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Original Article

Surface properties of micro surface patterned Cp-Ti alloy via electrical discharge machining

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ABSTRACT

The process of machining micro surface patterns on a workpiece to improve various performance aspects of engineering materials, including wear resistance, corrosion resistance, and biocompatibility, has been a hot topic of research in recent years. Due to the restricted machinability of titanium and its alloys, it is very challenging to process micro surface patterns with exact surface geometries using traditional machining methods. Consequently, non-traditional processing techniques, such as laser, electro-erosion, and chemical etching, may overcome these obstacles. In the present study, electrical discharge machining (EDM) is used to form micro surface patterns on Cp-Ti alloy samples. First, graphite electrodes with several channels were manufactured, and then square-shaped surface patterns were processed onto Cp-Ti samples using EDM. To evaluate the machining performance of the process and surface features of the obtained micro surface patterns, the surface morphology and topography of the processed samples were investigated by scanning electron microscopy (SEM) and three-dimensional (3D) optical profilometry, respectively. The average widths of the square-shaped surface patterns along the X and Y axes were 663.7±8 µm and 609.5±4 µm, respectively. For micro surface designs with square geometry, dimensional consistency was obtained with exceedingly small amounts of variation. However, a limited number of microcracks were observed due to rapid cooling during the processing of the surface patterns. The 3D surface topographies revealed that square-shaped micro surface patterns were successfully processed on the samples, indicating that micro surface patterns can be processed on Cp-Ti samples by using the proposed methodology, which has the potential for obtaining tailor-designed surface features, particularly for biomedical and tribological applications.

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INTRODUCTION

Titanium and its alloys are extensively used in biomedical applications owing to their exceptional mechanical properties, strong corrosion resistance, and biocompatibility [1]. The antibacterial surface qualities of the material play the most essential role in making titanium alloys more suitable for biomedical applications and enhancing their surface properties [2]. Commercially pure titanium (Cp-Ti) is widely used in medical and surgical applications, including bio-implantable bone replacements, owing to its excellent biocompatibility, corrosion resistance, and mechanical properties [3–5]. It is frequently employed in dental implants due to its desirable biological characteristics, low Young's modulus, and adequate strength [6]. Nevertheless, its wear rate and coefficient of friction (CoF) are comparatively weak, which limits its use to situations in which sliding, fretting, and rolling contact are unavoidable [5–9].

Numerous performance features of titanium and its alloys, including tribological, corrosion, and biocompatibility, are known to be closely related to their surface and subsurface properties [10]. However, in some applications (such as tribological applications), surface and subsurface properties may not provide sufficient performance and restrict the material's application range [11]. To be biocompatible, the surfaces of materials must be hydrophilic (wettable) and rough (to ensure cell adhesion) [12, 13]. Additionally, it is desirable for titanium alloys to have hydrophobic surfaces [14]. Using micro/nano surface patterning techniques, it is possible to modify biocompatibility, protein adsorption, and cell/surface interactions [15, 16]. In biological applications, patterned surfaces enhance cell adhesion and proliferation, which is crucial for tissue engineering [17]. Moreover, patterned features may enhance the corrosion resistance of titanium alloys by modifying the surface chemistry [9, 18]. As micro-bearings, well-designed surface patterns may boost the dynamic pressure between friction pairs, trap debris produced during the friction process, and store lubricant [19]. Therefore, processing patterned surfaces on titanium and its alloys is an efficient method for improving titanium's relatively weak surface characteristics and enhancing their performance in a variety of applications [19–22].

