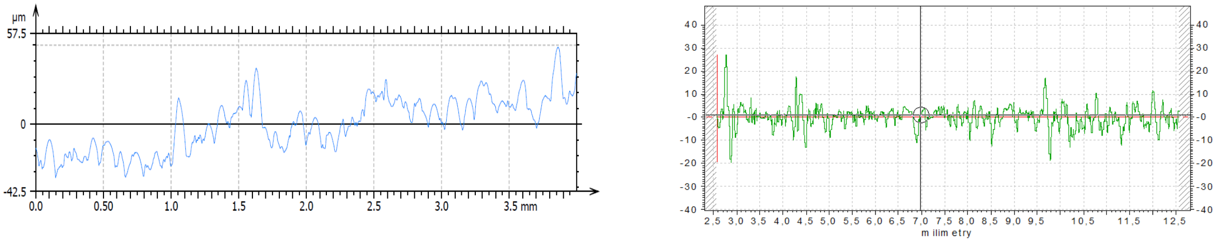
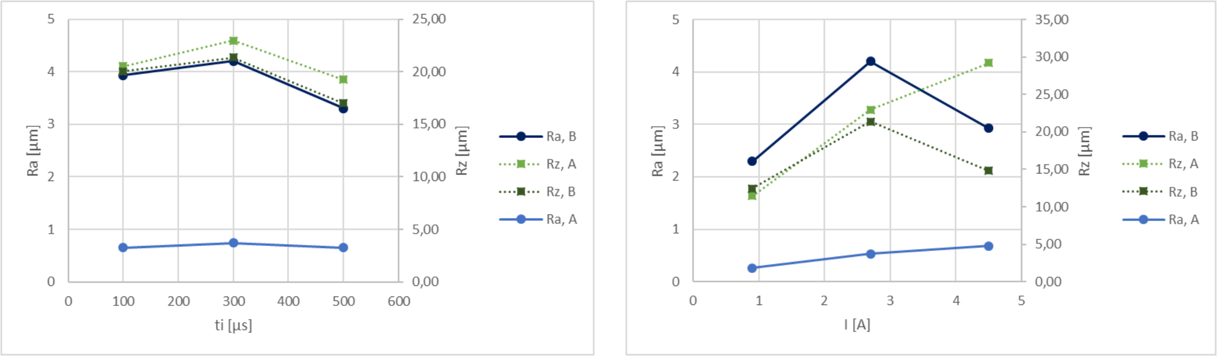


*Fig. 4. Comparison of surface roughness parameter Ra for Inconel 625 and titanium Grade 2.*

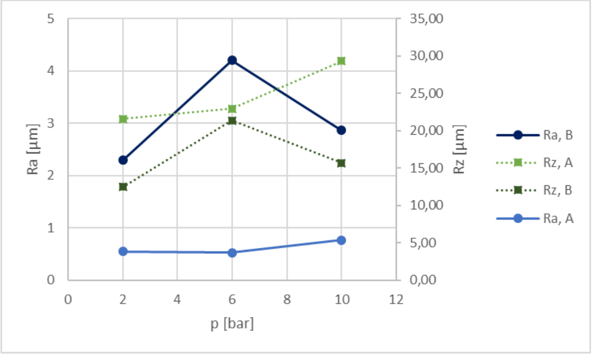


a) Inconel 625 b) titanium Grade 2

*Fig. 5. Comparison of surface roughness profiles of Inconel 625 and titanium Grade 2 for the research plan centre* $t_i$*=300 µs, U= 100 V, I=2.7 A, p= 6.*



a) pulse time - $t_i$, b) current intensity - I



c) gas presurre - p

*Fig. 6. Comparison of the influence of different process parameters:* $t_i$*, I and p on the surface roughness petameters Ra and Rz for Inconel 625 and titanium Grade 2 (relation based on the mean values according to Table 2), Standard deviations of Ra and Rz for samples machined with research plan central parameters (ti=300 µs, I=2.70 A, p= 6 bar): 1A: σRa= 1.65 µm; σRz=7.12 µm, 1B: σRa= 4.2 µm; σRz=21.6 µm.*

