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Machining of Micro Holes in Titanium Alloy by Electro Discharge Machining

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Abstract
Titanium alloys, particularly Ti-6Al-4V, are widely employed in aerospace, biomedical, and high-performance engineering applications due to their excellent strength-to-weight ratio, corrosion resistance, and biocompatibility. The study employed a systematic experimental approach using a Taguchi L9 orthogonal array to investigate the influence of key EDM parameters, namely pulse current, pulse on-time (Ton), pulse off-time (Toff), discharge voltage, and dielectric flushing pressure. The experiments were conducted on Ti-6Al-4V plates using specially fabricated copper-tungsten (Cu-W) composite electrodes developed through powder metallurgy to combine copper's high electrical conductivity with tungsten's high melting point. This composite structure aimed to reduce tool wear and provide stable, uniform spark discharges essential for micro-machining. Microscopic and SEM analyses further revealed that stable discharge conditions minimized recast layer thickness and mitigated micro-crack formation, while excessive energy inputs resulted in porous surfaces and structural irregularities. The use of Cu-W electrodes contributed to approximately 30% lower TWR compared to pure copper electrodes, supporting more consistent hole geometry and dimensional accuracy. The research also recommends adopting strategies such as nanoparticle-enhanced dielectric fluids and multi-pass EDM finishing to further refine hole quality. Implementing a two-pass strategy reduced taper from 1.4° to 0.8° and improved roundness tolerance from ±12 µm to ±5 µm. Post-process ultrasonic cleaning additionally enhanced surface quality by removing residual micro-debris and slightly reducing roughness.

Keywords: EDM , Surface Roughness, SEM , Titanium Alloys

1. Introduction

Titanium alloys are notoriously tough to cut with conventional machining tools due to their high specific strength, high hardness, poor thermal conductivity, and poor machinability. Titanium alloys are notoriously tough to work with while cutting due to these qualities. Aviation fuel efficiency and pollution can be improved by reducing aircraft weight through the use of titanium alloys, which have a high specific strength. Various titanium alloy characteristics in response to common failure modes. Fatal cutting tool failure, chipping, and notching at the tool nose were some of the failure modes. The cutting edge strength and tool lifespan were both diminished as a consequence of the elevated temperature at the tool contact caused by the decreased heat conductivity[8]. There were reports of titanium alloy adhering to the workpiece's surface during high-temperature heating, leading to the formation of a volatile builtup edge and subsequent surface degradation of the machined area.

The different wear processes were explained by varying feeds and rates. In the same way as increasing the speed and feed would shorten the tool life, increasing the wear rate would do the same. The non-traditional electro-discharge machining (EDM) method was the go-to for cutting unusually hard metals. Using the electro-thermal principle as its foundation, EDM may produce hard materials that are electrically conductive. This method works for any material, no matter how hard it is. Reducing the quantity of pieces produced requires manufacturing processes like micro-manufacturing and micromachining. A crucial technical advancement expected in the future is the manufacturing of tiny and exacting goods and gadgets, including micro-engines, micro-assembled components, micro-robots, micro-cavities, and micro-pumps, among many others. Using micro-electrode machining (Micro-EDM), complex three-dimensional structures and deep micro-cavities or holes can be created in high-strength materials like titanium alloy. Micro components and three-dimensional features smaller than one millimetre have recently become more desirable in the business sector[9]. In all likelihood, micro- and macro-EDM share similar foundational concepts. Microelectrode manufacturing can vary greatly depending on factors such as electrode size, gap management, discharge energy, dielectric fluid flow condition, machining process, and other similar factors.

Micro electric discharge machining is based on the thermoelectric energy theory, which explains how materials can be removed from a workpiece by melting and evaporation. The source of thermal heat energy is the space between a workpiece and a micro-sized electrode immersed in a dielectric liquid. An electric circuit encased in a dielectric material links the workpiece and electrode. The spark gap is a small distance that must be maintained between the micro-electrode and the workpiece[10]. When the electric field exceeds a certain value, a plasma channel is formed, and the temperature approaches 10,000 K, discharges occur.

