Heliyon 11 (2025) e41461

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Machinability and surface integrity analysis of Ti-17 alloy using WEDC for advanced aero-engine application

Ramatenki Chinna [a], Priyaranjan Sharma [a,*], Filipe Fernandes [b,c,**]

[a] Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Guntur, 522302, AP, India
[b] University of Coimbra, CEMMPRE, ARISE, Department of Mechanical Engineering, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal
[c] CIDEM, ISEP - Polytechnic of Porto, Rua Dr. António Bernardino de Almeida, 4249-015, Porto, Portugal

ARTICLE INFO

Keywords:
Aero-engine
Surface integrity
Recast layer
Residual stresses
Surface roughness
Fatigue life

ABSTRACT

Recent advancements in aerospace industry demand intricate aero-engine parts, leading to the increased use of titanium alloys, particularly Ti-17, due to its high strength, thermal stability, and corrosion resistance. However, its low thermal conductivity and tool wear tendency pose significant machining challenges, impacting surface integrity, fatigue life, and overall component performance. This study investigates the Wire Electrical Discharge Cutting (WEDC) process, revealing that the mechanism behind improved surface integrity lies in the controlled thermal input, which minimizes phase transformations and reduces residual stresses. Experimental results reveal that rough-cutting Ti-17 yields higher surface roughness of ~2.68 μm than that of finish cutting of ~1.01 μm, with increased microhardness up to 80 μm depth. Further, rough cutting leads to a thicker recast layer of ~10–15 μm, and higher residual stresses of ~540 MPa, while finish cutting achieves a thinner recast layer of ~2–5 μm and reduced stresses of ~304 MPa. The innovation of this study is the investigation of WEDC behavior in Ti-17 alloy, addressing a gap in understanding its surface integrity features to improve the performance, durability, and service life of aero-engine components, advancing next-generation aerospace manufacturing.

1. Introduction

The aerospace industry is driven by the need to continually enhance the performance and efficiency of aero-engines. With the increasing demand for high-performance machined components, materials like titanium (Ti) alloys are highly valued due to their exceptional mechanical properties, such as high strength-to-weight ratio, corrosion resistance, and thermal stability. These qualities make Ti alloys indispensable for next-generation aero-engine components, contributing to more than 25 % of the total weight of engines like the GE CF6 [1], as illustrated in Fig. 1. The machinability of titanium alloys and the resulting surface integrity such as microstructure, surface roughness, and surface hardness are vital considerations for aero-engine performance due to the stringent performance and safety demands of these components. For instance, the microstructure influences material stability under high temperatures and stresses, critical for aero-engine efficiency. Surface roughness affects aerodynamic performance, where smoother surfaces enhance fuel efficiency by reducing drag. Surface hardness ensures durability, with resistance to wear and fatigue essential for

* Corresponding author.
** Corresponding author. University of Coimbra, CEMMPRE, ARISE, Department of Mechanical Engineering, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal.
E-mail addresses: priya333ranjan@gmail.com (P. Sharma), filipe.fernandes@dem.uc.pt (F. Fernandes).

https://doi.org/10.1016/j.heliyon.2024.e41461
Received 22 August 2024; Received in revised form 19 December 2024; Accepted 23 December 2024
Available online 24 December 2024

the operational longevity of aero-engine components.

Titanium alloys, particularly advanced compositions like Ti-17, present unique machining challenges. The high tensile strength (around 1100–1200 MPa) and enhanced high-temperature performance of Ti-17 alloy make it suitable for advanced aerospace applications, especially in compressor disks, but these properties also make it difficult to machine conventionally due to rapid tool wear, high heat generation, and poor surface finish [2]. Conventional machining of Ti-17 is often accompanied by limitations in producing complex geometries essential for aerospace parts. This has led to the exploration of advanced machining approaches like Wire Electrical Discharge Cutting (WEDC), which operates through spark erosion, thus eliminating the physical contact between tool and workpiece and minimizing mechanical stresses while achieving high precision [3].

WEDC presents a promising alternative to conventional machining methods, especially for difficult-to-machine materials like Ti alloys. This process is well-suited for aerospace applications because it allows for precise material removal with minimal deformation. The WEDC process typically operates in two modes—rough cut and trim cut—depending on machining requirements. While rough cutting achieves faster material removal, it often results in surface defects, whereas trim cutting provides smoother finishes and enhanced dimensional accuracy, critical for aerospace standards [4]. Thus, balancing rough and trim cuts helps to optimize cost, efficiency and surface quality, enabling WEDC to address the specific machinability issues associated with titanium alloys.

One of the primary challenges in WEDC of titanium alloys is achieving high surface integrity while maintaining dimensional accuracy. The high temperatures generated in WEDC lead to the formation of a recast layer, often brittle and susceptible to micro-cracks, which can negatively impact fatigue performance. Moreover, titanium alloys tend to form a thicker heat-affected zone (HAZ), which increases susceptibility to thermal-induced distortions, degrading fatigue life [5]. Arikatla et al. [6] employed multi-pass WEDC for Ti-6Al-4V alloy using rough/trim cuts and achieved enhancement in surface integrity by reducing micro-cracks, white layer thickness, and heat-affected zones at lower pulse settings. Singh et al. [7] utilized the ultrasonic-assisted micro-EDM (UA-MEDM) for improvement in machining of Ti–6Al–4V alloy. They observed that UA-MEDM enhances the material removal rate (MRR) and reduces the tool wear and hole taper. With the combination of tool rotation and workpiece vibration, they achieved superior surface quality of microholes, as observed through SEM analysis, overcoming limitations in traditional EDM for difficult-to-cut titanium alloys. Sivaprakasam et al. [8] optimized the micro-WEDC process of Ti–6Al–4V alloy, revealing that voltage, capacitance, and feed rate significantly impact MRR, kerf width (KW), and surface roughness (SR). Using response surface methodology and genetic algorithm, they obtained optimal responses—0.01802 mm^3/min MRR, 101.5 μm kW, and 0.789 μm SR.