To improve the surface properties of titanium and its alloys, various mechanical, chemical, and physical techniques such as shot peening [23], ultrasonic peening [24], laser peening [25], anodization [26], grinding [27], physical vapour deposition [28], and die-sinking electrical discharge [29] are used. Surface treatment techniques for titanium and its alloys offer both benefits and drawbacks. Despite the fact that acid etching produced a surface with high cell adhesion and a rough texture, the desired dimensional stability could not be achieved. It was also noted that acid residues produce pollution, which may result in a variety of long-term issues [30]. Anodization may generate a controlled nanoporous oxide layer, although a non-homogeneous surface distribution occurs [31]. In the literature, it was discovered that laser patterning procedures were often used. Despite the fact that laser processing generates surfaces that promote cell adhesion and proliferation, it causes substantial thermal damage to the surface and subsurface as a result of its high heat penetration [32]. As the limitations of this method have been addressed using several pattern processing techniques, a new field of study has emerged. Excellent dimensional stability and surface quality may be achieved by optimization of many parameters of die-sinking electrical discharge machining (EDM) for titanium and its alloys. EDM-roughened Ti6Al4V alloy significantly improved osteoblast cell adhesion and proliferation, as shown by Harcuba et al. [33]. Prakash and Uddin [34] reported the development of a crack-free, nonporous, biomimetic layer on a Ti-35Nb-7Ta-5Zr alloy using the EDM on hydroxyapatite powder mixed with deionized water. Karmiris-Obrataski et al. [35] conducted an experimental study on the surface topography and integrity of EDM-machined Ti6Al4V ELI. Hasçalık and Çaydaş [36] studied the influence of process parameters on Ti6Al4V material using the EDM technique with various electrode materials, including graphite, electrolytic copper, and aluminum. The graphite electrode exhibited the greatest amount of material removal and the lowest wear rates.

Literature demonstrates that the surface patterning of titanium and its alloys by EDM in collaboration with the production of surface and subsurface mechanical and biological properties is limited. In this study, a new processing approach was used to create distinctive micro surface patterns on the surface of the Cp-Ti alloy using EDM. The desired surface patterns (depth, width, and roughness, etc.) were formed on the Cp-Ti alloy for this purpose. Consequently, the surface properties and topographies of the patterned surfaces were investigated comprehensively.

MATERIALS AND METHODS

Commercially pure titanium (Cp-Ti alloys) bars with a diameter of 20 mm were obtained from TIMET (Titanium & Medical & Mining Company, Kocaeli, Turkey). Afterwards, cylindrical samples (10 mm in thickness) were cut using a semi-automatic band saw. Prior to EDM, the samples were processed with 320-, 600-, and 1200-mesh grits using automated grinding equipment to provide a homogeneous and flat surface topography.

HK-75 graphite blocks (density: 1.82 g/cm^3, electrical receptivity: 16.5 m, hardness: 72 HS), which were in the ultra-thin graphite class (average grain size: 4 µm), were chosen to machine multi-channel graphite electrodes. Then, a multi-channel graphite electrode for EDM processing of Cp-Ti samples was machined using a CNC milling machine, as the schematic of the machined electrode is given in Figure 1. Cp-Ti samples were then machined using the prepared electrode in accordance with the specifications listed in Table 1, resulting in the formation of surface patterns, as Figure 2 schematically illustrates the EDM machining of Cp-Ti samples. The EDM process parameters were selected using a trial-and-error approach. The surface pattern characteristics were selected according to a literature survey of micro-surface patterning of titanium alloys [13, 16, 22, 37–40].

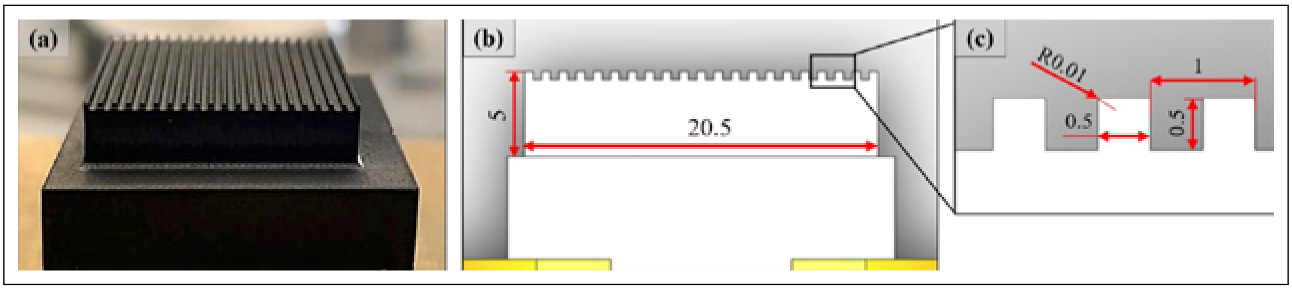

Figure 1. **(a)** Graphite electrode with multiple channels, **(b)** cross-sectional technical drawing of the surface pattern, and **(c)** dimensions of micro-patterns.

