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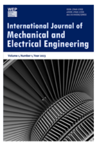

Influence of Ultrasonic Vibration on the Reinforced Layer of Titanium Alloys Strengthened by Quasi-dry EDM with Mixed Powders

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ABSTRACT

To address issues such as powder agglomeration and unstable discharges during mixed powder near-dry electrical discharge surface strengthening, a novel method termed Ultrasonic Assisted Powder Mixed Near Dry Electrical Discharge Surface Strengthening (UPMND-EDSS) is proposed. Ultrasonic vibration is employed to disrupt powder agglomerates, preparing a dispersed, homogeneous three-phase medium that enhances the surface quality and properties of the strengthened layer in TC4 titanium alloy. A systematic analysis of the effects of varying ultrasonic vibration on the surface and properties of the strengthened layer reveals: the hardness of the strengthened layer markedly increased under different ultrasonic powers, with an average hardness reaching 1289.06 HV, approximately 3–4 times that of the substrate; when ultrasonic power was increased to 1200 W, the surface quality of the strengthened layer was optimal, with an average microhardness of 1370.4 HV. In summary, the introduction of ultrasonic vibration effectively improves the surface quality of the TC4 titanium alloy strengthened layer.

KEYWORDS

Powder Mixing Quasi-dry; EDM; Ultrasonic Power; Reinforcement Layer.

1. INTRODUCTION

Against the backdrop of the dual carbon goals era, modern manufacturing continually seeks safe, reliable, green and economical technologies to enhance the performance and service life of components. Surface modification techniques strengthen materials through a series of chemical, physical or mechanical methods, altering surface microstructure and chemical composition to improve properties such as hardness, strength and longevity. Among numerous surface strengthening techniques, the Powder Mixed Near Dry Electrical Discharge Surface Strengthening (PMND-EDSS) method employs a solid-liquid-gas three-phase flow as its working medium. This approach effectively addresses issues such as high short-circuit rates inherent in traditional electrical discharge surface strengthening technologies. Its widespread adoption stems from its high processing efficiency and low cost [1].

PMND-EDSS technology involves incorporating various reinforcing powders into a quasi-dry working medium, thereby forming a solid-liquid-gas three-phase medium. During the intensification process, the incorporation of strengthening powders effectively reduces the dielectric strength of the working medium, inducing series discharge across the electrode gap. This increases the spark gap between electrodes, stabilising spark discharge during intensification and thereby enhancing erosion rates. Concurrently, metallurgical reactions occur between the electrode material, powder material, and substrate, forming multiple strengthening phases to achieve hybrid strengthening of the substrate surface [2].

However, during the PMND-EDSS process, powder particles readily agglomerate and deposit, affecting the discharge gap and leading to unstable discharges. This consequently compromises the discharge quality and performance of the strengthened surface layer. The introduction of ultrasound effectively resolves this issue. Our research group and others [3] have proposed the Ultrasonic Assisted Powder Mixed Near Dry Electrical Discharge Surface Strengthening (UPMND-EDSS) technique. UPMND-EDSS). The microjets generated by ultrasonic cavitation induce eddy currents in the working fluid, thereby acting as a stirring mechanism. This ensures uniform mixing of deionised water and powder, prevents powder sedimentation, increases the discharge rate, and promotes uniform discharge during the strengthening process. Concurrently, the mechanical and cavitation effects of ultrasound help prevent the deposition of machining debris, facilitating its removal [4].

