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Green-EDM approaches for biocompatible processing of rolled and 3D printed titanium alloys

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Abstract
The present study constitutes a research on the feasibility of employing dry electrical discharge machining (dry-EDM) for medical applications. The investigations aim to evaluate the surface integrity of titanium Grade 2 (rolled semi-finished product) and Ti6Al4V ELI alloy fabricated by direct metal laser sintering (DMLS), subjected to dry-EDM under different gaseous atmospheres. The findings are expected to identify the influence of material preparation method and individual gases on the technological surface layer condition, which is critical for ensuring biocompatibility and promoting osseointegration in biomedical applications. From an environmental perspective, the proposed approach aligns with the principles of *green-EDM*, a sustainable variant of EDM characterized by negligible ecological impact

dry-EDM, titanium, DMLS, medical applications

1. Introduction

Electrical discharge machining (EDM) is a non-conventional manufacturing process in which material is removed as a result of a series of controlled electrical discharges occurring in a narrow interelectrode gap filled with a dielectric medium. Conventional EDM employs liquid dielectrics, such as hydrocarbon-based fluids or deionized water, which present technological and environmental limitations. Hydrocarbon media may deteriorate surface layer integrity, while deionized water can induce oxidation and pose challenges in maintaining stable dielectric properties. For ecological and occupational health reasons, gas-based EDM is considered a promising alternative, as it eliminates harmful decomposition products associated with liquid dielectrics. However, the type of gaseous dielectric significantly influences machining stability, efficiency, electrode wear, and surface integrity [1]. Components such as implants, surgical instruments, and medical robotic elements intended for contact with blood and saliva require controlled surface morphology, chemical stability, and high surface integrity. The development of green-EDM and dry-EDM technologies may therefore constitute a crucial step toward environmentally responsible and clinically safe manufacturing solutions for advanced medical devices [2].

2. Methodology

Dry electrical discharge machining (dry-EDM), was conducted on a dedicated experimental test stand in milling kinematics The test stand was equipped with an electro-discharge generator MATRIX MPS–7163 (160 V / 3 A and gaseous supply system, enabling machining in a gaseous dielectric. In this configuration, carbon dioxide (CO_2) and argon (Ar) were delivered under controlled pressure directly into the interelectrode gap through a thin-walled tubular electrode, thereby ensuring dielectric circulation within the discharge zone (Fig. 1 a)). A single dry-EDM milling experiment involved the removal of ten successive material layers, executed in both tool feed directions, in each pass, the working electrode was lowered by 25 µm, which was established in the preliminary investigations The workpieces comprised two specimens fabricated by direct metal laser sintering (DMLS Ti6Al4V) and commercially pure Titanium Grade 2 rolled (semi-finished product), each with nominal dimensions of 40.6 × 15.0 × 12.1 mm. Each trial was repeted three times.

Table 1 Input parameters of the experimental plan

Symbol	Parameter	Values
t	Pulse on time	300 µs
U	Voltage	100 V
I	Current intensity	2.7 A
p	Gas pressure	6 bar

Table 2 Constant machining conditions during tests

Parameter	Values
Working Electrode (WE)	Thin-walled tungsten pipe
WE outer diameter	Ø1 mm
Rotational speed of the WE	250 rpm
Gas medium	Carbon dioxide/argon
Pulse duty factor (Ŋ)	0.5
Removed material layers per trial	10
Kinematics of WE movement	Milling

The material removal rate (MRR) was calculated according to the formula:

$$MRR = \frac{Vm}{t},$$

Where *Vm* is the volume of removed workpiece material and t is the total machining time per trial. 3D surface roughness measureents were conducted using an optical confocal profilometry technique with the Al/Surf 520 measurement system (Al/met). Measurement series were performed over areas of 8 × 2 mm. The following surface roughness parameters wereinvestigated: Ssk, Sku, Sz, Sa. Microstructural observations were performed using a JSM-IT200 scanning electron microscope.

3. Results

When comparing machining efficiency (Fig. 1 b)), the highest performance was observed for the DMLS-manufactured sample processed in a carbon dioxide atmosphere. In this case, the efficiency was more than three times higher than that obtained under argon. For Titanium Grade 2, machining in carbon dioxide also resulted in higher efficiency compared to argon; however, the difference was considerably less pronounced than that observed for the DMLS-manufactured sample.