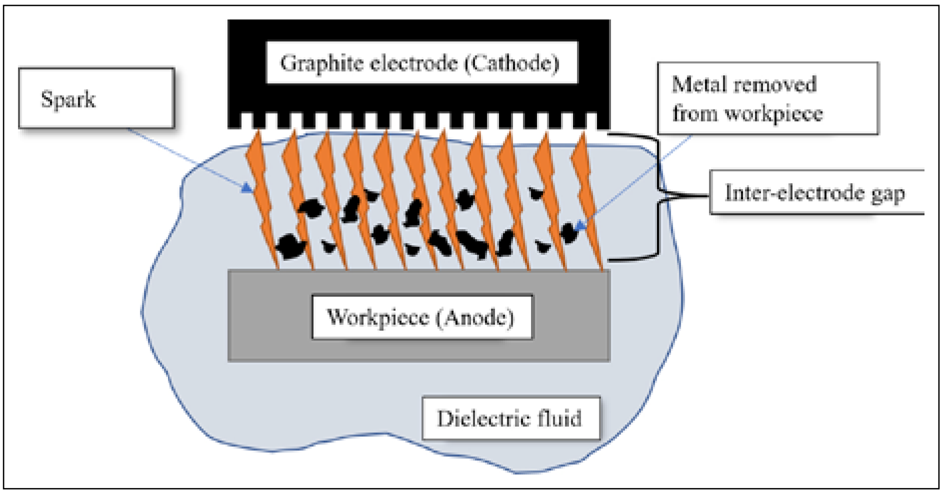

Figure 2. Schematic representation of the EDM process.

Table 1. EDM process parameters

Pulse on time	Pulse off time	Pulse current	Voltage	Servo voltage	Surface roughness
1.6 µs	6.4 µs	1A	200V	65V	0.32 Ra

EDM is a surface treatment technique that eliminates chips from the workpiece by generating high-frequency sparks between the electrode and the workpiece [40]. The target material (Cp-Ti alloy) was subjected to EDM utilizing a multi-channel electrode parallel to the X-axis of the EDM in the first stage. In the second stage, the multi-channel electrode rotated 90° and was used to machine the target material parallel to the Y axis of the EDM to obtain the square surface patterns.

The surfaces of the EDM machined samples were then cleaned for 10 minutes with alcohol and ultrasonication. A 3D optical profilometer was used to scan the surface features of the machined samples (Huvitz, Gyeonggi, Republic of Korea). The 3D surface topographies were then visualised using Mountains® 9 (Digital Surf, Besançon, France). An SEM (Jeol JSM-6060, Tokyo, Japan) with an energy dispersive spectroscopy (EDS) (Oxfords Instrument, Oxford, UK) detector was also used to analyse the surface morphologies of the samples.

The EDM machined samples were cross-sectioned using a diamond cutting disc and a precision cutter, and then the cross-sectioned specimens were moulded in resin. The moulded specimens were ground (320-, 600-, 1200-, and 2000- mesh grits) and polished (1 and 3 µm diamond suspension) using an automatic metallographic sample preparation system. In an ultrasonic bath containing alcohol, the specimens were cleaned for 10 minutes. Finally, cross-sectional examinations were performed using the SEM system previously described.

RESULTS AND DISCUSSION

The Surface Morphologies and Subsurface Features of Micro Surface Patterned Samples

In Figure 3, the surface morphologies of various channels and squares machined by EDM processing of Cp-Ti samples were given. On the X and Y axes, the average channel widths were calculated to be 362.4±4 µm and 390.8±9 µm, respectively (Fig. 3b). The channel width difference between the two axes is around 30 µm. In the X and Y directions, the average widths of the square-shaped surface patterns obtained by EDM processing of Cp-Ti alloy were 663.7±8 µm and 609.5±4 µm, respectively (Fig. 3c, d). Figure 4a shows an overall view of the surface patterns obtained via EDM. Due to electrode wear, regional melting was identified at the channel