Titanium grade 2 is characterized by low thermal conductivity and a single-phase α-structure, that is why no phase transformations were observed in the heat-affected zone (Fig. 7-9). The structural changes of the surface layer mainly involved the white layer, which is due to the lack of phase transformations and therefore it is difficult to observe the heat-affected zone. Of course, depending on the machining parameters used, changes in the shape of the grooves can be observed. The bottom of the groove is even and flat, the cross-section seems to reflect the actual shape of the working electrode. In the case of Inconel 625 (Fig. 7-9) surface layer morphology changes can be noticed (Fig. 7-9 A-F). With the increase of pulse time (Fig. 7 A-B), the depth of the milling grooves increases and also the recast layer becomes thicker ($t_i$= 500 µs). The cross-sections also show increasing surface irregularities and deepening the discharge craters. Similar relationships can be found with increasing current intensity (Fig. 8 C-D). The increase of gas pressure causes the white layer thickness decrease (Fig. 9 E-F). At the same time discharge craters become shallower and less amount of melted material can be found on the workpiece surface.

Inconel 625 and titanium Grade 2 after dry-EDM milling with additional workpiece cooling are characterized by different hardness. In the Fig. 10 the hardness of each RAW material (Inconel 625 and titanium Grade 2) is given. It is possible to say that the values of microhardness of Inconel 625 and titanium Grade 2 in most cases are lower than for RAW materials. The Inconel 625 hardness decrease comparing to the RAW material may be caused by chipping of the recast layer during preparation of metallographic microsections or the dissolution of the carbides in the heat affected zone. In the case of titanium Grade 2, the decrease of microhardness comparing to RAW material may be related to the changes that have occurred in the material as a result of energy - electrical discharges occurring there. In the initial state, titanium Grade 2 had been cold-formed before treatment and was therefore strengthened. Energy application (electrical discharge) may cause the internal stresses removal and dislocations can be regrouped (dislocations allow the material to deform if they are free to move), as well as the density of dislocations decreases. As a result, strength and hardness decrease, while plastic deformability increases.

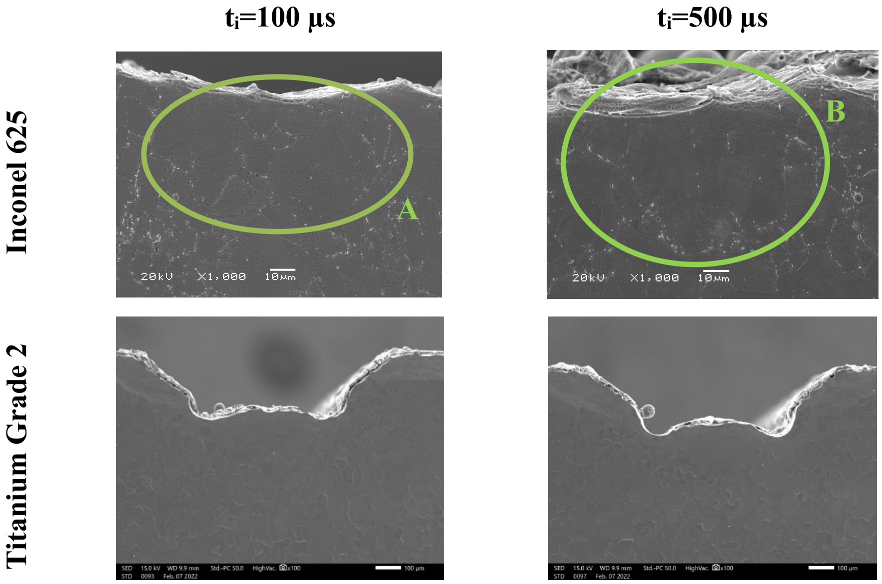


*Fig. 7. Comparison of the SEM photos of Inconel 625 and titanium Grade 2 after EDM process with pulse time $t_i$=100 µs and $t_i$=500 µs with the following machining parameters: U=100 V, I=2.7 A, p=6 bar.*