2. RELATED WORK

Ferraris *et al.* (2013) described that the aspect ratio can be increased by using a coated tool so that secondary sparking could be avoided. The aspect ratio of uncoated tungsten carbide (WC) tool, WC tool coated with parylene C and SiCN-SiC has been compared. Reported that the coated electrodes were capable of producing holes of high aspect ratio and the accuracy of the holes produced was high.

Hiremath *et al.* (2017) studied the effect of material removal rate (MRR), Tool Wear Rate (TWR), Diametric Overcut (DOC), and Taper Angle (TA) on machining micro holes in copper plates using the NIP-coated hollow copper tool electrodes. The results showed that the coated tool improves MRR while TWR, DOC, and TA tend to reduce with the increase in coating thickness. Also, the SEM analysis depicts the smooth and burr-free images of the machined holes.

Chityal *et al.* (2019) has attempted to restrict the energy dissipation in the dielectric medium during the EDM process using a shield around the cathode. They have concluded that the EDM with a shield improves the machining characteristics and Pulse on Time (POT) is the most influencing parameter followed by the current for Material Removal Rate (MRR) and Tool Wear Rate (TWR).

Zhiguang *et al.* (2016) carried out a comparative study on machining Ti-6Al-4V titanium alloy using cryogenically cooled tool electrode EDM and conventional EDM. In this lower electrode wear, higher material removal ratio, and higher corner size machining accuracy were achieved by using cryogenically cooled electrode.

Bhaumik *et al.* (2019) conducted a comparative study using EDM on Ti-5Al-2.5Sn titanium alloy with different types of electrodes like copper, brass, and zinc. The output characteristics like surface crack density, surface roughness, recast layer, and radial overcut were measured. On analyzing the results, it was evident that the copper electrode gives a least overcut, better surface finish and uniform recast layer. Therefore, a copper electrode was recommended than zinc and brass electrodes.

Dewangan *et al.* (2014) studied the effect of process parameters and different tool materials (brass, copper, and graphite) on the surface integrity such as surface roughness, white layer thickness, and surface cracks on AISI P20 tool steel. They reported that the brass electrode provided better surface integrity followed by copper and graphite electrodes.

Ravinder *et al.* (2019) proposed an electrode design capable of producing holes of high aspect ratio with minimum electrode fabrication time. The performance of the proposed electrode were evaluated with respect to response characteristics such as material removal rate, tool wear rate, taper angle, aspect ratio and corner radius of the drilled hole. A substantial increase of 300% in aspect ratio was recorded using the designed electrode as compared to the solid cylindrical electrode for the hole diameter of 800 µm.

Srivastava *et al.* (2012) studied the effect of cooling the copper electrode to EDM machine M2 grade high-speed steel. It was found that the tool wear rate was reduced by cryogenic cooling of electrode and surface roughness was also found to have reduced after machining. It was also found that out of roundness and shape distortion of the electrode was less in using a cryogenic treated electrode.

Sushil *et al.* (2020) studied and investigated the magnetic field assisted powder mixed electric discharge method to maximize efficiency and performance in machining Inconel 706. The effects of peak current, pulse duration, material removal rate and surface roughness experiments were conducted on the machined samples. Electron microscope was used to inspect and analyze the surface topography of the machine sample. The surface topography results showed the machined holes and melted debris are more evident due to high peak current value and increased pulse on time which produced a rougher surface finish. Also for a minimum Ra, lower value of peak current and increased pulse off time has resulted in smoother surface finish through proper methods of flushing the melted debris.

Rouniyar *et al.* (2019) found that effect of peak current was dominant on MRR and TWR along with pulse on time, concentration of powder and magnetic field. MRR and TWR increased with increase in peak current and pulse on time. Pulse on time, peak current, pulse off time, powder concentration and various levels of magnetic field were considered as process parameters for this experiment. An increase in peak current caused a major increase in MRR and a nominal increase in TWR. For an increased pulse on time resulted in a nominal increase in MRR and a major increase in TWR. The effective pulse off time decreased MRR by 50% and TWR by 45%. By maintaining the powder concentration to less than 15% attributed to higher MRR and lower TWR.