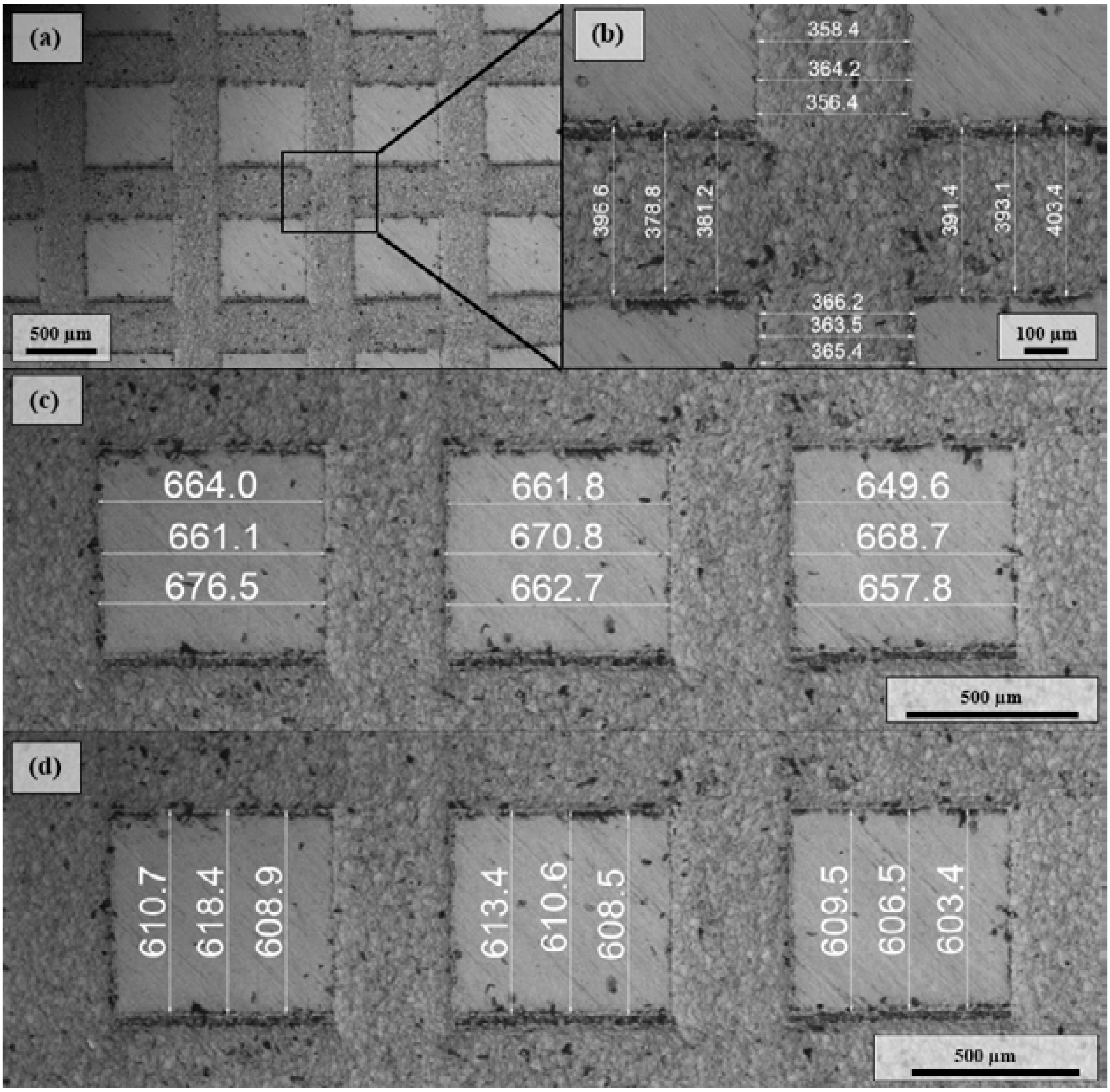

Figure 3. Micro surface pattern size measurements **(a)** General view, **(b)** Channels measurement in X and Y directions, average widths of the square-shaped surface patterns; **(c)** X direction, **(d)** Y direction.

