EFFECT OF CYCLING AND STIRRING PARAMETERS ON SURFACE EVOLUTION OF TI-6AL-4V ALLOYS BY PLASMA ELECTROLYTIC POLISHING

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Abstract

The improvement of surface quality in difficult to cut materials is critically important for enhancing service life. Plasma electrolytic polishing (PeP) is a promising surface finishing technology that provides high quality and eco-friendly smoothing of metal surfaces. This study presents the effects of PeP parameters on the surface modification of Ti-6Al-4V alloys. The PeP parameters were determined as cycle stages (1, 2, and 3) and stirring speeds (0 and 300 rpm). Other constant parameters were cathode material (SS304), voltage (300 V), electrolyte type (hydroxylamine hydrochloride and sodium fluoride), electrolyte concentration (5% and 0.8%), electrolyte temperature (80°C), and polishing time (6 min). Surface roughness, gloss, and material removal rate (MRR) were selected as output parameters. In addition, the current time graph was recorded during the polishing process. The experimental results showed that the surface roughness decreased significantly after PeP. Moreover, the results indicated that an optimized cycle configuration, particularly the double cycle condition, led to the most effective improvement in surface roughness, while excessive cycling reduced surface uniformity. Similarly, a considerable increase in surface gloss was observed, demonstrating the strong influence of process stability and parameters on gloss. Similarly, the MRR values were affected by the cycle strategy.

Keywords: Plasma electrolytic polishing, surface roughness, material removal rate, titanium alloys, gloss.

1. INTRODUCTION

Ti-6Al-4V is a metallic alloy widely prefered in aerospace and biomedical applications due to its high specific strength, superior corrosion resistance, and biocompatibility [1]. Its microstructure consists of a balanced distribution of α-phase (hexagonal close packed) and β-phase (body centered cubic), providing the material with both high mechanical strength and good ductility. However, its low thermal conductivity and high chemical reactivity make machinability difficult; conventional production methods lead to surface roughness and residual stresses. These surface defects can negatively impact critical performance parameters such as fatigue strength, wear resistance, and biocompatibility. Therefore, there is a growing need for advanced finishing techniques to improve surface quality. In this context, plasma electrolytic polishing (PeP) stands out as a promising surface finishing method for difficult to cut alloys such as Ti-6Al-4V. The plasma envelope formed under high voltage enables the selective dissolution of surface micro peaks, resulting in a smoother and brighter surface. Compared to traditional electropolishing methods, the use of environmentally friendly electrolytes and the ability to process parts with complex geometries homogeneously increase the importance of this method in industrial applications. However, a complete understanding of the effects of process parameters such as voltage, electrolyte temperature, and processing time on surface morphology is a critical requirement for optimizing the process.

Tan et al. [1] investigated the effects of different voltages on the surface modification of Ti-6Al-4V samples produced by laser powder bed fusion (LPBF) using the PeP method. The study reported that the R_a (12 µm) and R_z (120 µm) values were improved by 59.8% and 46.6%, respectively. In a similar study, Ng et al. [2] polished LPBF produced Ti-6Al-4V samples using the PeP method under lower immersion rates and different cycle conditions, reporting that surface roughness was correlated with the material removal rate (MRR). Wang et al. [3] examined the polishing behavior of Ti-6Al-4V at voltage levels ranging from 260 to 380 V and found that the lowest surface roughness was obtained at 300 V, while higher voltages led to increased roughness due to enhanced ionic mobility. Xu et al. [4] reported that processing time was reduced by applying a hybrid method combining PeP and mechanical polishing to additively manufactured Ti-6Al-4V samples. Yang et al. [5] observed a significant improvement in surface roughness and noted that oxide layer formation was associated with increased oxygen content on the surface. Ghezri et al. [6] suggested that the PeP method has the potential to replace traditional multi-stage polishing workflows for Ti-6Al-4V, offering significant reductions in cost, time, and environmental impact. Similarly, Liu et al. [7] reported that PeP provided better and more homogeneous surface roughness compared to mechanical polishing (MP). Zou et al. [8] investigated the effects of PeP parameters on surface roughness and ranked them, from most to least influential, as temperature, time, voltage, and depth. Ng et al. [9] proposed a hybrid approach combining heat treatment and PeP to improve the surface quality of titanium samples. Finally, Smyslova et al. [10] reported that surface roughness decreased rapidly within the first 3 minutes, followed by a linear reduction thereafter.