Current research by scholars both domestically and internationally on ultrasonic-assisted electrical discharge machining (EDM) surface strengthening techniques indicates that the introduction of ultrasonic vibration enables complementary advantages between EDM surface strengthening and ultrasonic vibration. This achieves enhanced surface quality of the strengthened layer and improved functional properties of the workpiece. Amir et al. [5] utilised copper tool electrodes to machine cemented carbide, comparing the effects on surface morphology under ultrasonic-assisted and non-assisted conditions. They observed that ultrasonic-assisted machining significantly reduced the heat-affected zone and remelted layer, while markedly decreasing surface and cross-sectional cracks in the workpiece. Xijing et al. [6] observed that eddy currents and pumping effects generated by ultrasound reduced adhesion of electrolytic products, improved discharge conditions, and achieved approximately 10% shorter strengthening times compared to conventional powder-mixed EDM, alongside a roughly 15% reduction in surface roughness. Xu Jia-yuan et al. [7] applied ultrasonic excitation to the tool electrode. Results indicated that the surface roughness and microhardness of the strengthened layer correlated with ultrasonic power. However, ultrasonically assisted layers did not universally outperform their non-assisted counterparts; selecting an appropriate ultrasonic power value could further enhance the wear resistance of the strengthened layer. Chang Xiaolong et al. [8] introduced ultrasonic vibration into powder-mixed EDM surface strengthening to investigate its effect on surface roughness. Results indicated that surface roughness initially decreased then increased with rising ultrasonic power. Qi Li et al. [9] validated the efficacy of adding ultrasonic vibration to the working medium, preventing powder sedimentation, reducing abnormal discharges, and promoting the removal of electroerosion products. Building upon the PMND-EDSS technique, our research group has incorporated ultrasonic vibration into the three-phase working medium. This aims to address agglomeration issues within the triphasic medium, increase the discharge gap, thereby improving the surface quality of the strengthened layer, enhancing its microhardness, and reducing surface roughness. This paper employs PMND-EDSS technology to modify the surface of TC4 titanium alloy, experimentally analysing the influence of varying ultrasonic power levels on the microstructure and properties of the strengthened layer.

2. TEST PROCEDURE

2.1. Test Materials

The test substrate material selected for this study was TC4 titanium alloy, with dimensions of 10mm × 10mm × 5mm. Specimens were sequentially polished using sandpaper of varying grades to remove surface oxides, ensuring sufficient surface smoothness. Specimens were then placed in anhydrous ethanol for 15 minutes of ultrasonic cleaning, followed by air-drying prior to use. The composition of the TC4 titanium alloy specimen (10 mm × 10 mm × 4 mm) is detailed in Table 1.

Table 1. Composition of Ti-6Al-4V

Chemical Composition	Al	V	Fe	C	Ti
Content (%)	5.5-6.8	3.5-4.5	≥0.3	≥0.1	allowance

2.2. Reinforcement Layer Preparation

The machine tool employed in this experiment is the AF1100 CNC electrical discharge machining (EDM) machine. An ultrasonic-assisted powder mixing device was independently designed, comprising two principal components: the powder mixing unit and the ultrasonic vibration unit, operating at a frequency of 20kHz. To ensure uniform powder mixing and prevent agglomeration that could compromise machining outcomes, a stirring mechanism was installed within the mixing vessel to agitate the working fluid. A three-phase medium generation unit performed medium injection. During operation, the rubber hose delivering the working fluid was coupled with the ultrasonic horn to achieve uniform and dispersed three-phase medium output. The experimental apparatus schematic is illustrated in Figure 1. Graphite was selected as the tool electrode, connected to the positive terminal of the power supply, while the workpiece was connected to the negative terminal. The workpiece was secured on the platform fixture. Utilising the Z-axis drive of the EDM machine tool platform, the tool electrode was advanced towards the workpiece. The machining depth was set to 0.1 mm for conducting the UPMND-EDSS experiment. Following the strengthening process, the specimen underwent cleaning and drying to obtain the TC4 titanium alloy strengthened layer.