borders along the X axis. According to the image of the channel area captured at a greater magnification (Fig. 4b), molten structures were developed because of sparks generated by electro-erosion during the EDM processing. Furthermore, a limited number of microcracks between the molten formations are also visible on the surface (Fig. 4c), which could be attributed to the rapid cooling of the machined surface features by plunge electro-erosion [41]. As a consequence of the rapid cooling of the micro pattern features, residual tensile tension is also formed. Meanwhile, dielectric liquid is used to remove debris from the surroundings that has broken off from the substance. A portion of the debris cooled on the material without removal and created the remelted layer known as the white layer [36]. Usually, surface cracks caused by the EDM process do not penetrate the substrate material. Nevertheless, cracking defects occur in the so-called white layer or re-solidified layer and in the heat-affected zone [42]. Surface defects in the form of cracking that may occur with EDM cause a decrease in the corrosion resistance of the material [43]. Tai and Lu demonstrated that EDM-machined tool steel with surface cracks would have a reduced fatigue life [44]. There is research involving the use of EDM in combination with other surface treatments to eliminate these defects and enhance the material's performance. By combining EDM, acid etching, and shot peening, Otsuka et al. [45] increased the fatigue strength and nature of cell adsorption in the Ti6Al4V alloy. Strasky et al. [46] used a combination of EDM, chemical treatment, and shot peening on the same alloy. According to reports, it improves fatigue performance and promotes osteoblast proliferation. According to these