Studies have shown that optimizing WEDC parameters is essential for improving surface finish and minimizing defects. Ezeddini et al. [9] investigated the influence of parameters on the surface roughness of Ti-6242 alloy, finding that settings like servo voltage at 100V, pulse-on time of 0.9 μs, feed rate of 29 mm/min, and a flushing pressure of 60 bar minimized roughness. Similarly, Veera et al. [10] explored Ti-16Al-14Nb machining, reporting that higher peak currents increase both MRR and SR, affecting surface integrity. They observed that strong pulses at higher currents enhance the cutting rate but also increase roughness, emphasizing the importance of controlled energy input for desirable surface quality.

In recent years, researchers have introduced innovative wire electrode materials to improve WEDC performance of few titanium alloys. Nano-coated wires and cryogenically treated wires show promise in reducing wire wear and enhancing surface finish [11]. For example, Kumar et al. [12] studied Ti-3Al-2.5V alloy machining with a specialized “Bronco Cut-X″ wire, achieving notable improvements in kerf-width, surface roughness, and cutting speed by 2.36 %, 7.99 %, and 9.55 %, respectively. This led to increased machining stability, efficiency, and reduced costs, which are advantageous for aerospace applications. Smaller diameter wires, as observed by Sharma et al. [13], improve productivity and surface quality by reducing recast layer thickness, making them preferable for achieving higher quality finishes. Usman et al. [14] further demonstrated that using a 0.15 mm brass wire in multi-pass WEDC of Ti6Al4V significantly enhanced surface integrity, reducing recast layer thickness by 25 % compared to other diameters and coatings.

Surface characteristics in WEDC process are also influenced by the formation of the recast and white layers. Maher [15] discussed the importance of wire electrode material properties, noting that zinc-coated wires improve production but are associated with issues like straightness challenges, high cost, and suboptimal surface quality. Antar et al. [16] examined Udimet 720 components and observed that post-WEDC fatigue performance improved significantly. Studies by Li et al. [17] revealed that under high discharge

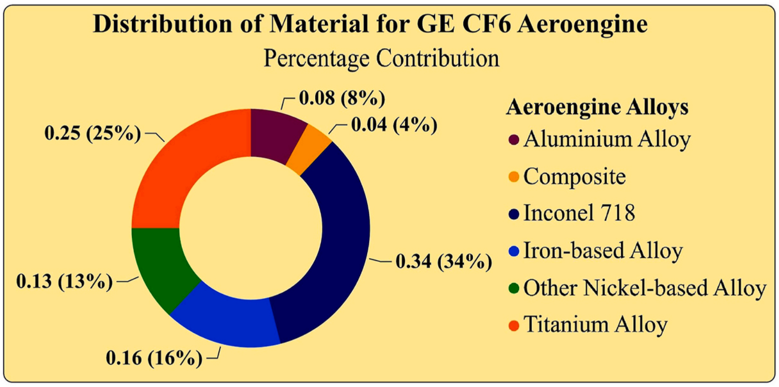

Fig. 1. A schematic illustration of distribution of material in GE-CF6 aero-engine.

energy, Inconel 718 develops a pronounced white layer, whereas under trim-cut conditions, this layer was significantly reduced. The white layer's microhardness is notably reduced due to abrupt temperature changes during WEDC operation, highlighting the importance of pulse control in mitigating undesirable surface alterations.

To address issues with surface integrity and machinability, researchers have explored hybrid machining techniques. Wang et al. [18] employed a low-speed WEDC setup combined with magnetic fields and ultrasonic vibration to machine thick shape-memory alloys, finding this configuration improved the surface quality and machining effectiveness. Similarly, Radhakrishnan et al. [19] demonstrated that vibration-assisted WEDC enhances titanium alloy machining capabilities, with a 100 Hz frequency improving removal rates and reducing microcracks. Additionally, Das et al. [20] evaluated residual strains in wire electrodes to predict wire rupture during machining. They reported that higher voltage and current levels result in increased residual stresses, which are critical for maintaining accuracy and preventing tool damage.

Modeling and optimization techniques are increasingly employed to enhance the performance of WEDC for aerospace alloys, including titanium. Several researchers [21–24] have focused on minimizing deflection errors to improve dimensional accuracy. Optimizing machining parameters through multi-objective approaches, as demonstrated by several researchers [25–29], has shown effectiveness in improving outcomes like surface finish, MRR, and dimensional accuracy. These modeling techniques, combined with advanced machine learning algorithms, help to predict optimal conditions for various alloys, ensuring more precise control over machining processes.