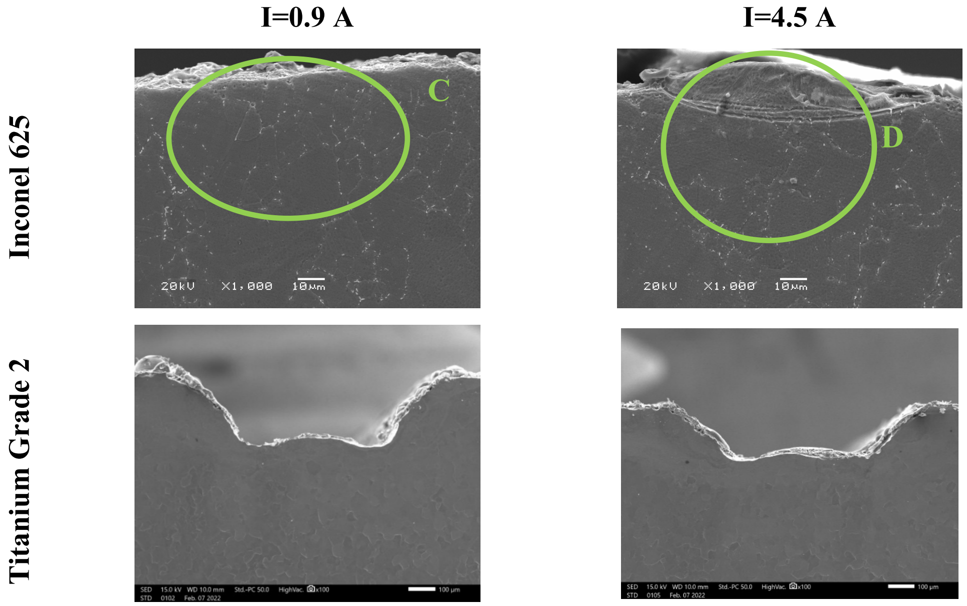


*Fig. 8. Comparison of the SEM photos of Inconel 625 and titanium Grade 2 after EDM process with current I=0.9 A and I=4.5 A s with the following machining parameters: $t_i$= 300 μs, U=100 V, p=6 bar.*

