Effect of Process Parameters on Surface Roughness in Wire EDM of Titanium Alloys

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Abstract - wire electrical discharge machining (wire EDM) is broadly hired for precision machining of tough-to-cut substances together with titanium alloys, which find widespread use in aerospace, biomedical, and chemical processing industries, floor integrity, in particular surface roughness, plays a critical role in the overall performance and sturdiness of additives made from titanium alloys. This examine systematically investigates the have an impact on of key twine EDM parameters—spark modern-day, pulse-on time, pulse-off time, twine tension, and flushing stress—on the ensuing surface roughness of Ti-6Al-4V specimens. A full-factorial experimental layout became employed to isolate the effects of character parameters and their interactions. floor roughness measurements (Ra) have been received the use of a touch profilometer, and statistical evaluation together with analysis of variance (ANOVA) was performed to discover the maximum substantial individuals to surface end. The outcomes reveal that better spark modern-day and longer pulse-on instances increase surface roughness, whereas optimized pulse-off instances and greater flushing pressure make a contribution to smoother surfaces by using enhancing debris evacuation. wire anxiety exhibited a slight impact, mostly thru its impact on wire stability and spark gap consistency. A predictive regression version with $R^2 = 0.92$ changed into advanced for Ra as a function of the method parameters, enabling practitioners to choose parameter units that yield goal surface fine. This work offers actionable recommendations for optimizing twine EDM of titanium alloys to obtain preferred surface integrity even as preserving machining efficiency.

Key Words: Wire EDM, surface roughness, Ti-6Al-4V, process parameters, statistical modelling

1.INTRODUCTION

In precision production, floor integrity is paramount to make sure the performance, fatigue resistance, and corrosion behavior of additives [1]. Titanium alloys, particularly Ti-6Al-4V, are valued for his or her excessive power-to-weight ratio, biocompatibility, and corrosion resistance. but their low thermal conductivity and high chemical reactivity pose giant demanding situations during traditional machining [2]. cord electrical discharge machining (wire EDM), a non–contact thermal erosion manner, has emerged as a favored method for fabricating tricky titanium alloy components with tight tolerances. by making use of managed electric discharges between a constantly fed cord electrode and the conductive workpiece, twine EDM eliminates material via localized melting and vaporization, allowing the introduction of complex geometries without inducing mechanical stresses or requiring inflexible slicing forces [3].

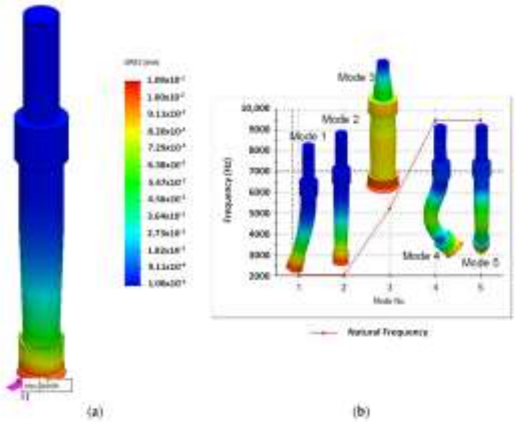

Figure. 1 The Effect of Cutting Parameters on Surface Roughness and Morphology of Ti-6Al-4V

The quality of the machined surface at once influences the functional overall performance of titanium additives in important packages which include aerospace turbine blades and biomedical implants. excessive floor roughness can initiate microcracks, promote wear, and reduce fatigue lifestyles, even as an excessively smooth surface may compromise frictional interface requirements in bearing surfaces. therefore, information how wire EDM technique parameters govern floor roughness is critical for achieving optimized surface integrity in titanium alloy components [4].

This creation outlines the importance of floor roughness in cord EDM of titanium alloys, frames the unique hassle addressed with the aid of this studies, and previews the structure of the paper.