Extensive research exists on the machinability of various titanium alloys, yet a significant gap remains in understanding the machining behaviour of advanced titanium alloys like Ti-17, known for its high tensile strength and excellent high-temperature performance [30]. This alloy presents challenges in conventional machining, leading to rapid tool wear, excessive heat generation, and poor surface finishes. These limitations highlight the need for advanced techniques such as WEDC process, which offers high precision and minimizes mechanical stresses due to its non-contact nature. WEDC shows promise for machining of various titanium alloy, especially in aerospace applications requiring complex geometries and strict surface integrity. However, the unique thermal properties of Ti-17 alloy greatly influence the efficiency, precision, and surface quality during WEDC, making this research crucial for advancing aero-engine component manufacturing. Despite WEDC's potential, challenges like recast layer formation, heat-affected zones (HAZ), and micro-cracks can compromise fatigue performance. This research aims to bridge this gap by investigating the machining performance of Ti-17 alloy using WEDC process, focusing on achieving superior surface integrity, minimal defects, and enhanced machining efficiency. The innovation lies in employing a combination of rough and trim-cut strategy and utilizing appropriate control parameters in WEDC process, ultimately improving surface quality, durability, and service life of the aerospace components. The findings will provide critical insights into overcoming Ti-17's machining challenges, contributing to the development of next-generation aero-engine components. The flow chart of the detailed experimental plan has been shown in Fig. 2.

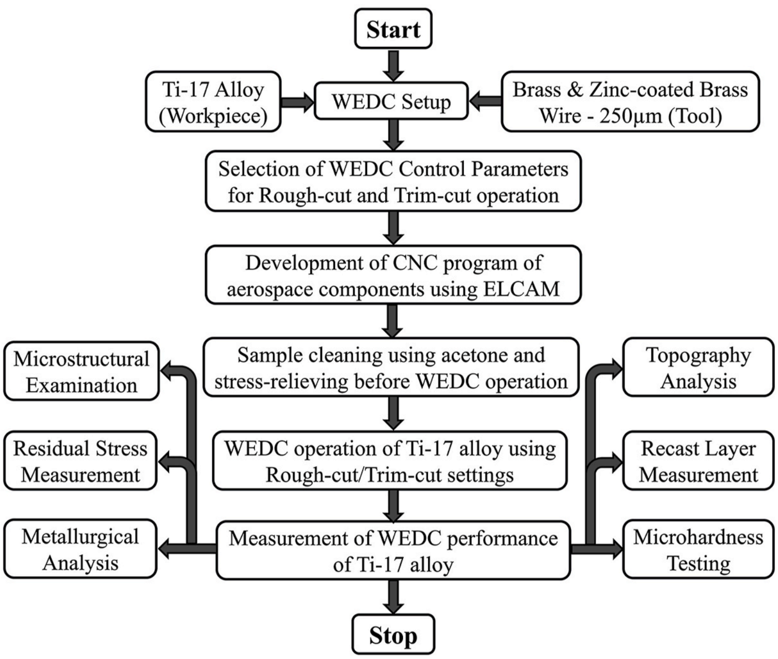

Fig. 2. Flow chart of the experimental plan.

2. Materials and methods

2.1. Selection and preparation of materials

A Ti-17 alloy plate was chosen as the workpiece for the WEDC experiments. The plate had dimensions of 120 mm × 80 mm × 8 mm in thickness. The alloy, with a certified composition of Ti-5Al-2Sn-2Zr-4Cr-4Mo, was procured from Special Metal in Mumbai, India. The detailed elemental composition is outlined in Table 1. The as-received Ti-17 alloy was mechanically polished to achieve a smooth surface. Polishing was carried out sequentially using 1000, 1500, and 2000 grit-size silicon carbide (SiC) waterproof abrasive papers on a mechanical polishing machine. Further cloth-polishing was performed using diamond paste (~1 μm grit size) to attain a mirror-finish surface. Prior to WEDC, the alloy underwent initial heat treatment at temperatures below its recrystallization point to minimize distortion during the cutting process.

2.2. Experimental details

The experiments were conducted using an Electronica Eco-cut wire-electrical-discharge (WED) machine. De-ionized water was employed as the dielectric fluid throughout the process to enhance the cutting performance and prevent contamination. Two types of wire materials, each 250 μm in diameter—pure brass and zinc-coated brass—were used as the tool electrode (see Fig. 3). The wire materials were selected based on their capability to improve cutting efficiency and surface quality.

Based on prior research on aerospace materials, the flushing pressure was maintained at 1.96 bar with a wire feed rate of 6 m/min for consistent performance [29]. Two modes of cutting were employed. First one is rough-cut mode which is selected for initial material removal, focusing on faster cutting rates (see Fig. 4). Second one is fine-cut or finish-cut mode which is utilized to enhance surface integrity, crucial for aero-engine component manufacturing. The initial parameters, such as pulse current, pulse-on time, pulse-off time, and servo voltage were chosen based on existing literature which focus on optimizing WEDC processes for aerospace-grade materials [23]. For instance, parameters that have been effective in minimizing surface roughness and improving surface integrity in aerospace applications were prioritized. Remaining parameters, such as wire-offset and wire-feed are selected based on various experimental trials to achieve required dimensional accuracy.