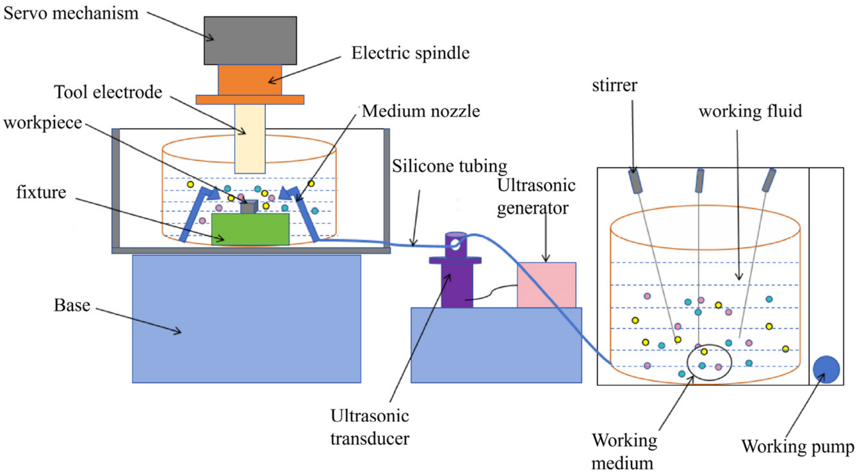

Figure 1. Schematic Diagram of Ultrasound-Assisted Powder Mixing and Electrical Discharge Machining Strengthening Device

This experiment investigated the effects of varying ultrasonic power levels on the microstructure and properties of the TC4 titanium alloy strengthening layer during the UPMND-EDSS process. The ultrasonic power levels employed were 300W, 600W, 900W, 1200W, and 1500W. The working medium comprised air, deionised water, and mixtures of three solid strengthening powders: carbon, boron carbide, and aluminium. The discharge voltage between the power supply electrodes was set at 120V, with a pulse width of 100μs, a pulse interval of 100μs, and a peak current of 8.2A.

2.3. Testing Methods

The microstructure morphology, phases, surface roughness, and microhardness of the TC4 titanium alloy strengthening layer under different strengthening process parameters were analysed. A field emission scanning electron microscope (SEM) was employed to observe the microstructure morphology of the strengthening layer and analyse the distribution of surface defects such as cracks and pores. Phase analysis of the hardened layer was conducted using a Bruker D8 X-ray diffractometer with a copper target, set at a scanning range of 20°–100° and a scanning speed of 4°/min. Three-dimensional topography images of the hardened layer were captured and surface roughness measured using a BRUKER Contour GT-K white light interferometer. Microhardness testing of the strengthening layer was conducted using an HMV-V27 Vickers hardness tester, with a load of 0.2 N and a load-holding time of 10 seconds.

3. RESULTS AND DISCUSSION

3.1. Microstructural Morphology of the Reinforcement Layer

Microstructural morphology of the strengthening layer at different ultrasonic power levels, as shown in Figure 2.

