

Magnetorheological-Assisted Plasma Electrolytic Polishing of Ti-6Al-4V Alloy

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Abstract— *Ti-6Al-4V* titanium alloy is widely used in aerospace and biomedical applications, yet it remains highly challenging to finish using conventional methods due to its low thermal conductivity and high work-hardening tendency. This study proposes an integrated multi-field finishing technology combining mechanical action, electrochemistry, micro-plasma discharge, and magnetorheological finishing to polish *Ti-6Al-4V* surfaces. Finite element method (FEM) simulations were conducted to analyze the temperature field during the process. Furthermore, an automated control system based on a PLC-HMI architecture was successfully fabricated. Experimental trials were carried out using an active slurry composed of core-shell $Fe_3O_4@SiO_2$ magnetic abrasive particles dispersed in an orthophosphoric acid H_3PO_4 electrolyte matrix. The simulation and experimental results demonstrate that the multi-field coupling achieves a dynamic thermal equilibrium of the plasma sheath at 4371 K, enabling material removal at the nanometric scale. Consequently, the surface roughness R_a of the *Ti-6Al-4V* specimen was drastically reduced from 184,73 nm to 1,06 nm, achieving a roughness reduction efficiency of 99,43%. This method opens up a new, safe, and environmentally friendly avenue for ultra-precision surface finishing technologies.

Keywords— *Ti-6Al-4V*; Plasma electrolytic polishing; Magnetorheological finishing; Core-shell nanoparticles; Surface roughness.

I. INTRODUCTION

Ti-6Al-4V titanium alloy exhibits a high strength-to-weight ratio, excellent corrosion resistance, and outstanding biocompatibility, making it a cornerstone material for manufacturing critical components such as aircraft turbine blades and orthopedic biomedical implants. However, conventional mechanical polishing techniques rely heavily on aggressive micro-cutting actions, which inevitably induce unwanted residual stress, surface work-hardening, and severe limitations when handling complex geometric shapes. Conversely, traditional electrochemical polishing is often hindered by the rapid formation of a highly stable and passive oxide film on the titanium surface, which severely restricts uniform anodic dissolution.

To thoroughly address these technological bottlenecks, a hybrid technology merging magnetorheological finishing (MRF) and plasma electrolytic polishing (PEP)—termed magnetorheological-assisted plasma electrolytic polishing—is proposed. This integrated mechanism utilizes a chain of magnetic abrasive particles organized under a high-gradient magnetic field, acting as a flexible "magnetic brush" to provide delicate micro-abrasion. Simultaneously, micro-plasma discharges generated under high voltage induce localized high temperatures that effectively weaken and break down the passive oxide layer. This multi-field interaction creates a powerful synergistic effect, allowing selective and rapid removal of microscopic peak asperities with superior efficiency and surface quality.

II. THEORETICAL BACKGROUND AND METHODOLOGY

2.1. Fundamental Formulation

Material removal via electrochemical dissolution follows the modified Faraday's law:

$$m = \frac{MIt}{nF}$$

Where m is the mass of dissolved material, M is the molar mass of the metal, I is the current, t is the machining time, n is the valency of the metal ions, and F is the Faraday constant. The material removal rate v as a function of current density j and material density ρ is expressed as:

$$v = \frac{jM}{nF\rho}$$



Furthermore, the initiation of micro-plasma requires the average electric field intensity within the working gap to exceed a critical threshold:

$$E = \frac{U}{d}$$

Where U is the applied voltage and d is the working inter-electrode gap between the tool cathode and the workpiece anode.