The experimental procedure aimed to achieve precise cuts on an intricate aero-engine component made of Ti-17 alloy during WEDC process. The initial design for the aero-engine parts was carefully designed in AutoCAD, leveraging its powerful modeling capabilities to handle complex geometries. Once the design was finalized, ELCAM V2.0 software is used to simulate the cutting process and generate the computer numerical control (CNC) program. This CNC program is essential for controlling the WEDC equipment, allowing precise, automated execution of the intricate design. In the WEDC process, depicted in Fig. 5, an electro-thermal method is used to remove material with high accuracy and precision. The system consists of a workpiece (acting as the positive electrode) and a wire (negative electrode), which interact via rapid, high-frequency electrical discharges. A key component in this process is the dielectric fluid, deionized water, which insulates the electrodes and sustains a high potential difference between them. The deionized water flows continuously to maintain insulation, cool the cutting zone, and flush away debris formed during machining.

When the electrical potential reaches a threshold level, it creates a strong electrostatic force, prompting electrons from the wire electrode to accelerate towards the workpiece. As the intensity of the electric field surpasses the molecular bond strength of the deionized water, ionization occurs, forming a dense plasma channel. This channel, filled with electrons and ions, provides a low-resistance path that facilitates an intense flow of electrons and ions visually seen as spark. The resulting spark converts the kinetic energy of these particles into heat, raising the local temperature to approximately 10,000°C—sufficient to melt and vaporize the material. The high heat generated in the discharge zone rapidly melts and evaporates the workpiece material in localized areas, creating precise cuts. Each discharge pulse lasts only milliseconds, limiting the heat-affected zone (HAZ) and ensuring minimal thermal damage. The CNC-controlled wire, with multi-axis movement capabilities, enables complex shapes to be accurately cut, maintaining geometric precision and surface integrity with reduced dimensional variation. By using CNC-guided WEDC, the setup can achieve intricate, high-precision cuts needed for aero-engine components, which demand exact dimensional accuracy and minimal surface defects. The integration of AutoCAD design, ELCAM simulation, and WEDC under CNC control demonstrates a robust approach to manufacture components for next generation aero-engine with consistent quality and precision.

2.3. Measurement of WEDC performance characteristics

The WEDC performance characteristics were measured to assess the microstructural and mechanical effects on Ti-17 alloy, focusing on surface integrity and material properties after WEDC process. To ensure clean and accurate microstructural examination, samples were meticulously prepared. Surface contaminants and particles were removed by washing with acetone, followed by etching using a solution of H_2O, HNO_3, and HF. The etching process exposed the alloy's duplex microstructure prior to machining, revealing β phase

Table 1
Material composition of Ti-17 Alloy.

Alloy (%)	Ti	Al	Cr	Mo	Zr	Sn
Ti-17	83	5	4	4	2	2

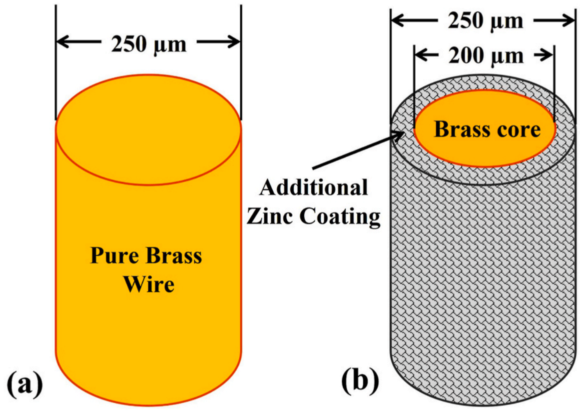

Fig. 3. Cross-section of wire-electrode, (a) Pure brass wire, (b) Zinc-coated brass wire.

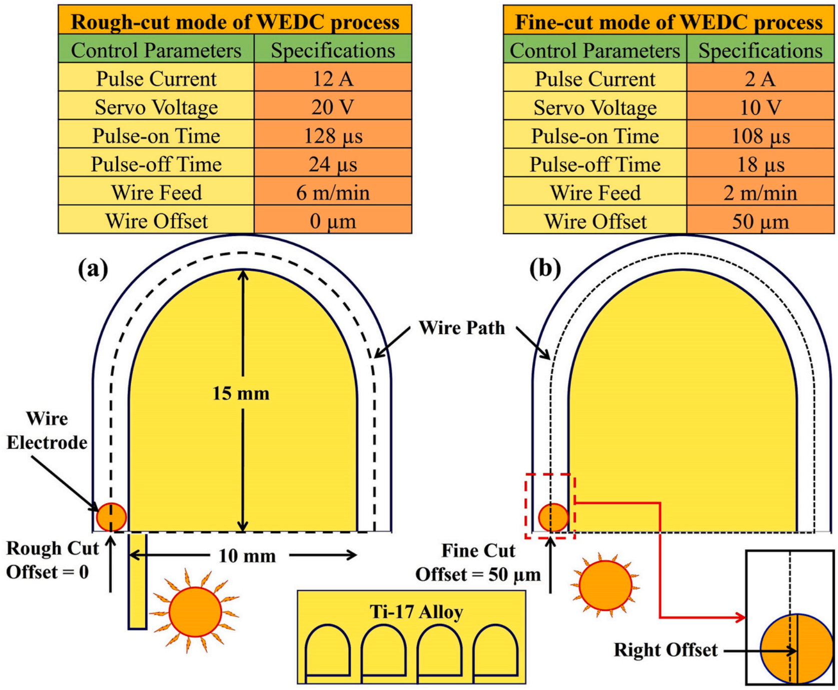

Fig. 4. A schematic illustration of rough-cut and fine/finish-cut strategy of WEDC process along with corresponding control parameters.

flakes surrounding the α phase. The red circle highlights the α phase, while the yellow arrow indicates β phase as illustrated in Fig. 6. This specific microstructure is essential, as it directly contributes to Ti-17 alloy's strength and toughness, making it suitable for high-stress aerospace applications. A scanning electron microscope (SEM) was used for detailed observation, revealing the coarse and fine microstructure under rough-cut and trim-cut settings that helps to examine the alloy's mechanical properties.