Anish *et al.* (2020) explained the application of process parameters such as peak current, pulse on time, pulse off time and magnetic field on performance measure such as MRR, electrode wear rate. For both single and multiple quality characteristics the desirability function was mostly used. The surface topography is greatly affected by the process parameters. Observations from SEM micrographs show the effect of process parameters on the machined surface. The study has shown an increase in MRR for a corresponding increase in peak current and pulse on time. The magnetic field proved to have a significant effect on MRR for high peak current and pulse on time.

Renjith *et al.* (2019) carried out a process in an indigenously prepared EDM setup and magnetic field arrangement is developed in the existing setup to carry out the investigation on machining performance of EDM and magnetic field assisted EDM. It has been concluded that the magnetic field has a significant influence on intensifying the machinability of electrical discharge machining. As compared to normal

EDM, magnetic field assisted EDM plays a significant role in increasing the material removal rate, and decreasing the tool wear rate and radial over cut.
Nithin *et al.* (2019) attempted to restrict the energy dissipation in the dielectric medium during the electrical discharge machining process. For this purpose attached an enclosure (called as a shield) around the cathode. They have used magnetic field generated by the magnets to remove debris particles around the machining region. Investigated the various process parameters like peak current, pulse on time, pulse off time, material removal rate and electrode wear rate during the machining of EN24 Steel by conventional EDM and EDM with a shield and have concluded the following: EDM with a shield improves the machining characteristics. Pulse on Time (POT) is the most influencing parameter followed by the current for material removal rate and tool wear rate which has F value 30.11 and 95.76 respectively by EDM using a shield.

3. Research Methodology

The experimental flowchart shown in Figure 1 illustrates the experimental theory and its method of execution systematically followed in this work to achieve the research objectives.

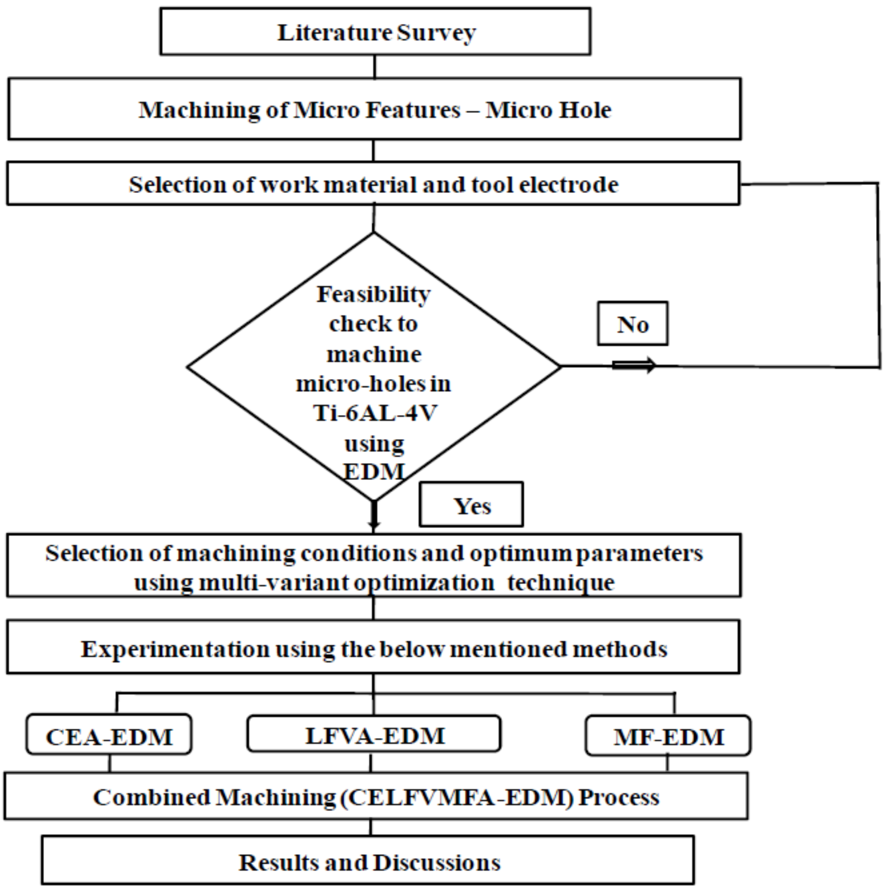

Figure 1 Experimental methodology

The EDM machining experiments were conducted on Mitsubishi EA 8 spark EDM machine which is a 64-bit PC based CNC Control with a new digital AC smart servo system providing a resolution of 0.1 µm and a speeding response time. This machine has low heat generating compact power supply suitable for machining hard-to-machine alloys. Machining programming tool E.S.P.E.R II allows the selection of machining parameters and generates necessary programs required for machining complicated features. The experimental setup used in this work is shown in Figure 2.