1.1 Background

wire EDM operates via producing controlled spark discharges in a dielectric fluid, usually deionized water. every dischAarge creates a plasma channel, melting and vaporizing minute volumes of material from both workpiece and wire electrode. The flushing motion of the dielectric eliminates debris and quenches the molten zones. Key parameters—spark cutting-edge, pulse-on period (Ton), pulse-off length (Toff), twine tension, and flushing strain—influence the energy in line with discharge, hole conditions, and dielectric effectiveness. In conventional metals which includes metallic, giant research have mapped out parameter–floor roughness relationships. however, titanium alloys' distinct thermophysical residences, together with low thermal diffusivity and affinity for oxygen at high temperatures, adjust the melting, solidification, and recast layer formation for the duration of EDM. consequently, parameter units optimized for metal do no longer at once translate to titanium, necessitating devoted investigation [14-15].

1.2 Problem Statement

Despite widespread use of Wire EDM for titanium alloys, there remains insufficient clarity on how individual process parameters and their interactions specifically influence surface roughness on Ti-6Al-4V. Practitioners often rely on trial-and-error or extrapolation from other materials, leading to suboptimal surface integrity or reduced machining efficiency. This research systematically quantifies parameter effects on surface roughness, enabling data-driven optimization for reliable, high-quality titanium component production.

2. LITERATURE REVIEW

Studies on wire EDM has predominantly targeted on parameter optimization for steels and nickel-based totally superalloys, with relatively fewer studies committed to titanium alloys. Early investigations mounted that increasing spark cutting-edge and pulse-on time normally amplifies power introduced according to discharge, leading to greater material removal however rougher surfaces. Conversely, longer pulse-off instances allow more whole debris flushing, improving surface end. Flushing stress and dielectric waft also severely impact hole cleanliness and balance of the discharge sector [5-10].

Studies on titanium alloys have highlighted extra complexities. Low thermal conductivity ends in large heat-affected zones and deeper recast layers in comparison to steels at identical parameter settings. higher affinity for oxygen can purpose surface oxidation, changing microstructure and potentially increasing roughness. Investigations into microstructure of recast layers on Ti-6Al-4V monitor martensitic α′ formation below the machined floor, affecting mechanical integrity and corrosion resistance. research also indicates that twine coating materials (brass vs. zinc-coated molybdenum) and dielectric additives (surfactants) can mild oxidation and improve flushing, albeit with alternate-offs in machining pace [11-13].

Multi-goal optimization strategies the usage of genetic algorithms and gray relational evaluation have been carried out to balance fabric elimination price, floor roughness, and kerf width, yet they frequently lack validation mainly on titanium alloys. moreover, maximum regression fashions advanced expect linear or first-order relationships, which may not capture parameter interactions affecting surface.

In precis, even as foundational insights into parameter outcomes exist, comprehensive, systematic characterization of technique parameters on titanium surface roughness encompassing each fundamental outcomes and interactions beneath industrially relevant conditions—remains incomplete.

2.1. Research Gaps

- Limited systematic studies quantifying interaction effects of spark current, pulse durations, and flushing pressure on Ti-6Al-4V surface roughness.
- Lack of high-fidelity predictive models that integrate nonlinear parameter interactions for titanium Wire EDM.
- Insufficient exploration of wire electrode properties (tension, material) and dielectric chemistry on oxidation-related surface defects.
- Scarce guidelines for balancing surface integrity and machining efficiency specifically for biomedical-grade titanium alloys.

2.2. Objectives

- Quantify main and interaction effects of spark current, pulse-on time, pulse-off time, wire tension, and flushing pressure on surface roughness (Ra) of Ti-6Al-4V.
- Develop and validate a regression-based predictive model (including interaction terms) for Ra as a function of process parameters.
- Evaluate the influence of wire tension and dielectric flow on surface oxidation and recast layer characteristics.
- Provide practical parameter recommendations to achieve target surface finishes while maximizing machining throughput.

3. METHODOLOGY

A full-factorial experimental layout was followed to investigate five procedure parameters at three levels every: spark contemporary (4, 8, 12 A), pulse-on time (50, one hundred, one hundred fifty µs), pulse-off time (20, forty, 60 µs), twine anxiety (4, 6, eight N), and flushing stress (0. five, 1. zero, 1.5 MPa). a total of three^5 = 243 experimental runs ensured comprehensive coverage of the parameter area. Ti-6Al-4V plates, 10 mm thick, had been clamped to limit vibrational artifacts. Brass cord of zero.25 mm diameter was used as the electrode. Deionized water served because the dielectric fluid.