One of the key factors determining surface quality in the PeP process is the movement of the sample within the electrolyte and the applied processing cycles. In this context, immersion strategies (single, double and triple stages) directly affect the continuity of the plasma layer, temperature distribution, and ion transfer. Continuous immersion (single stage) ensures an uninterrupted process, whereas multiple immersion approaches provide a more controlled polishing mechanism by reducing thermal accumulation on the surface through the periodic removal and reimmersion (double and triple stages) of the sample. In addition, stirring within the electrolyte increases ion mobility, contributing to rapid plasma formation and producing a uniform polishing effect across the surface but it can change with combined influences of inpuıt factors. The aim of this study is to systematically investigate the effects of different immersion strategies and stirring conditions on the surface roughness and morphology of Ti-6Al-4V in the PeP process and to determine the most suitable processing parameters.

2. MATERIALS AND METHODS

Ti-6Al-4V, one of the most widely utilized titanium alloys, was chosen as the anode material in this study. The specimens were prepared with dimensions of 8.85x25x2 mm3 using a wire electrical discharge machining system (DK7740, Hightech, China) equipped with a 0.18 mm molybdenum wire. To achieve a consistent surface roughness of approximately 0.75 µm, the samples were sequentially ground using abrasive papers with grit sizes of 120, 240, 360, 400, 600, and 800.

As illustrated in **Figure 1**, the experimental system was composed of a pulse power supply, an electrolyte container, a heating unit, and temperature monitoring devices. All experiments were conducted in a 1 L glass beaker. A SS304 cathode plate was positioned and fixed inside the beaker. A high-power programmable DC power supply (Owon 2060H, China) with a maximum capacity of 2 kW was utilized. Heating was provided by a DLAB MS-H280-PRO magnetic stirrer with integrated heating functionality (DLAB Scientific Co. Ltd., Beijing, China). Once the electrolyte reached the target temperature, the setup platform was adjusted, and the anode was immersed into the solution to a depth of 20 mm.

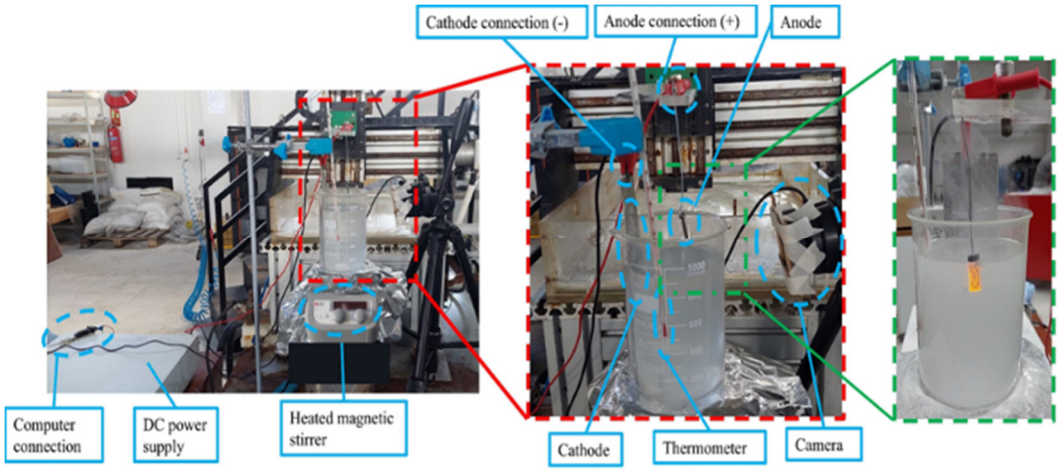

Figure 1 Schematic of PeP process.

The PeP process involves several parameters, including voltage, electrolyte temperature, concentration, and polishing time, and optimizing these parameters is essential for achieving high surface quality. Therefore, certain variables were defined as constant parameters based on findings reported in the literature. The voltage was set to 300 V, the electrolyte temperature to 80°C, the electrode distance to 80 mm, the immersion speed to 20 mm/s, and the immersion depth to 20 mm. The electrolyte consisted of a mixture of NaF and NH_4F, with concentrations of 1.8 wt.% and 2.7 wt.%, respectively. The variable parameters were selected as cycle stages and mixing conditions. Cycle stages refer to the repeated immersion of the anode into the electrolyte and were defined as single stage (6 minutes), double stages (3 minutes + 3 minutes), and triple stages (2 minutes + 2 minutes + 2 minutes). In each stage, the anode was removed from the electrolyte and then re-immersed. For the mixing condition, stirring was applied at a constant speed of 300 rpm throughout the polishing process. The PeP conditions are detailed in **Table 1**.