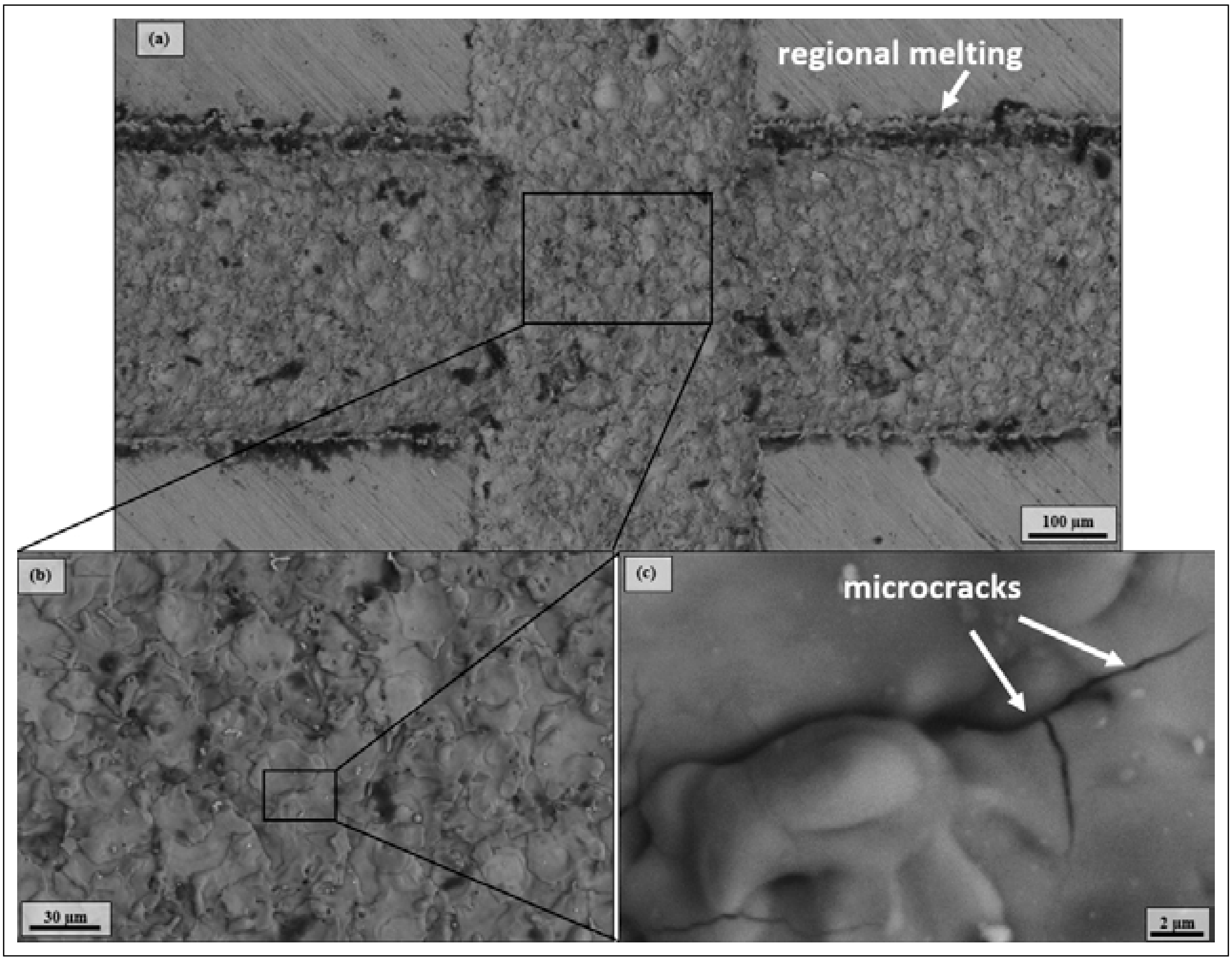

Figure 4. **(a)** Surface morphologies of the patterns, **(b)** A high magnification view of the targeted region, and **(c)** Surface microcracks.

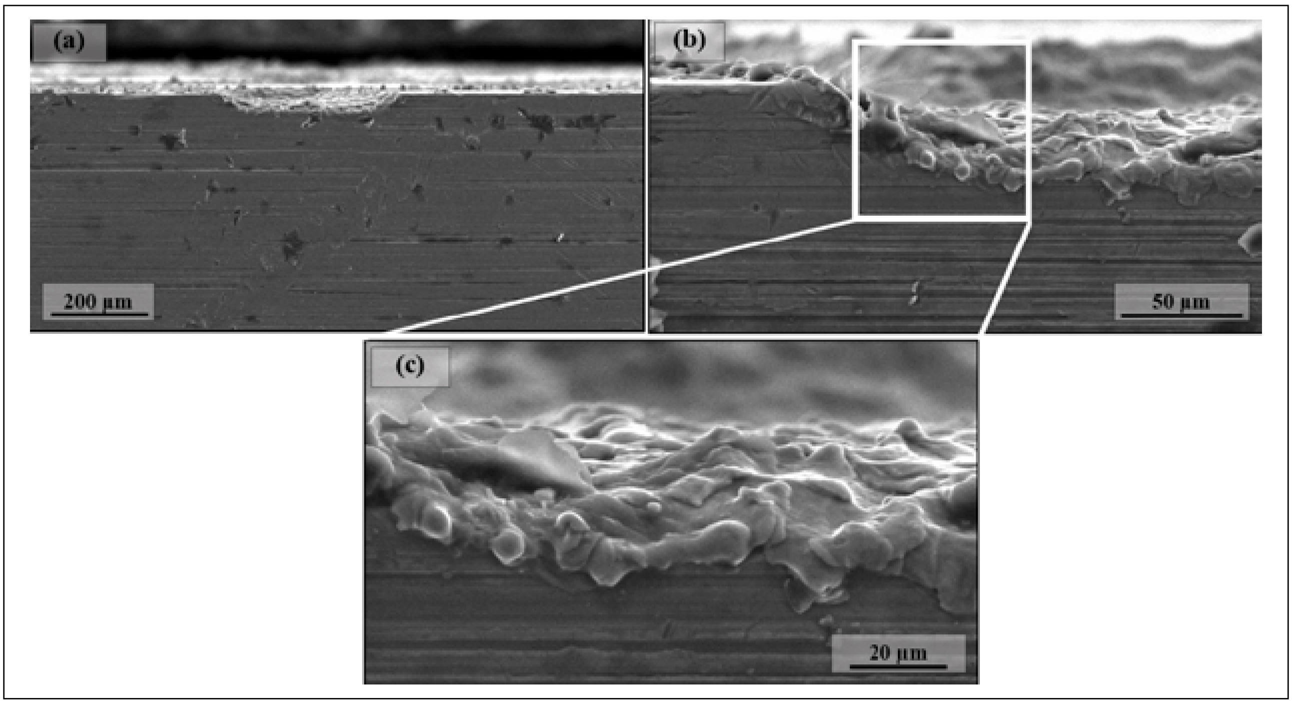

Figure 5. EDM-treated Cp-Ti alloy microstructure in cross-section **(a)** Low magnification, **(b)** High magnification, and **(c)** Overlapping recast layers.