To achieve a precise topographical profile, a 3D laser microscope with a fine 0.4 μm spot diameter was employed. This device scanned a 1280 × 1280 μm^2 cross-section area, generating accurate three-dimensional images without physical contact. The high resolution was used for detailed analysis of surface roughness and texture. Polishing the Ti-17 alloy cross-sections using successive grades of silicon carbide paper enabled precise measurement of the recast layer thickness using SEM, which forms due to rapid melting and solidification. The thickness of this layer is critical because it affects the alloy's fatigue life and performance. A Vickers micro-hardness tester was used to determine the microhardness of the cut surfaces, providing insights into the hardness variation due to heat-affected zones, which are prone to brittleness and micro-cracking. Residual stresses, which can impact fatigue and mechanical performance, were measured using the PROTO-iXRD stress measuring system. This measurement is vital for understanding the long-term stability of the material under operational stresses. X-ray diffraction (XRD) analysis provided information on metallurgical changes in the Ti-17 alloy's cut surface, such as phase transformation or grain structure alterations, which can influence performance under high-temperature or high-stress conditions typically experienced in aerospace applications.

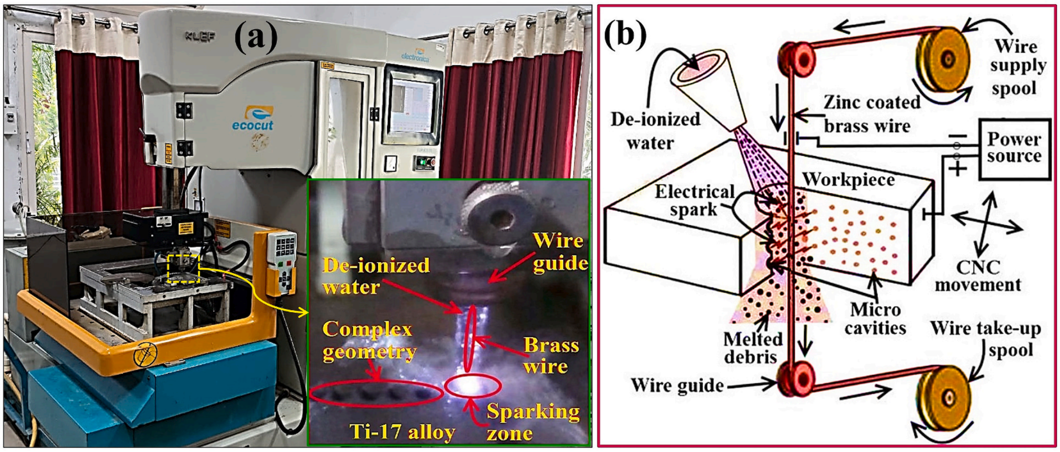

Fig. 5. Experimental setup of WEDC process, (a) Actual setup; (b) Schematic illustration [25].

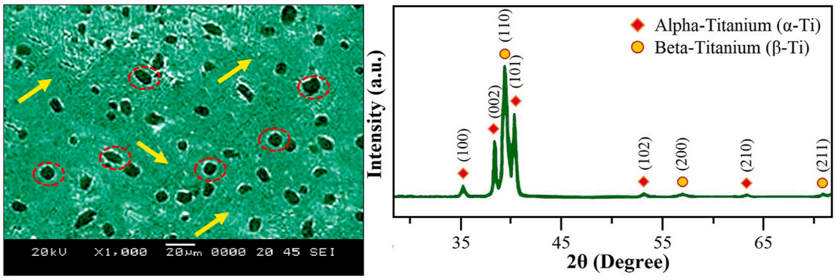

Fig. 6. SEM image and XRD plot of as-received Ti-17(Ti-5Al-2Sn-2Zr-4Cr-4Mo) alloy, where red-colored circle indicates the presence of α phase, and yellow-colored arrow indicates the β phase].