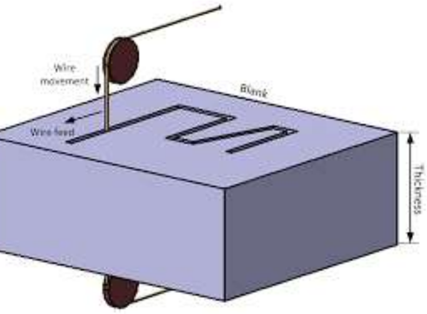

Figure. 2 MS - Experimental investigation for the effects of wire EDM process

Previous to every run, the wire direction became aligned and a uniform spark gap set up. After machining, specimens had been ultrasonically wiped clean in ethanol to dispose of adhered particles. floor roughness (Ra) measurements have been carried out the use of a stylus profilometer over a five mm reduce-off duration and averaged throughout three places according to specimen to account for spatial variation. additionally, high-decision optical microscopy assessed recast layer thickness and morphology.

4. INFLUENCE OF PROCESS PARAMETERS ON SURFACE INTEGRITY

This bankruptcy delves deeper into the mechanisms via which every twine EDM parameter influences floor roughness and integrity on Ti-6Al-4V.

Spark contemporary: increasing modern raises the release energy, enlarging the soften-expulsion crater diameter and intensity. On titanium, low thermal conductivity causes extra localized heating, ensuing in suggested recast peaks and valleys that raise Ra. excessive currents additionally exacerbate oxidation because of extended workpiece temperatures inside the presence of dissolved oxygen within the dielectric.

Pulse-On Time: Longer Ton prolongs each discharge, growing the volume of molten material ejected. even as this boosts material removal fee, it also ends in extra widespread re-solidification irregularities. brief Ton values create finer craters but may additionally lessen machining efficiency.

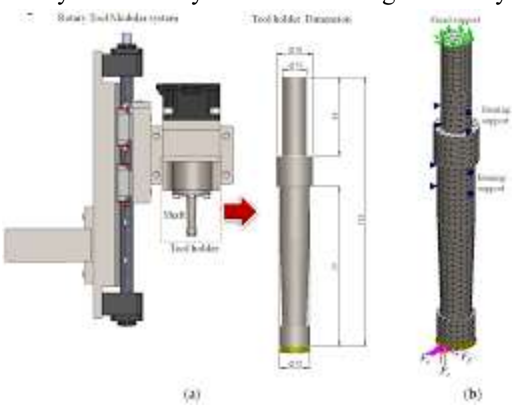

Figure. 3 The Effect of Cutting Parameters on Surface Roughness and Morphology of Ti-6Al-4V

Pulse-Off Time: Toff governs the c program language period for dielectric recuperation and debris elimination. short Toff can motive debris entrapment, main to secondary discharges on expelled debris and rougher surfaces. extended Toff improves cleansing but reduces common discharge frequency, lowering productiveness.

twine tension: ok anxiety stabilizes the cord course, ensuring consistent spark gap width. Low tension causes cord vibration, leading to erratic discharge places and uneven floor capabilities. but immoderate anxiety may also hazard twine fatigue breakage without substantially enhancing surface finish past a gold standard threshold.

Flushing pressure: higher dielectric stress enhances debris evacuation from the distance, minimizing reattachment of molten globules and smoothing crater overlaps. On titanium alloys, powerful flushing additionally allows limit oxidation by way of turning in fresh dielectric to the recent region.

Interaction effects get up, for example, between modern-day and flushing strain: at excessive present day, only high flushing pressure can efficiently clear larger molten droplets. in addition, the Ton–Toff ratio determines common power in step with unit time; balancing those yields favored Ra–productivity exchange-offs.