Table 1 PeP experimental conditions

PeP Conditions	Cycle Time	Stirring Conditions
1	Single cycle (6 min)	No
2	Single cycle (6 min)	Yes (300 rpm)
3	Double cycle (3 min + 3 min)	No
4	Double cycle (3 min + 3 min)	Yes (300 rpm)
5	Triple cycle (2 min + 2 min + 2 min)	No
6	Triple cycle (2 min + 2 min + 2 min)	Yes (300 rpm)

In order to determine the polishing efficiency of the PeP process, the MRR was also considered as an output parameter. For this purpose, the samples were weighed before and after the PeP treatment using an electronic balance with a precision of 0.001 g (IsoLab, Turkey). The MRR was then calculated by dividing the mass loss by the polishing time. In addition, dimensional measurements were performed using a Mitutoyo caliper to determine the geometric changes of the samples before and after PeP treatment.

To evaluate the influence of the process parameters on surface quality, surface roughness and gloss were selected as response variables. Surface roughness was measured using an ISR-C002 roughness tester (Insize, China). Measurements were taken at five different locations on each polished sample, and the mean value was reported as the surface roughness. Surface gloss was assessed using an SL268 gloss meter

(SerLab, Turkey). For each specimen, five readings were recorded at an angle of 60°, and the average of these readings was presented as the surface gloss.

3. RESULTS AND DISCUSSIONS

As demonstrated in **Figure 2**, The current-time curves obtained under different processing conditions (Condition 1-6) exhibit the characteristic behavior of the PeP process. In all cases, a high initial current is observed at the beginning of the treatment, followed by a gradual decrease over time. This trend can be attributed to the transition from an active electrochemical dissolution regime to a plasma-assisted regime. At the initial stage, the metal surface is directly exposed to the electrolyte, resulting in high current density and rapid material removal. As the process progresses, a gaseous envelope forms around the surface due to intense electrochemical reactions and localized heating. This gas layer acts as an insulating barrier, increasing the electrical resistance and consequently reducing the current. The system then reaches a quasi-steady state condition, where a stable plasma layer governs the polishing mechanism. Condition 1 indicates a smooth and gradual current decrease, indicating a stable process but with a relatively low material removal rate. Condition 2 shows a similar trend with a higher initial current, suggesting more aggressive early-stage dissolution and a faster transition to the plasma regime. In Condition 3, the current decreases rapidly and stabilizes at a lower level compared to the Conditions 1 and 2, implying the formation of a thicker or more resistive plasma layer. Condition 4 shows a comparable behavior, but the decay is more gradual, suggesting a more uniform and controlled plasma evolution. Condition 5 presents more pronounced fluctuations throughout the process, which indicates reduced plasma stability, likely influenced by repeated cycling. In contrast, Condition 6 demonstrates a smoother and more gradual decay with relatively stable behavior after the initial stage, pointing to a more controlled but slower polishing process.