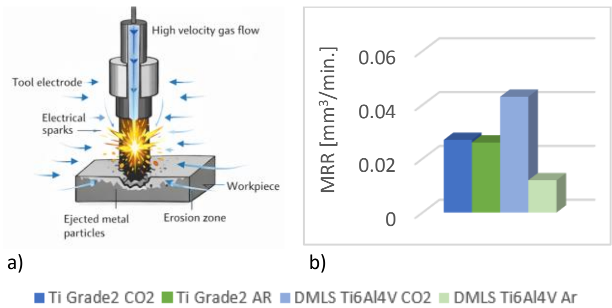


Figure 1. a) Scheme of dry-EDM process, **b)** Material removal rate

EDM is inherently nonlinear and stochastic, with process behavior governed by the workpiece material, dielectric medium, and machining kinematics. Sz represents the total height range and is sensitive to extreme features such as deep craters or resolidified droplets. The highest value was reported for sample fabricated by direct metal laser sintering (DLMS) in argon environment, which was almost two times higher comparing to EDM in CO_2. Lower Sz values were observed for Titanium Grade 2, for which machining in a CO_2 atmosphere also resulted in reduced surface roughness (Fig. 2a)). Sa reflects the overall roughness amplitude and increases with discharge energy, as larger and deeper craters are formed. It can be noticed (Fig. 2a)) that the highest value of Sa was observed for sample fabricated by direct metal laser sintering (DLMS) in argon environment. What is more Sa parameter was also higher for titanium Grade2 machined in Ar compared to CO_2.

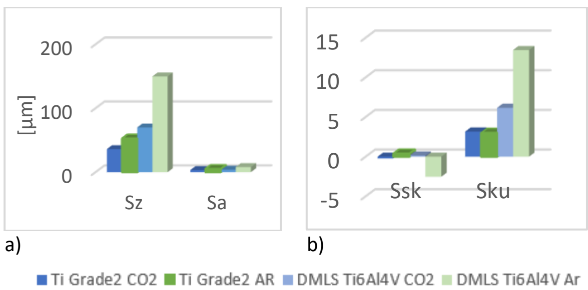
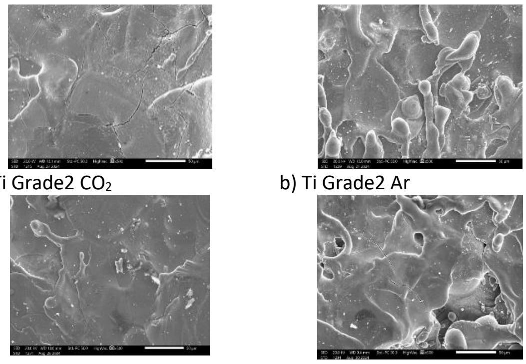


Figure 2. Areal surface texture parameters **a)** Sz, Sa, **b)** Ssk, Sku

The combined selection of Rsk and Rz (Fig. 2b)) is justified by the inherently stochastic character of EDM, where surface topography results from the random superposition of discharge craters formed during machining. Ssk indicates surface asymmetry; EDM surfaces are often valley-dominated (negative Ssk due to crater formation). The lowest Ssk value was recorded for the DMLS-manufactured sample machined in an argon atmosphere. Sku characterizes the sharpness of the height distribution, with high values indicating pronounced peaks or deep valleys typical of stochastic discharge events. The highest Sku value was recorded for the DMLS-manufactured sample machined in an argon atmosphere.
Pronounced differences in the density of microcracks and oxide inclusions were observed in the SEM micrographs of the analyzed surfaces (Tab. 3). In the case of Titanium Grade 2 machined in an argon atmosphere, no microcracks were detected, which may indicate sufficiently effective cooling of the machining zone under these conditions. In contrast, distinct microcracks were identified after machining Titanium Grade 2 in a carbon dioxide atmosphere, as well as in additively manufactured (DLMS) titanium processed in both argon and carbon dioxide environments. The most extensive and pronounced microcracking was observed for Titanium Grade 2 machined in carbon dioxide.

Table 3 SEM micrographs of Titanium Grade 2 and DLMS titanium surfaces after dry EDM in CO_2 and Ar, x500



a) Ti Grade2 CO_2 b) Ti Grade2 Ar
c) DMLS Ti6Al4V CO_2 d) DMLS Ti6Al4V Ar

3. Conclusions

In dry-EDM, electrical breakdown occurs only at very small interelectrode gap widths (<50 µm), which may result in the coexistence of short-circuit discharges and prolonged ignition delay times. The breakdown mechanism under gaseous conditions differs fundamentally from that observed in conventional EDM using liquid dielectrics. Based on the conducted experiments, machining efficiency under identical process parameters was higher in a carbon dioxide atmosphere than in argon. A particularly pronounced increase in efficiency was observed for the DMLS-manufactured sample processed in CO_2, where the performance was markedly greater compared to machining in argon. Analysis of the surface roughness parameters indicates that, for both materials, machining in argon resulted in higher surface roughness. The most significant differences were recorded for the DMLS-produced specimen. SEM observations revealed the presence of microcracks and oxide precipitates on several of the analyzed surfaces. However, no microcracks were detected in Titanium Grade 2 machined in an argon atmosphere. This may suggest that, under these conditions, the process proceeded in a stable manner, with appropriately selected parameters and effective heat dissipation from the machining zone.

References

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