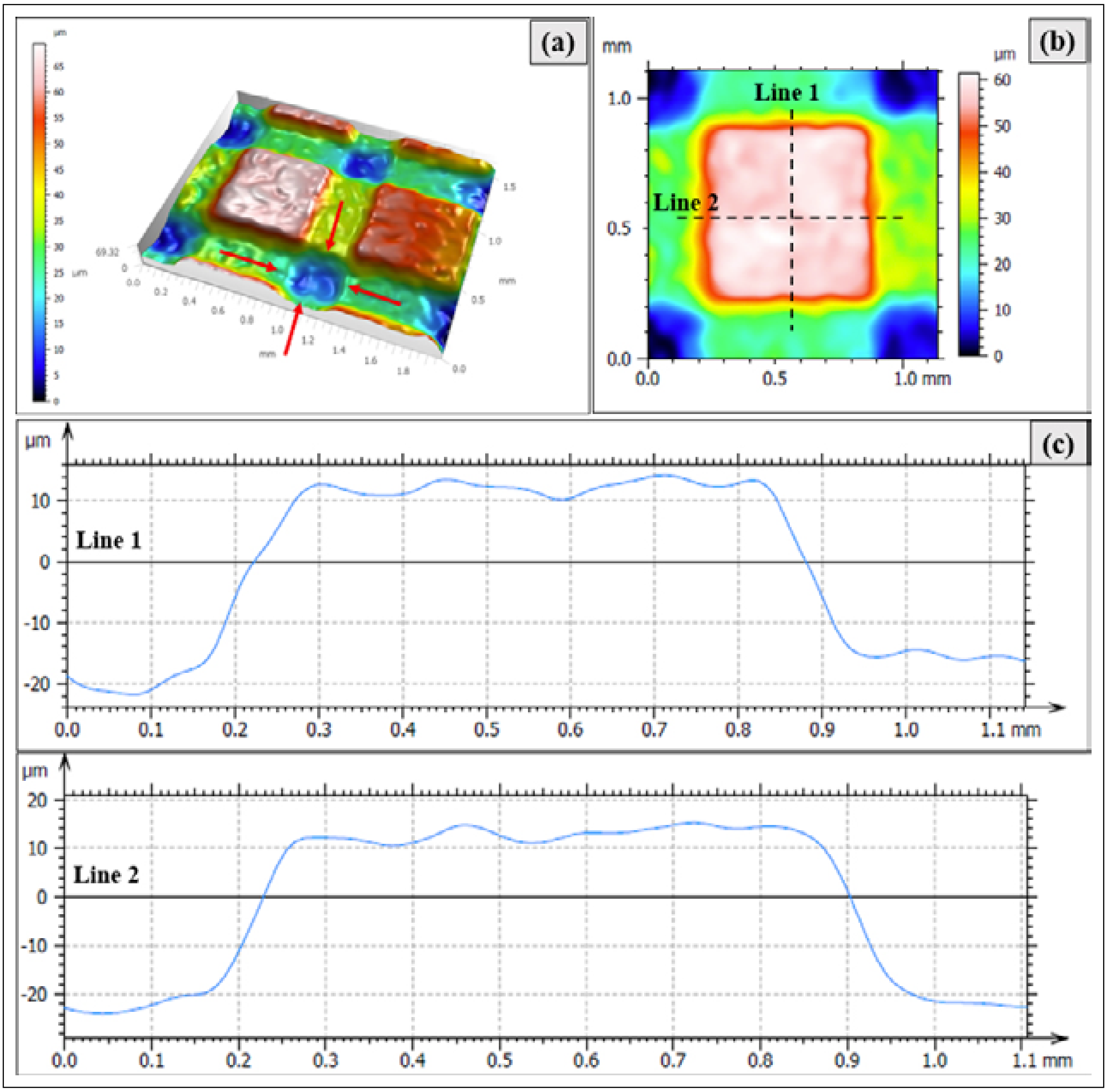

Figure 6. EDM-modified surface topographies of Cp-Ti specimens **(a)** Several square-shaped surface patterns, **(b)** A single square-shaped surface pattern, and **(c)** The surface profile of a single square-shaped surface pattern.

findings, combined machining processes may eliminate the negative effects of surface defects. However, the lack of a combined EDM process for Cp-Ti alloy in the existing literature has revealed an important topic of research.