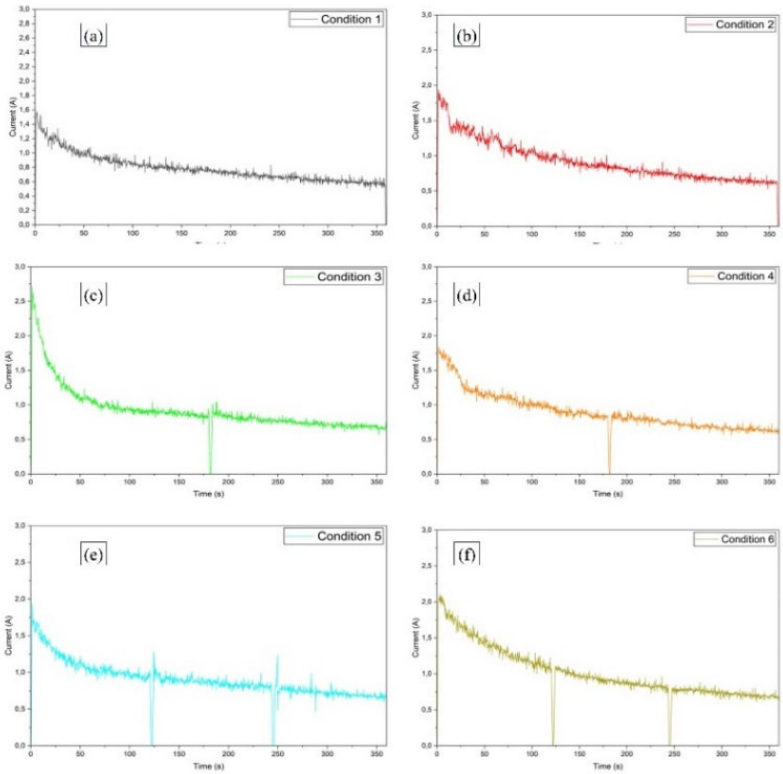

Figure 2 Current time graphs related on PeP conditions a) 1, b) 2, c) 3, d) 4, e) 5 and f) 6

In **Figure 3a,** thickness change is significantly higher than width change for all conditions, indicating that material removal predominantly occurs in the vertical direction. Conditions 1 and 2 exhibit moderate thickness-

width changes and steady MRR values, indicating a balanced and stable polishing regime. Condition 3, with lower stabilized current, results in relatively limited dimensional change but achieves the highest MRR, suggesting efficient material removal despite reduced current levels. Condition 4 shows moderate dimensional changes and slightly lower MRR, aligning with its more gradual and controlled current decay. Conditions 5 and 6, which exhibited more fluctuations due to multiple cycles, show increased dimensional changes. This indicates that repeated cycling enhances material removal locally but reduces overall process stability.

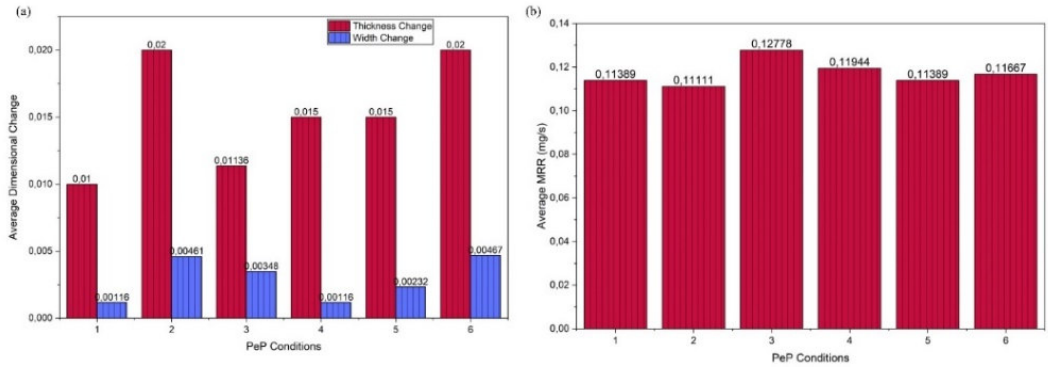

Figure 3 Accordance with PeP conditions a) Thickness and width change b) Average MRR values

Figure 4 shows the bar plots for surface roughness and average gloss according to PeP conditions. Conditions 1 and 2 show moderate roughness and gloss values, reflecting balanced but less optimized polishing performance. Condition 3 provides the best surface quality with the lowest roughness and highest gloss. This indicates that a stable but relatively low current regime promotes efficient and uniform material removal. Condition 4 achieves acceptable surface quality but not as effective as Condition 3, in line with its moderate MRR. Conditions 5 and 6 result in higher roughness and reduced gloss compared to Condition 3. This suggests that repeated interruptions in the plasma reduce surface uniformity despite comparable material removal rates. Consequently, smoother and more stable current behavior leads to improved surface finish and gloss, while increased cycling and instability negatively affect surface quality.