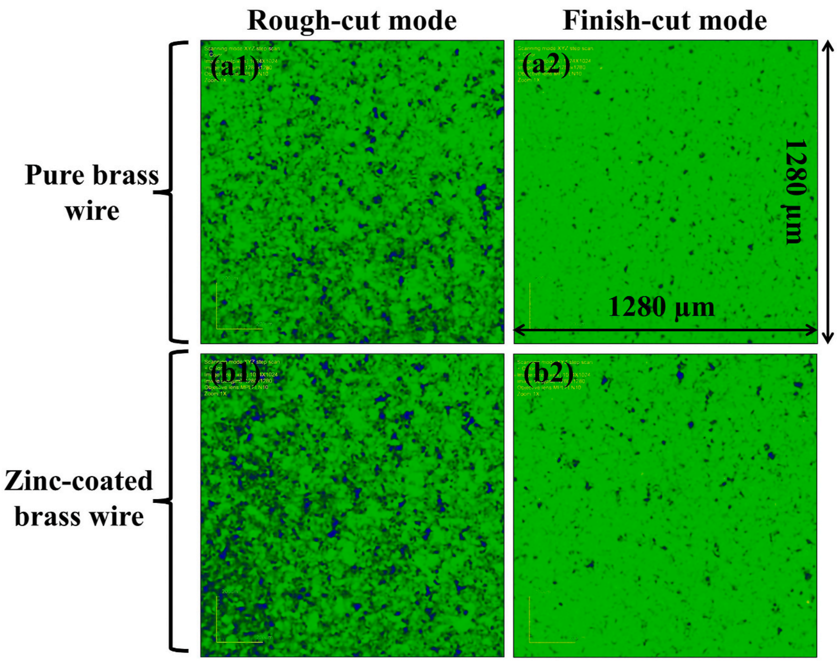

Fig. 7. Surface topography of WED cut surface (1280 × 1280 μm^2) of Ti-17 alloy using, (a1, a2) Pure brass wire under rough and finish-cut mode, (b1, b2) Zinc-coated brass wire under rough and finish-cut mode.

3. Results and discussion

3.1. Topographical analysis

The topography of WED cut surface of Ti-17 alloy as a function of the machining conditions and cutting wire types are shown in Fig. 7. The rough-cut condition generates a surface with higher roughness values (~2.54 μm for pure brass wire and ~2.68 μm for zinc-coated wire), as shown in Fig. 7(a1, b1). This increased roughness results from the high discharge energy applied during the process, which introduces significant thermal energy to the machined surface. The intense heating leads to substantial melting, and subsequent rapid cooling causes re-solidified material to form large, deep craters [31]. These craters create surface irregularities that contribute to the overall roughness and may impair the alloy's performance in applications where smooth surfaces are critical. In rough cut conditions, the thermal energy absorbed by the material is significant due to high discharge energy. During the pulse-off period (when no discharge occurs), pressurized waves are generated in the dielectric fluid, which assists in removing some of the molten material. However, as the plasma channel dissipates, some molten material re-solidifies, leading to large and uneven craters across the surface. These large craters introduce surface irregularities that contribute to roughness and are clearly visible in Fig. 7(a1, b1).

Conversely, the finish cut condition utilizes lower discharge energy, minimizing the thermal impact on the machined surface. This results in smaller, shallower craters, as depicted in Fig. 7(a2, b2). With only minimal material melting and re-solidifying, finish-cut surfaces exhibit much lower roughness values (~1.01 μm for pure brass wire and ~1.06 μm for zinc-coated wire). This reduced roughness is particularly advantageous for applications requiring high fatigue strength and surface quality, as the finish cut yields a smoother, more consistent surface. The lower discharge energy in finish cut conditions minimizes melting and allows the molten material to be flushed away more uniformly, preventing large crater formation. As a result, only micro- or nano-sized craters remain, leading to a smoother surface. This controlled crater formation enhances surface integrity, providing a more desirable finish for Ti-17 alloy components used in high-performance applications, such as aerospace.

Pure brass wire generally produces a smoother surface compared to zinc-coated wire, as seen in the topography analysis, as reported by Sharma et al. [32] for other aerospace materials. The smoother finish (~1.01 μm roughness) can be attributed to brass wire's superior thermal conductivity, which allows for more efficient heat dissipation and uniform thermal distribution across the cutting surface. Additionally, pure brass wire supports more stable electrical discharges, leading to consistent material removal and reducing the likelihood of deep crater formation. Although zinc-coated wire can also produce fine surface finishes (~1.06 μm in finish-cut conditions), its slightly higher roughness values in both cutting modes may stem from additional electrochemical reactions during cutting. These reactions can affect debris removal efficiency, potentially leaving more re-solidified material on the surface. Consequently, this wire type might lead to slightly rougher surfaces than pure brass wire, as shown in Fig. 7(b1, b2).