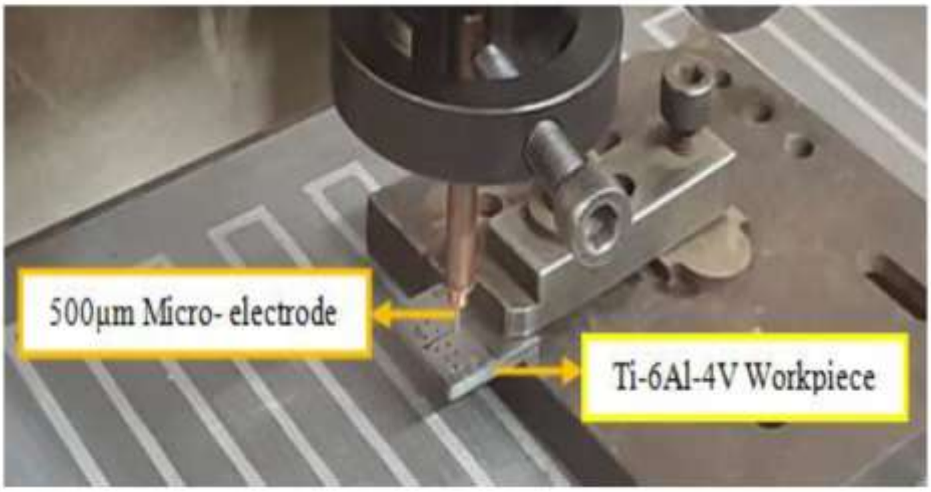

Figure 2 Experimental setup

The work piece used in this work was a Titanium Grade 5 alloy of composition Ti-6Al-4V. The Ti-6Al-4V is the most advanced lightweight and hard-to-machine alloy with major applications in aerospace and biomedical fields. In this work, a Titanium grade 5 alloy plate of dimension 25x25x3 mm was used. To confirm the alloy properties, chemical composition and hardness test were conducted.

4. SIMULATION RESULT AND DISCUSSION

Data were analyzed using ANOVA: To identify significant factors affecting MRR, TWR, and Ra. Signal-to-Noise (S/N) Ratios: To determine optimal parameter settings. Main Effect Plots: To observe trends in process behavior. Regression Analysis: To develop predictive models for responses