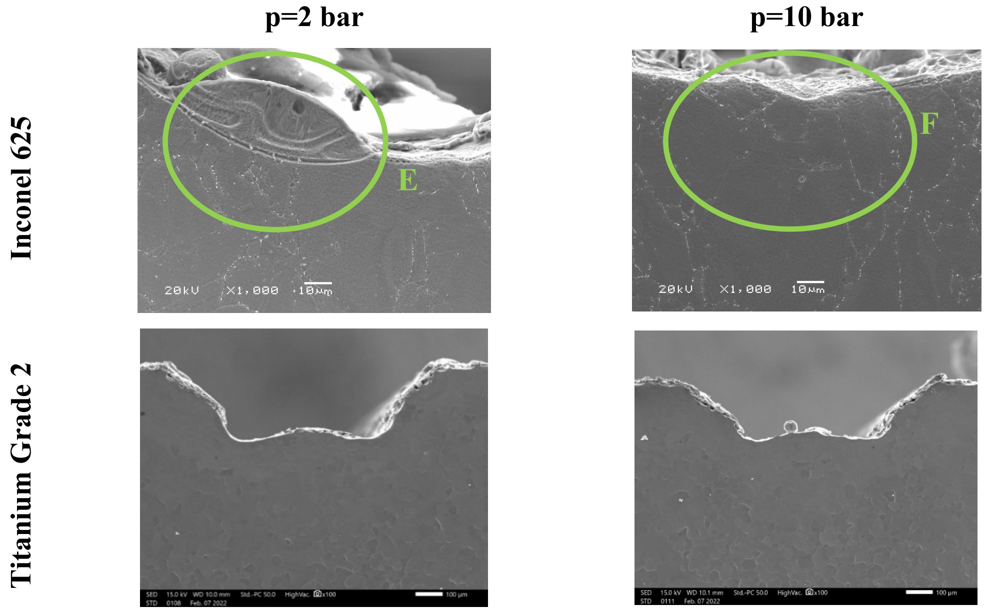


*Fig. 9. Comparison of the SEM photos of Inconel 625 and titanium Grade 2 after EDM process with pressure p=2 bar and p=10 bar with the following machining parameters: $t_i$= 300 μs, U=100 V, I=2.7 A.*

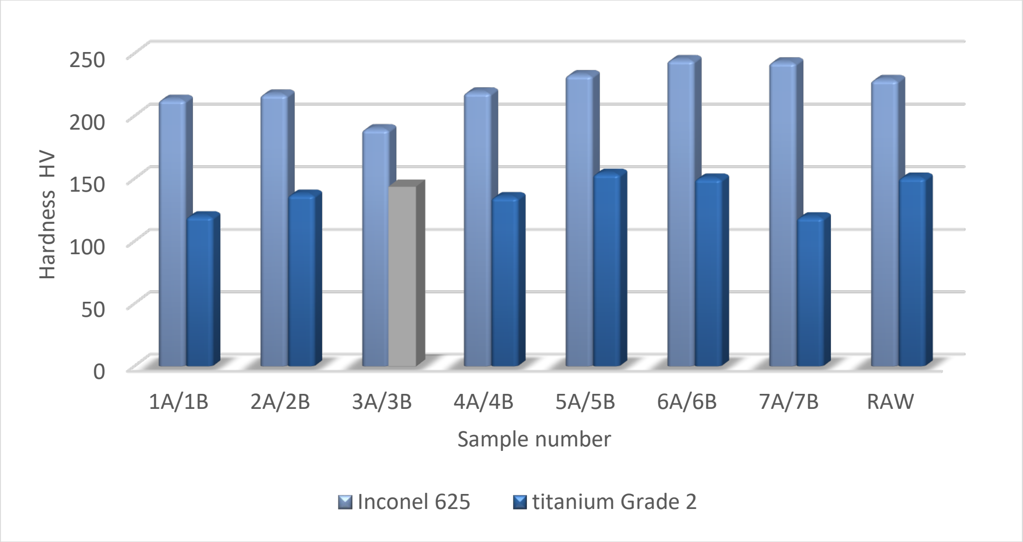


*Fig. 10. Results of microhardness measurements of Inconel 625 and titanium Grade 2, average values from repetitions at three levels, RAW material hardness for reference for Inconel 625 and titanium Grade 2.*

## Summary

According to the research work carried out, the type of material (and, in particular, its internal structure, thermal and electrical conductivity) which was EDM milled in carbon dioxide, is crucial for the conducted machining process, obtained machining efficiency, working electrode wear, as well as surface roughness. However, is worth to underline that, regardless of the type of machined material, the productivity of the process is very low, which favours micro machining as an application area for the investigated process. In this application, the benefits of external cooling, such as better surface layer properties (roughness, lower thermal changes) and lower working electrode wear, result in easier designing of the machining process (it is easier to compensate the occurring lower working electrode wear) and determine the application area (better surface layer properties). It is worthy to underline, that considering the nature of the dry-EDM with additional workpiece cooling, it is hard to identify the relation between roughness parameters. It is caused by the stochastically distribution of discharge craters during the dry-EDM process. The better representation of roughness is considered to be obtained after 3D roughness measurements, which should much better represent the state of the surface roughness (especially given the randomness of the EDM discharges). Therefore, in further research it is recommended to conduct 3D roughness measurements.

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