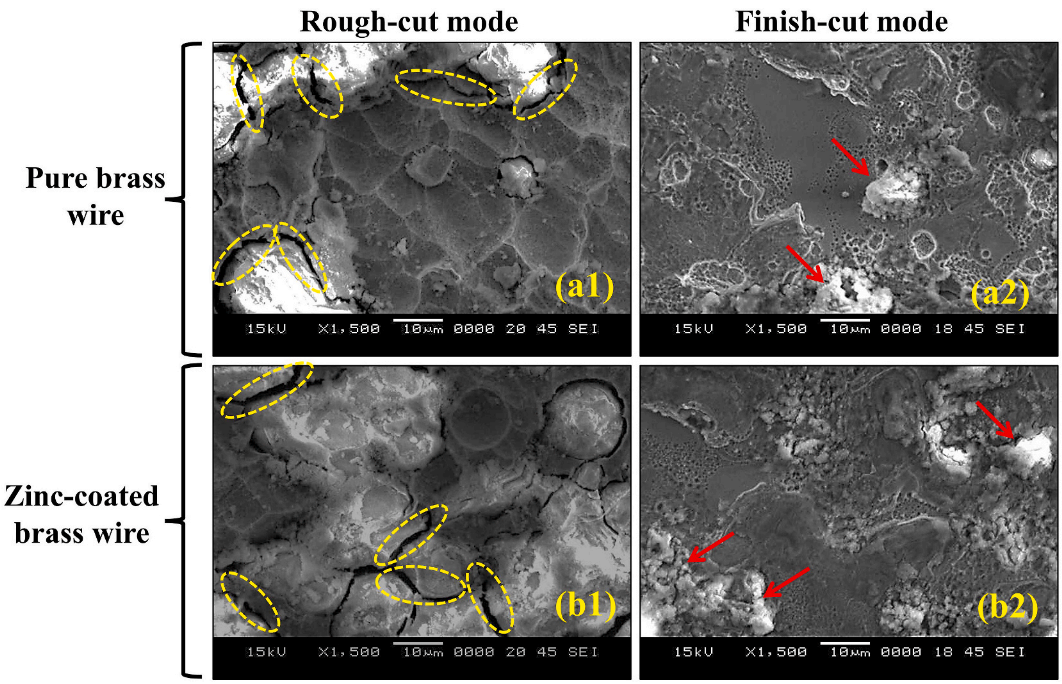

Fig. 8. Surface morphology of WED cut surface of Ti-17 alloy using, (a1, a2) Pure brass wire under rough and finish-cut mode, (b1, b2) Zinc-coated brass wire under rough and finish-cut mode [A yellow-colored interrupted circle indicates the micro-cracks, and red-colored arrow represents the formation of melted debris].

3.2. Microstructural analysis

Fig. 8 shows the microstructure of WED cut surface of Ti-17 alloy, highlighting the influence of machining conditions and wire types. The rough-cut condition utilizes high discharge energy, causing significant thermal input into the Ti-17 alloy. This intense heat generates rapid melting, followed by abrupt cooling, which results in a coarse and irregular microstructure on the cut surface, as illustrated in Fig. 8(a1, b1). The rapid melting and re-solidification process leads to a microstructure characterized by large grains, known as a coarse microstructure. This coarseness is associated with the formation of micro-globules—small, globular particles that are remnants of the molten material that re-solidified on the surface. These micro-globules can act as weak points, making the surface prone to wear and structural degradation under stress. The high discharge energy in rough cutting not only creates deep craters but also introduces potential micro-cracks on the machined surface. These defects arise due to the rapid cooling rate, which traps stress within the solidifying material. Pressurized waves generated during the pulse-off period (non-discharge intervals) contribute to molten metal being forcefully ejected, leading to trapped air bubbles within the molten pool. Upon re-solidification, these air bubbles form micro-craters [4], further adding to surface irregularities and potentially weakening the material's structural integrity. Both pure brass wire and zinc-coated wire exhibit similar coarse microstructures in rough-cut conditions, but the differences in thermal conductivity and melting point between these wires can slightly affect how heat is distributed across the Ti-17 alloy surface. Brass wire, with its high thermal conductivity, might distribute heat more evenly than zinc-coated wire, though the overall coarse grain structure and defects remain prominent in both cases.

The finish-cut condition employs a lower discharge energy, which reduces the thermal load on the Ti-17 alloy. This controlled thermal input limits excessive melting, allowing for finer grain structure and smoother re-solidification. The result is a fine microstructure with minimal grain coarsening, as illustrated in Fig. 8(a2, b2). With lower thermal impact, the finish cut generates fewer micro-globules, reducing the likelihood of micro-cracks and other surface defects. Additionally, as only a minimal amount of material is melted, the flush waves effectively remove this material from the cut surface, forming micro- or nano-sized cavities rather than large craters. This results in a smoother, more refined surface that enhances the mechanical properties of the machined alloy. The finer microstructure produced in finish cutting reduces stress concentrations that could lead to crack initiation. By maintaining a stable microstructure with minimal defects, finish-cut Ti-17 surfaces exhibit greater resistance to fatigue and mechanical wear. Thus, making it highly advantageous for advanced aero-engine components that require fine surface finishes and high resistance to fatigue. This finish-cut condition not only improves the Ti-17 alloy's performance but also prolongs the lifespan of components exposed to high-stress environments.

3.3. Recast layer analysis

The recast layer is a thin layer of re-solidified molten material that forms on the surface of the Ti-17 alloy during the WEDC process.