2.2. Synthesis of $Fe_3O_4@SiO_2$ Abrasives

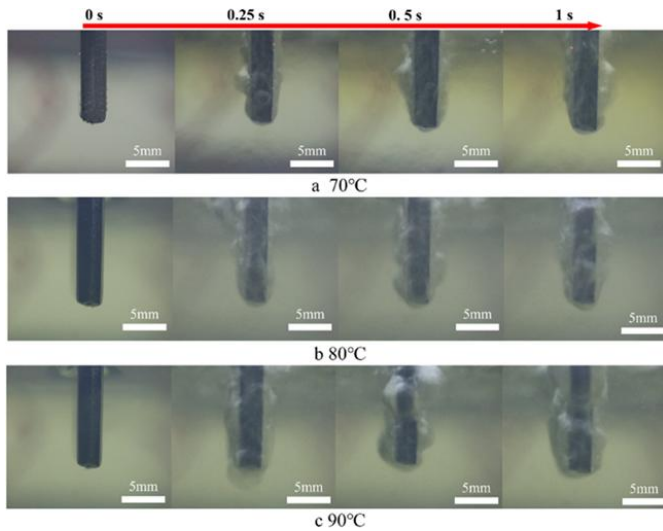
Fe₃O₄@SiO₂ Core: Synthesized via chemical co-precipitation of FeCl₃ and FeCl₂ (ratio 2:1) at 85°C with NaOH under N₂ atmosphere.

SiO₂ Shell: Synthesized through the sol-gel method. The Fe₃O₄ cores were ultrasonically dispersed and coated with a protective silica layer via tetraethyl orthosilicate (TEOS) hydrolysis for 480 minutes.

2.3. Plasma Sheath Thermal Simulation

Finite Element Method (FEM) simulation using COMSOL verified a concentric ring cathode design:

Transient Phase (0 - 0.33 s): Localized Joule heating raises the tip temperature from 293 K to 2311 K, triggering electrolyte boiling.



Steady Phase (0.999 s): A symmetric plasma sheath encapsulates the anode. The surface temperature reaches a dynamic equilibrium of 4371 K, enabling uniform nanometric material removal.

III. DESIGN AND FABRICATION OF EXPERIMENTAL SETUP

3.1. Mechanical Design of the Z-Axis Linear Module

The Z-axis linear motion module is vertically oriented to support a total mass load of $M = 2.3$ kg with a maximum velocity of $V_{max} = 60$ mm/s. The system utilizes a Misumi standard ball screw with a nominal shaft diameter $D_{sb} = 16$ mm and a pitch lead $l = 2.5$ mm. Calculations indicate that the peak axial load during downward acceleration is $F_{amax} = 23.28$ N. This value is significantly below the permissible buckling load ($P_u = 10219.7$ N) and the allowable axial load limit ($P_{dt} = 5109.85$ N), ensuring a rigid, vibration-free setup. The nominal fatigue life of the nut assembly reaches 536458 hours, safely exceeding the targeted requirement of 30000 hours.

3.2. Integrated PLC - HMI Control System

The control architecture is centered around a Siemens SIMATIC S7 PLC, which interfaces with a Weintek graphical HMI touchscreen for real-time monitoring and parameter input. The PLC delivers high-frequency pulse trains ($f = 2500$ Hz) to a TB6600 stepper motor driver to govern the Z-axis immersion depth precisely. Mechanical limit micro-switches and a latching

emergency stop button are integrated into the hardware to mitigate operational hazards.

IV. RESULTS AND DISCUSSION

4.1. Experimental Configurations

Workpiece: Pre-cleaned Ti-6Al-4V titanium alloy specimens.
Active Working Fluid: An orthophosphoric acid H₃PO₄ electrolyte matrix blended with synthesized core-shell Fe₃O₄@SiO₂ magnetic abrasive nanoparticles.

Field Activation: A circular Halbach permanent magnet array placed beneath the processing cup generates a high-gradient magnetic field to structure the abrasive chains. An induction heating element maintains the electrolyte within the optimal electrochemical window.

4.2. Surface Morphology and Roughness (Ra) Reduction Efficiency

Prior to finishing, the Ti-6Al-4V surface displayed severe micro-defects and parallel micro-grooves from prior machining. The initial average surface roughness was measured at $R = 184.73$ nm.

Following the hybrid finishing cycle, microscopic examinations revealed that the abrasive grooves and microscopic peak asperities were fully leveled, yielding a mirror-like specular finish. The final average surface roughness dropped to a mere $Ra = 1.06$ nm.