Figure 5 shows the cross-sectional microstructure of the Cp-Ti alloy after the EDM process. It is clear that EDM causes melt pools on the near surface due to the rapid heating and cooling of the surface. Due to the current value and pulse duration, a thin molten layer was formed on the surface (Fig. 5b). The overlap of these molten layers indicates that these layers were formed between the pulse on and pulse off times. As the processing parameters (pulse on time, pulse off time, and voltage) are kept constant, the shape and geometry of the melt pools are uniform. In the sample's cross-sectional images, no cracks or crack initiation perpendicular to the surface were detected. The thickness of the remelted layer following EDM processing was approximately 40 µm, while the thickness of the untreated region was around 5 µm. The cross-sectional images provide essential information for determining the sample's heat-affected zone. This will make it easier to optimise the process parameters and achieve the desired material qualities for the desired application.

The Topographies of Surface Patterned Cp-Ti Alloy

After the EDM process, the topographies of the surface patterns were examined with an optical profilometer, and 3D surface topographies and surface profiles were analysed (Fig. 6). The melted material at the intersection of the first and second processes caused melt collapse, creating flow from the channel areas to the crater section (Fig. 6a).

A single square-shaped surface pattern topography is given in Figure 6b. It is visible that EDM processing causes relatively low surface roughness as peaks and valleys having less than 1μm height were formed on the surfaces (Fig. 6c). Examining the profiles of the square-shaped surface patterns in the x and y directions revealed that the peaks and valleys had similar features (Fig. 6c). The surface of the Cp Ti alloy was accurately patterned using multi-channel graphite electrodes, as determined by surface profile investigations.

Maressa et al.'s [47] research on laser processing of various surface patterns on Ti6Al4V alloy is used as a reference for selecting square surface patterns in the present investigation. Multiple channel surfaces, contrary micro-pits, and complicated processing forms have been shown to have a beneficial influence on bone cell behavior. Additionally, EDM machining produced channel forms with an average surface roughness of 0.1–10 μm (for Ti6Al4V alloy) [48] and 2.5–10 μm (for aluminum alloy) [49] in channel forms. In this work, a high level of surface quality was attained by reducing the Cp-Ti alloy's surface roughness in consideration of the high accuracy required for micromachining.

CONCLUSIONS

The present study comprises electrical discharge machining of micro surface patterns onto the surface of the Cp-Ti alloy. The surface morphology and topography of the processed samples were examined by scanning electron microscopy (SEM) and three-dimensional (3D) optical profilometry to assess the machining performance of the process and the surface characteristics of the produced micro surface patterns.

- The study clearly shows that micro surface patterns with excellent dimensional accuracy can be obtained following the proposed EDM methodology (i.e., designing multi-channel graphite electrodes and following the given EDM parameters). Dimensional consistency is maintained across the surface patterns in numerous square geometries.
- Due to the two-stage processing, melt collapse occurred at the intersections of the processing zones, which caused microcracks in the channel sections due to the quick cooling action. Molten spherical particles were shown by high magnification SEM photos. According to the 3D surface topographies of the processed samples, a limited surface roughness was observed on the processed features with peaks and valleys of less than 1μm in height.

The present study showed that processing micro surface patterns by using the proposed methodology has the potential to obtain tailor-designed surface features with excellent dimensional and geometrical stability and less amount of surface defects, which can pave the way for improving the biocompatibility, tribological, and corrosion performance of titanium alloys in respective scientific and industrial usage. Future studies should focus on processing and examining the subsurface properties (i.e., microstructural features and mechanical properties) of similarly processed titanium samples using electron microscopy, microhardness mapping, and indentation mapping.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Alperen Kürşat Balta: Conception, Design, Supervision, Materials, Data Collection and Processing, Analysis and Interpretation, Literature Review.

Mustafa Armağan: Conception, Design, Supervision, Materials, Data Collection and Processing, Analysis and Interpretation, Literature Review, Writer, Critical Review.

Yasemin Yıldıran Avcu: Conception, Design, Supervision, Data Collection and Processing, Writer, Critical Review.

Eray Abakay: Conception, Design, Supervision, Materials, Data Collection and Processing, Writer, Critical Review.

Egemen Avcu: Conception, Design, Supervision, Fundings, Materials, Data Collection and Processing, Analysis and Interpretation, Literature Review, Writer, Critical Review.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

There are no ethical issues with the publication of this manuscript.

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