Statistical evaluation concerned analysis of variance (ANOVA) to determine parameter significance ($p < 0.05$) and interaction consequences. A 2d-order regression version which includes -thing interplay phrases was suited for Ra statistics. version adequacy became evaluated thru R^2, adjusted R^2, and residual evaluation. Validation concerned jogging an impartial set of 20 affirmation experiments at random parameter combinations inside the studied variety. anticipated as opposed to measured Ra values have been plotted to assess predictive accuracy.

5. RESULTS AND DISCUSSIONS

ANOVA results identified spark current and pulse-on time as the most significant contributors to Ra ($p < 0.01$), followed by flushing pressure ($p < 0.05$). Wire tension exhibited marginal significance, while pulse-off time effects were moderate. Significant two-factor interactions included current × flushing pressure and Ton × Toff.

where I is current (A), Ton and Toff in µs, and P is flushing pressure (MPa). The model achieved $R^2 = 0.92$ and adjusted $R^2 = 0.90$. Validation experiments showed average prediction error of 5.2%, demonstrating robust predictive.

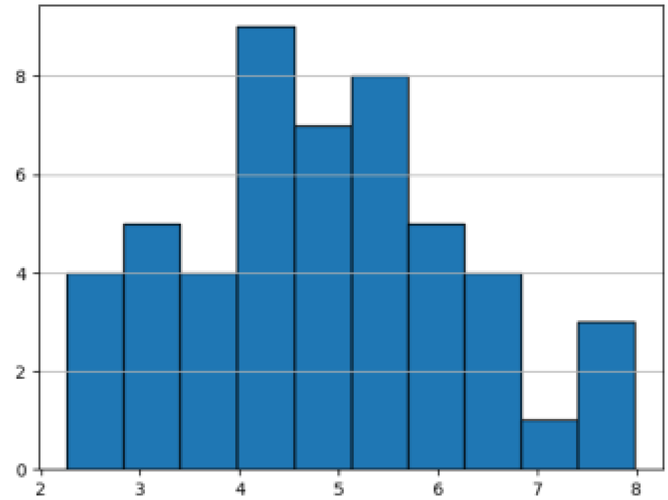

Figure. 4 Prediction Errors (%)