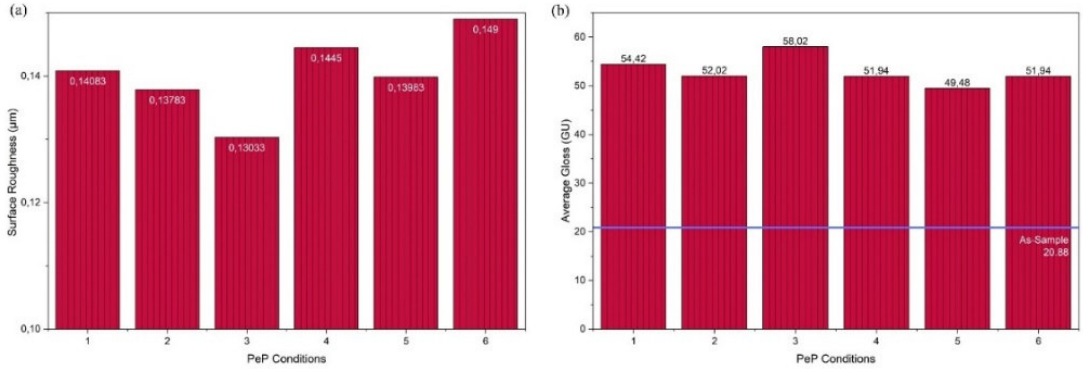

Figure 4 PeP conditions a) Surface roughness and a) Average gloss

The surface of before PeP (**Figure 5a**) shows pronounced machining marks and directional grooves on both the front and side, indicating a rough and anisotropic texture. After PeP (**Figure 5c**), these grooves are almost completely removed, and the surface becomes significantly more uniform and homogeneous. The post-PeP micrographs reveal a smooth, isotropic morphology with only minor residual features, confirming effective material removal. This aligns with the highest MRR observed for Condition 3 and its stable, lower current regime, which promotes uniform plasma distribution. The sample surface appears brighter and more reflective after processing, indicating improved gloss.

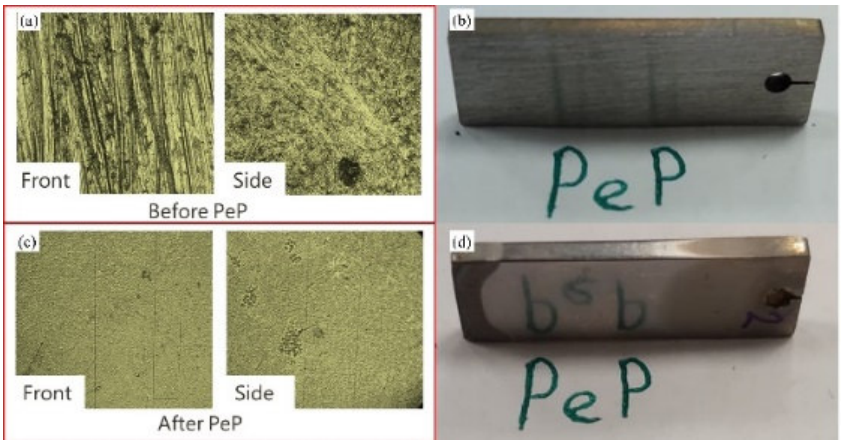

Figure 5 Before PeP of a) Optical images, b) Reflectivity; PeP condition 3 of c) Optical images and d) Reflectivity

4. CONCLUSION

In this study, the effects of cycle strategy and electrolyte stirring on the plasma electrolytic polishing (PeP) performance of anodic Ti-6Al-4V were systematically investigated. The results demonstrated that all conditions exhibited the characteristic PeP current time response, with a rapid initial decrease followed by stabilization due to the formation of a plasma gas envelope. However, multi cycle conditions introduced periodic current interruptions, observed as drops to zero, which directly influenced process stability. Increasing the number of cycles led to more frequent plasma interruptions and increased fluctuation in the discharge behavior. Among all conditions, Condition 3 (double cycles, no stirring) provided the most favorable overall performance. Despite operating at relatively lower stabilized current levels, it achieved the highest MRR, the lowest surface roughness, and the highest gloss values. Surface analyses confirmed that this condition effectively removed initial machining marks and produced a uniform, isotropic, and highly reflective surface. This indicates that a stable but moderately low current regime is optimal for efficient and homogeneous material removal in PeP. In contrast, Conditions 5 and 6 (triple cycles) showed increased dimensional changes and current instability due to repeated plasma interruptions, resulting in higher surface roughness and lower gloss despite comparable MRR values. Consequently, the findings reveal that process stability plays a more critical role than high current intensity in achieving superior surface quality in PeP of Ti-6Al-4V. Therefore, a two-cycle strategy without electrolyte stirring is recommended as the optimal condition for achieving a balance between high material removal efficiency and excellent surface finish.