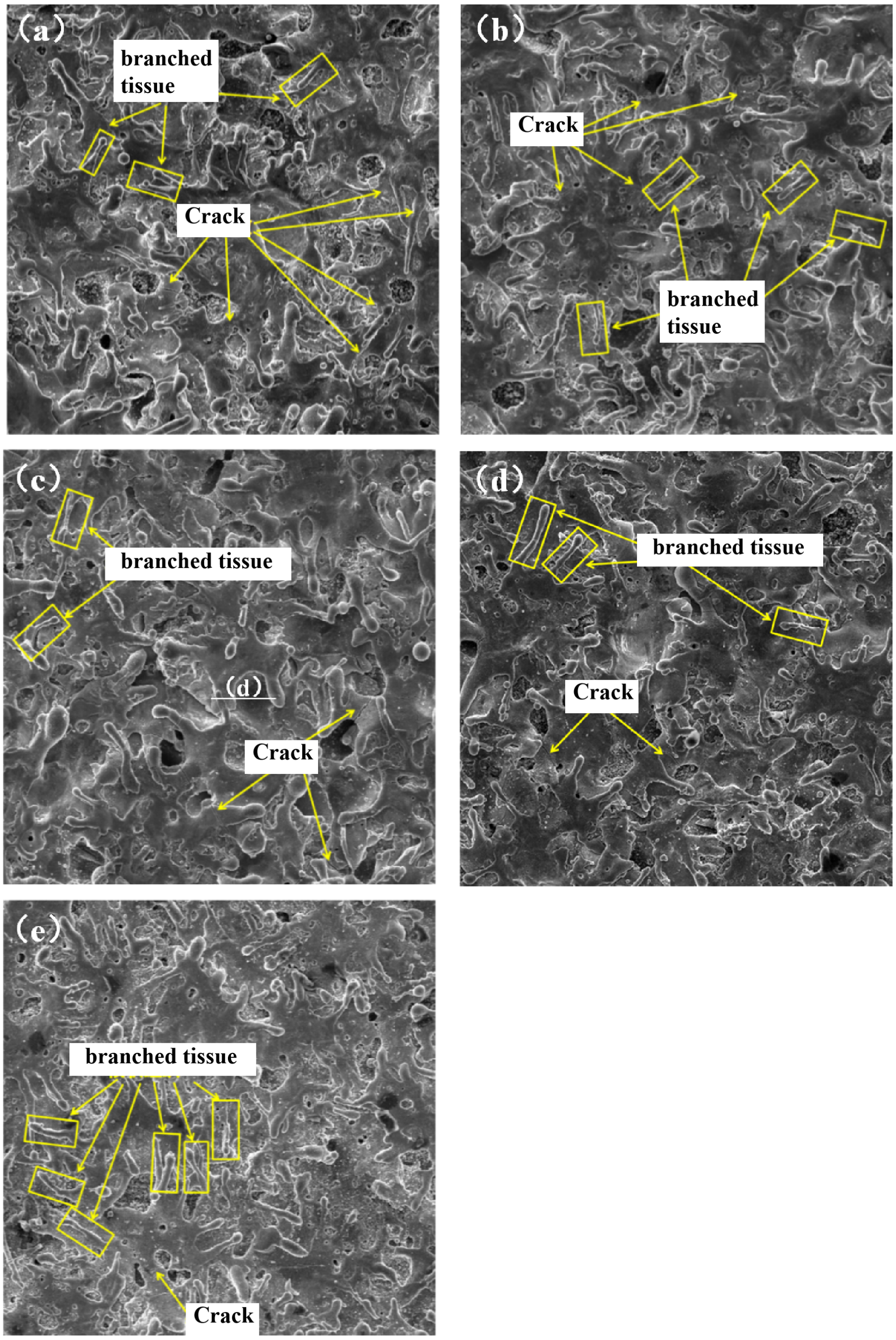

Figure 2. Microstructural morphology of different ultrasonic power-enhanced layers: (a) 300W; (b) 600W; (c) 900W; (d) 1200W; (e) 1500W.

At low ultrasonic power, the strengthened layer exhibits numerous dendritic structures following splash cooling, with elongated crack dimensions and wide opening widths. Some cracks traverse the dendritic structures, accompanied by a small number of micro-pores (as illustrated in Figure 3(a)). Upon increasing the ultrasonic power, the discharge erosion pits within the strengthening layer gradually proliferate and enlarge in diameter. The dendritic structures surrounding these pits become more abundant and coarser. The microstructure in Figure 3(c) exhibits greater density compared to Figures 3(a) and 3(b), with a marked reduction in crack formation, though surface finish deteriorates. At 1200 W ultrasonic power, the strengthening layer exhibited more vigorous growth with shorter dendritic spatter formations. Crack initiation within the layer markedly decreased, with reduced crack length and opening width. The surface became smooth and dense, exhibiting the highest surface quality (as shown in Figure 3(d)). When the ultrasonic power was further increased to 1500 W, the bonding between microstructures in the strengthened layer became loose, reducing its compactness. The surface roughness of the strengthened layer increased, resulting in poorer surface quality. This was primarily due to the enhanced cavitation and vibration effects accompanying the increased ultrasonic power. Concurrently, the elevated temperature of the three-phase working medium reduced the cooling effect on the strengthened surface. Consequently, some molten material was expelled before reacting with the substrate, thereby degrading the surface quality of the strengthened layer. Consequently, alterations in ultrasonic power exert a discernible influence upon the microstructural morphology of the strengthened layer. As ultrasonic power increases, the microstructure becomes smoother and denser; however, excessive power levels result in diminished surface quality of the strengthened layer.