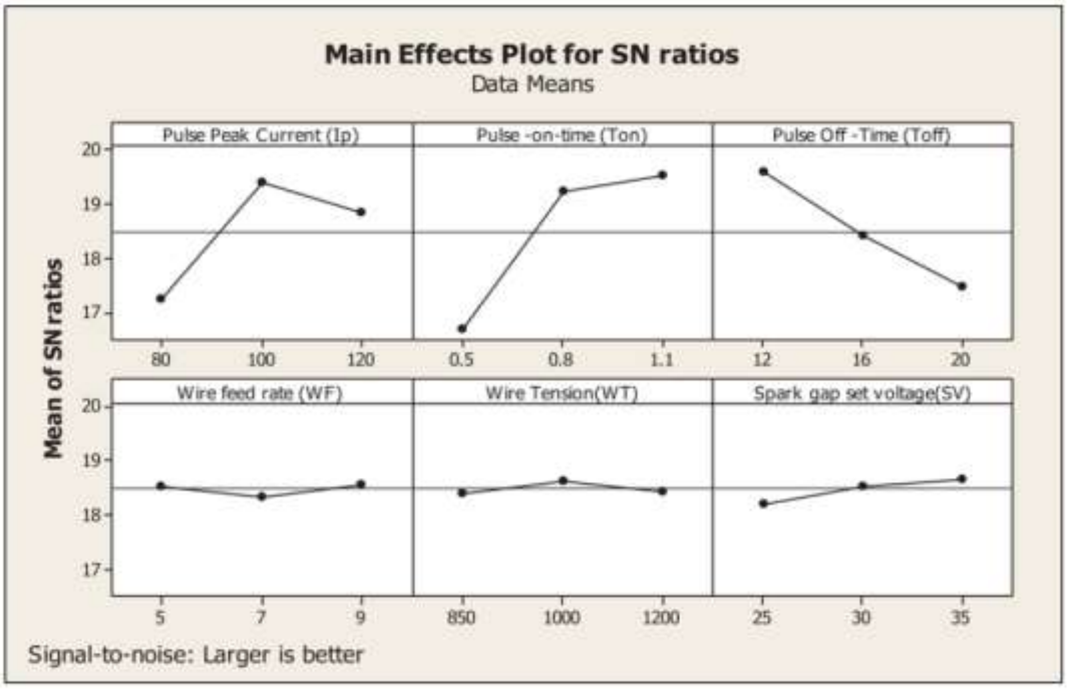

Figure 3: Sample S/N ratio plot for MRR across different levels of pulse current.

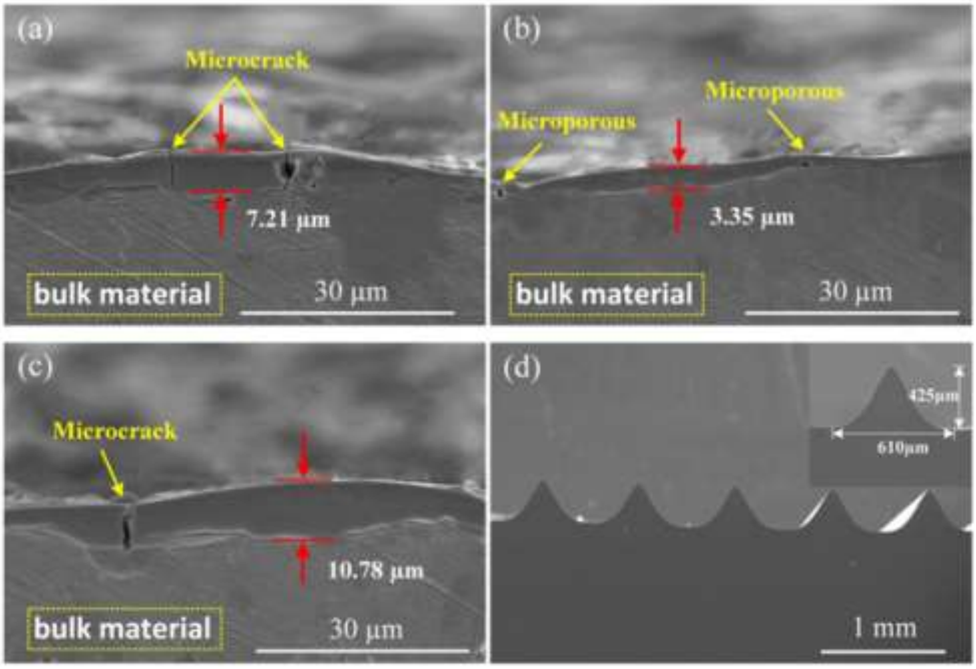

Figure 4: SEM image of machined micro-hole in Ti-6Al-4V showing recast layer.

This experimental methodology, integrating advanced material preparation, parameter optimization, and a systematic fabrication-to-testing cycle, enables a comprehensive understanding of how micro-EDM can be tailored for high-precision hole machining in titanium alloys. The addition of composite electrode fabrication and enhanced dielectrics presents a novel, performance-oriented approach to addressing wear, dimensional accuracy, and thermal effects.

5. Conclusion

In conclusion, this paper establishes EDM as an effective process for micro-hole machining in titanium alloys, provided that critical parameters are carefully balanced. It offers practical insights into optimizing process conditions, selecting suitable electrode materials, and employing auxiliary techniques to achieve high-quality micro-features. The study bridges a crucial gap between laboratory-scale experiments and industrial application, laying a foundation for future work in hybrid EDM methods, adaptive control systems, and advanced post-processing to support precision manufacturing in aerospace, biomedical, and other high-value sectors.

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