REFERENCES

[1] TAN, X. Y., NG, Y., MENG, T. L., SUN, C. N., HUANG, Z., NGO, A. C. Y., and LIU, H., “Plasma Electrolytic Polishing-Induced Surface Chemical and Structural Evolutions of Additively Manufactured Ti-6Al-4V Coupons,” *Surf. Coatings Technol.*, 2024, vol. 494(September). Available from: https://doi.org/10.1016/j.surfcoat.2024.131557.

[2] NG, Y., TAN, X. Y., MENG, T. L., SUN, C. N., HUANG, Z., NGO, A. C. Y., and LIU, H.,“Material Removal and Surface Finishing of Additively Manufactured Ti-6Al-4V Coupons by Cyclic Process of Plasma Electrolytic Polishing,” *Surf. Coatings Technol.*, 2025, vol. 498(January), p. 131872. Available from: https://doi.org/10.1016/j.surfcoat.2025.131872.

[3] WANG, J., ZHANG, L., CHENG, J., LIU, J., ZOU, Y., WEI, D., CHENG, S., and WANG, Y., “A Precise Machining Surface Obtained Electrolyte Plasma Polishing on Ti–6Al–4V Alloy: Microstructure and in-Situ Mechanical Behaviors,” *J. Manuf. Process.*, 2025, vol. 133(September 2024), pp. 979–991. Available from: https://doi.org/10.1016/j.jmapro.2024.11.100.

[4] XU, M., LIN, Z., CHENG, H., and LIN, Y., 2026, “Effect of Plasma Electrolytic Polishing on the Fatigue Performance of Additive Manufactured Ti-6Al-4V Removable Partial Denture Clasps,” *J. Prosthet. Dent.* Available from: https://doi.org/https://doi.org/10.1016/j.prosdent.2025.11.009.

[5] YANG, D., SUN, H., JI, G., XIANG, Y., and WANG, J., “Effect of Electrolytic Plasma Polishing on Surface Properties of Titanium Alloy,” *Coatings,* 2024, vol. 14, no. 5. Available from: https://doi.org/10.3390/coatings14050615.

[6] GHEZRI, A., NELIS, T., BURGER, J., and BESSIRE, C., “Surface Finishing of Additive Manufactured Titanium Alloy by Plasma Electrolytic Polishing Without Pretreatments,” *Materials (Basel)*., 2025, vol. 18, no. 20, pp. 1–8. Available from: https://doi.org/10.3390/ma18204719.

[7] LIU, D., ZONG, X., XUE, P., GAO, Z., WU, W., SONG, Z., YE, F., PANG, Y., ZHANG, Y., ZHOU, H., LI, H., and LU, B., “Effects of Plasma Electrolytic Polishing Treatment on the Surface Morphology, Microstructure and Corrosion Resistance of Additively Manufactured TC4 Titanium Alloy,” *J. Mater. Res. Technol.*. 2025, 35(January), pp. 7008–7017. Available from: https://doi.org/10.1016/j.jmrt.2025.03.067.

[8] ZOU, Y., WANG, S., CHEN, G., WANG, Y., ZHANG, K., ZHANG, C., WEI, D., OUYANG, J., JIA, D., and ZHOU, Y., 2023, “Optimization and Mechanism of Precise Finishing of TC4 Alloy by Plasma Electrolytic Polishing,” *Surf. Coatings Technol*., 467(April), p. 129696. Available from: https://doi.org/10.1016/j.surfcoat.2023.129696.

[9] NG, Y., TAN, X. Y., MENG, T. L., YONG, A. M., SUN, C. N., HUANG, Z., and LIU, H., “Effect of Buildup Angle and Post Laser Powder Bed Fusion Heat Treatment on Plasma Electrolytic Polishing of Additively Manufactured Ti–6Al–4V Coupons,” *Adv. Eng. Mater.*, 2025, 202502538, pp. 1–12. Available from: https://doi.org/10.1002/adem.202502538.

[10] SMYSLOVA, M. K., TAMINDAROV, D. R., PLOTNIKOV, N. V., MODINA, I. M., and SEMENOVA, I. P., “Surface Electrolytic-Plasma Polishing of Ti-6Al-4V Alloy with Ultrafine-Grained Structure Produced by Severe Plastic Deformation,” *IOP Conf. Ser. Mater. Sci. Eng.,* 2018, vol. 461, no. 1. Available from: https://doi.org/10.1088/1757-899X/461/1/012079.