3.2. Analysis of Reinforcement Layer Hardness

Microhardness tests were conducted at nine randomly selected points on the surface of the hardened layer for each specimen, with the average hardness values calculated. The test data are presented in Table 2. The average microhardness of the TC4 alloy substrate material was approximately 350 HV. Following ultrasonic-assisted electrical discharge machining, the hardness values of the strengthened layer exceeded those of the substrate material by approximately 3-4 times, significantly enhancing the hardness characteristics of the titanium alloy. The hardness of the strengthened layer initially increased and then decreased with rising ultrasonic power. This phenomenon arises because ultrasonic vibration, during ultrasonic vibration-assisted EDM strengthening, refines and homogenises electroerosion products. As ultrasonic power increases, these effects intensify, resulting in a denser strengthening layer surface [4]. Furthermore, the formation of the high-hardness strengthening phase TiC contributes to the enhancement of microhardness at the surface of the strengthened layer. At an ultrasonic power of 1200 W, the TiC phase content is highest, the chemical reaction is optimal, and the hardness is also highest, with an average value of 1370.4 HV. However, excessively high ultrasonic power intensifies vibration effects on the triphasic working medium, reducing deposition of electrolytic products and diminishing discharge stability. This hinders reinforcement layer formation, meaning excessively high ultrasonic power does not significantly enhance layer hardness.

Table 2. Microhardness of the strengthened layer at different ultrasonic power levels

powder	Ultrasonic-power	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Position 7	Position 8	Position 9	mean
$C+B_4C+Al$	300W	1062	1171	1230	1262	1236	1133	1290	1168	1213	1196.1
	600W	1115	1208	1180	1234	1238	1377	1337	1352	1238	1253.2
	900W	1217	1320	1319	1362	1356	1326	1384	1270	1250	1311.6
	1200W	1362	1378	1370	1364	1359	1381	1369	1355	1396	1370.4
	1500W	1327	1310	1297	1315	1324	1322	1291	1321	1319	1314.0

4. SUMMARY

This study employed the UPMND-EDM method for surface modification of TC4 titanium alloy. A systematic analysis was conducted on the effects of varying ultrasonic power levels on parameters such as the microstructural morphology and hardness of the strengthened layer. The following conclusions were drawn:

(1) At low ultrasonic power levels, the impact of ultrasonic vibration on the medium is limited, resulting in a greater number of microcracks within the strengthened layer. As ultrasonic power increases, the ultrasonic effect within the medium becomes more pronounced. When power reaches 1200W, the strengthened layer exhibits optimal performance, featuring a uniform and smooth surface with fewer cracks and voids. However, excessively high ultrasonic power causes the medium temperature to rise, leading to loose bonding between the microstructures within the strengthened layer and a deterioration in surface quality.

(2) The microhardness of the strengthening layer produced by UPMND-EDM technology consistently exceeds that of the TC4 titanium alloy substrate, reaching approximately 3-4 times the base material's hardness. The highest microhardness of the strengthening layer was achieved at an ultrasonic power of 1200W, with an average value of 1370.4 HV.

In summary, the UPMND-EDM method demonstrates superior surface quality and performance in the strengthened layer compared to the PMND-EDM approach. The best surface quality of the TC4 titanium alloy strengthened layer was achieved at a current of 8.2 A and an ultrasonic power of 1200 W.

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