The absolute reduction in surface roughness is given by:

$$\Delta Ra = 184,73 - 1,06 = 183,67 \text{ nm}$$

The overall roughness reduction efficiency (η) is calculated as:

$$\eta = \frac{184,73 - 1,06}{184,73} \times 100\% \approx 99,43\%$$

4.3. Discussion on the Multi-Field Synergistic Mechanism

The exceptional surface finishing efficiency (99.43%) validates the seamless synergy of the coupled physical fields. Under the Halbach magnetic field array, the core-shell Fe₃O₄@SiO₂ nanoparticles automatically align into directional abrasive chains that adaptively conform to the workpiece profile. When the plasma sheath stabilizes at its peak temperature (4371 K), the passivated titanium oxide film is thermally broken down, selectively softening the underlying metallic peaks. Consequently, the rigid SiO₂ outer shells of the structured magnetic chains easily perform micro-mechanical sweeping, cleanly shearing away the weakened material peaks without scratching the deeper bulk material substrate.

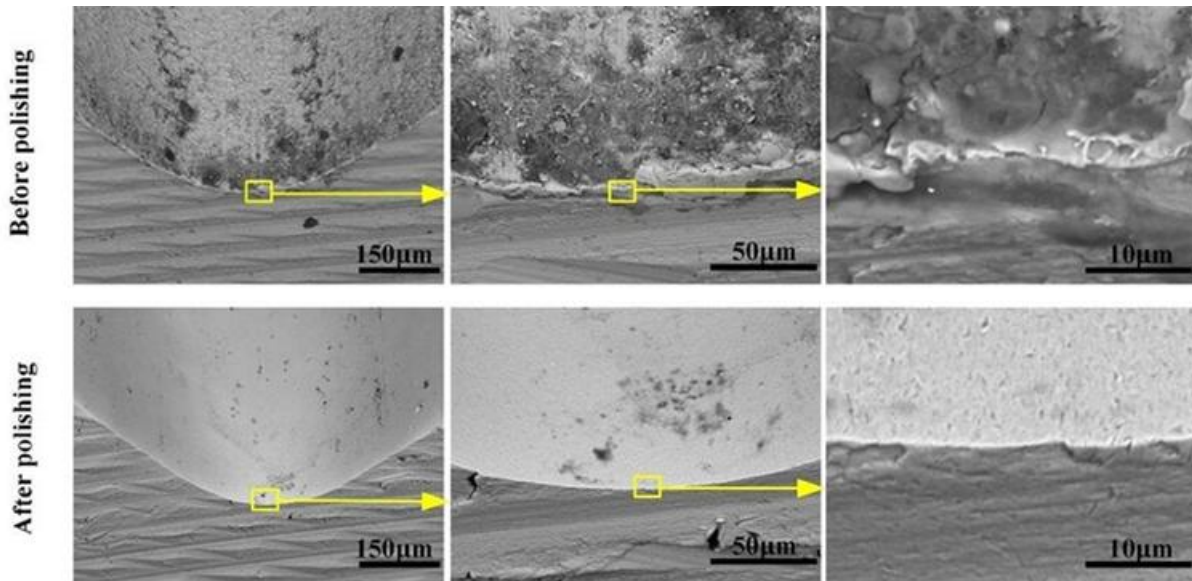
Experimental observations also indicate that processing time and voltage input must be strictly regulated. Excessive voltage or prolonged exposure delivers an over-concentration of plasma energy, triggering aggressive, uncontrollable electrochemical etching that induces pitting defects and degrades the surface finish.

V. CONCLUSION

This study successfully designed, simulated, and fabricated an automated hybrid finishing system managed by a PLC-HMI unit. The platform demonstrated exceptional stability and

technological capability in handling hard-to-machine Ti-6Al-4V titanium alloys. The experimental surface roughness dropped drastically from 184.73 nm to 1.06 nm (a 99.43% processing efficiency). This system offers a compelling

baseline for commercial high-efficiency green manufacturing equipment, meeting the rigorous precision requirements of the aerospace and biomedical implant industries.



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