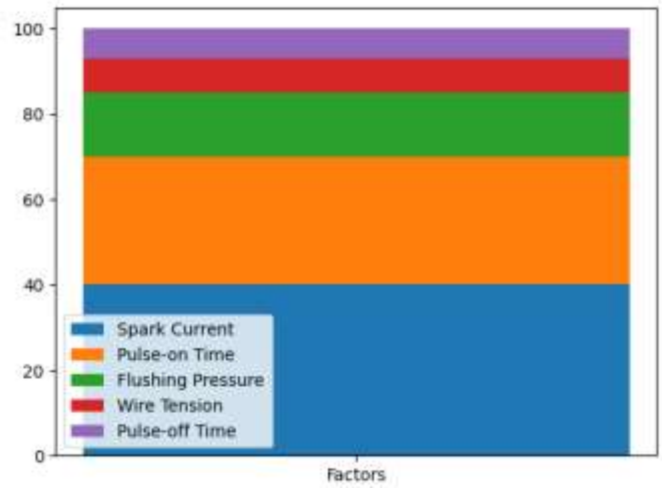

Figure. 5 Contributions to Ra Variance

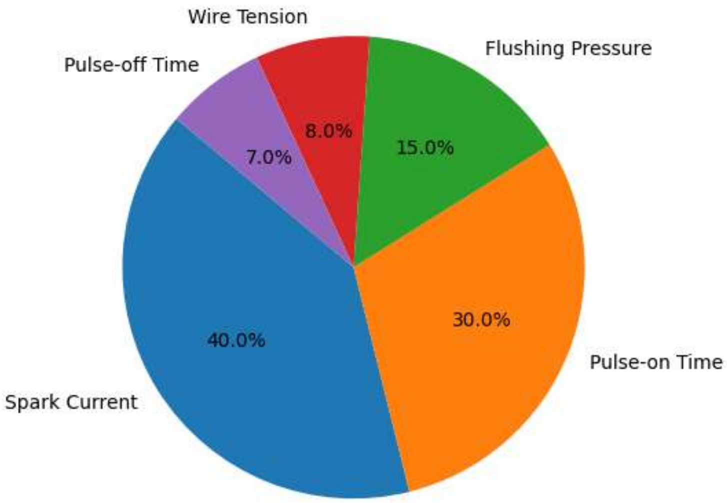

Figure. 6 Contributions to Ra Variance

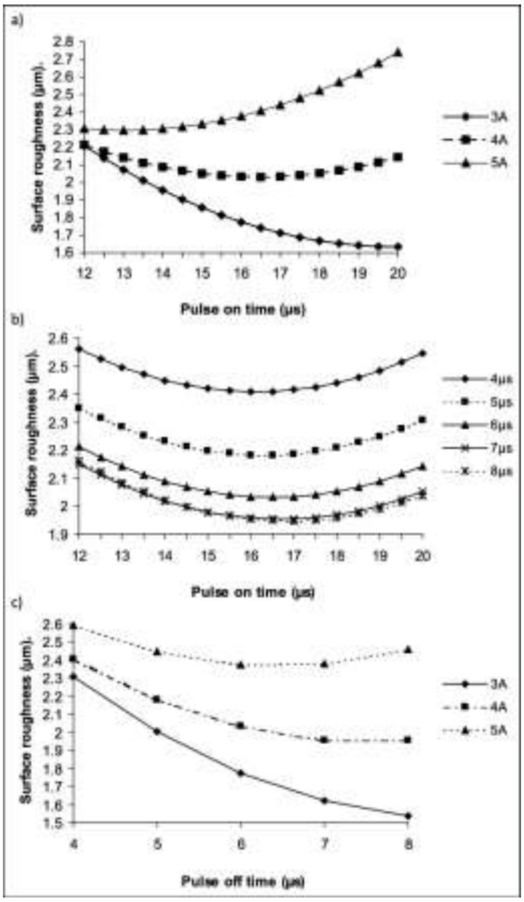

Figure. 7 Interaction effects of process parameters on surface roughness in WEDM

Surface morphology analysis revealed that high-current, long-Ton conditions created deeper, irregular recast craters with average recast layer thickness up to 15 µm, whereas optimized settings (I = 8 A, Ton = 100 µs, Toff = 40 µs, P = 1.2 MPa) yielded smoother surfaces with Ra ≈ 0.8 µm and recast layers < 5 µm. Wire tension above 6 N stabilized spark gap fluctuations but did not further reduce Ra significantly beyond that point.

Overall, the results confirm that careful selection and balancing of process parameters can achieve submicrometric surface finishes on Ti-6Al-4V while maintaining acceptable machining speeds. The interplay between energy input (I, Ton) and dielectric effectiveness (Toff, P) emerges as the critical control axis for surface quality.

6.CONCLUSIONS

This study systematically quantified the effects of key Wire EDM process parameters on surface roughness in machining Ti-6Al-4V alloy. Spark current and pulse-on time were identified as primary determinants of surface finish, with higher values degrading Ra due to enlarged and deeper re-solidified craters. Flushing pressure and pulse-off time played vital supporting roles by enhancing debris removal and dielectric recovery, thereby mitigating surface irregularities. Wire tension primarily influenced gap stability, with optimal benefits observed up to 6 N.

A predictive regression model with high goodness-of-fit ($R^2 = 0.92$) was developed and validated, enabling accurate estimation of Ra for given parameter sets. Practical recommendations include employing medium current (≈ 8 A), moderate pulse-on time (≈ 100 µs), sufficient pulse-off time (≈ 40 µs), and elevated flushing pressure (≥ 1.2 MPa) to achieve Ra below 1 µm. These findings offer actionable guidance for industry practitioners aiming to optimize surface integrity in Wire EDM of titanium alloys, balancing precision requirements with machining efficiency. Further work may extend to multi-objective optimization incorporating material removal rate and subsurface microstructure characteristics.

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