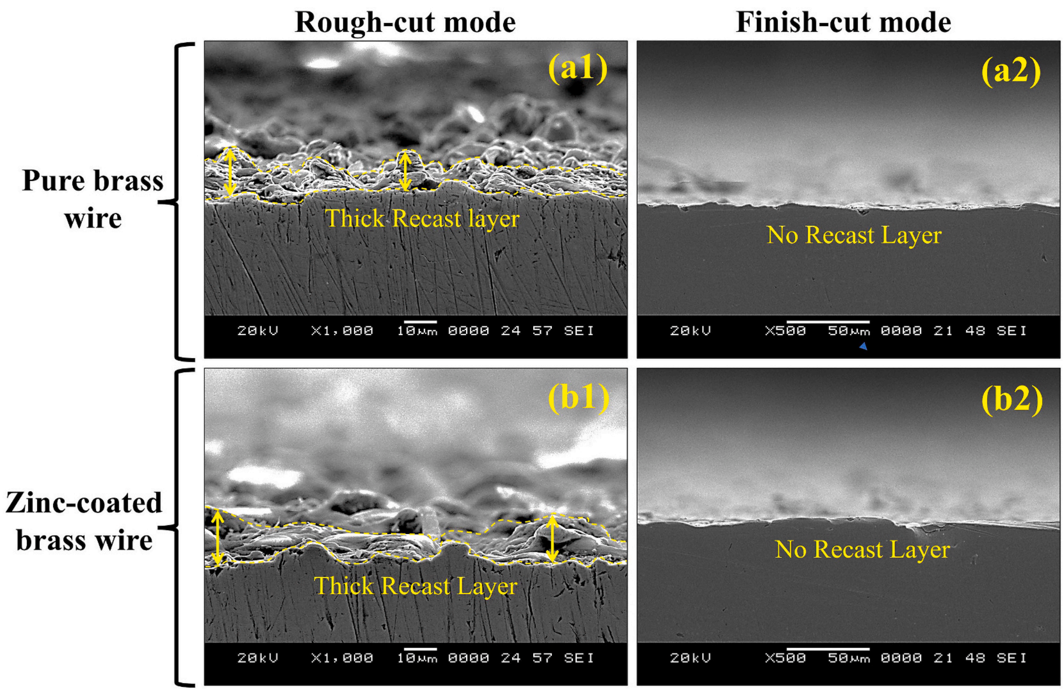

Fig. 9. Recast layer formed on WED cut surface of Ti-17 alloy using, (a1, a2) Pure brass wire under rough and finish-cut mode; (b1, b2) Zinc-coated brass wire under rough and finish-cut mode [A yellow-colored double-sided arrow represents the thick recast layer].

This layer results from intense heat generated by electrical discharges [33], causing localized melting of the alloy's surface, which then re-solidifies as it cools. The characteristics of this layer, including thickness and surface quality, vary significantly depending on the WEDC parameters used in rough cut and finish cut mode (see Fig. 9).

Rough cutting uses high discharge energy, which subjects the Ti-17 alloy to intense localized heating. This rapid heating and cooling cycle facilitate fast material removal but also results in additional molten material re-solidifying unevenly on the surface. As a result, a thick and irregular recast layer form, with measurements typically in the range of ~10–15 μm, as shown in Fig. 9(a1, b1). Further, the higher thermal energy in rough cutting induces rapid cooling, which can trap defects like microcracks, voids, and inclusions within the recast layer. These defects arise from the high thermal gradients and rapid solidification that cause uneven material contraction, creating residual stresses. Such defects can significantly affect the performance of the aero-engine materials by reducing fatigue strength [34], making it more susceptible to crack initiation under cyclic loading, and decreasing corrosion resistance.

Finish cutting uses a lower discharge energy and slower MRR, leading to a more controlled machining environment. This lower thermal input minimizes the extent of molten material melting and deposition, allowing a thinner recast layer to form, typically in the range of ~2–5 μm, as depicted in Fig. 9(a2, b2). Consequently, this thinner layer is more uniform, containing fewer microstructural defects. This smoother, less stressed recast layer enhances the overall surface quality and improves the alloy's resistance to fatigue and corrosion, making it beneficial for aero-engine application.

3.4. Sub-surface microhardness analysis

The Wire Electric Discharge Cutting (WEDC) process creates intense thermal and mechanical stresses within the material, particularly near the surface. These stresses influence the sub-surface microhardness, which is a measure of how resistant the material is to deformation just below the cut surface. Rough cutting, with its high discharge energy, subjects the Ti-17 alloy to intense heat, resulting in rapid thermal cycling and fast cooling. This quick cooling leads to the formation of a hardened recast layer [33], where the high temperatures followed by abrupt cooling create a martensitic-like structure in the titanium alloy, enhancing its hardness. As illustrated in Fig. 10, rough-cutting increases the microhardness of the Ti-17 alloy to a depth of approximately 80 μm beneath the surface. This depth is significant, indicating that the high thermal load penetrates deeply into the material, leading to a thicker recast layer and a hardened sub-surface. The combination of rapid cooling and mechanical stress in the recast layer increases hardness, which can potentially improve wear resistance but may also introduce brittleness near the surface.

Finish cutting uses a low discharge energy, which results in a lower thermal impact on the Ti-17 alloy. This reduced energy input means that the heating and cooling cycles are less severe, avoiding the extensive hardening seen in rough cutting. Consequently, finish cutting results in minimal changes to the sub-surface microhardness, as the reduced heat and slower cooling prevent significant alterations in the material's microstructure. Experimental data (Fig. 10) shows that the increase in microhardness for finish cutting is limited to about 5–10 μm below the machined surface. This shallow hardening suggests that the finish cut maintains the original properties of the alloy more effectively, avoiding deep penetration of thermal stress. The thin recast layer also indicates fewer material transformations, resulting in a smoother and softer sub-surface profile that is less prone to brittleness.

The differences in sub-surface microhardness between rough-cut and finish-cut conditions underscore the critical impact of WEDC parameters. Increased microhardness in the rough-cut condition can enhance wear resistance but may introduce brittleness and susceptibility to crack initiation under cyclic loading, as discussed by Rajurkar et al. [34]. In contrast, the finish-cut condition achieves a balance, minimizing thermal damage and preserving ductility in the material just below the surface. This more consistent sub-surface profile is beneficial for aero-engine applications that require a balance of strength and flexibility in titanium alloys.

3.5. Residual stress analysis

Residual stresses on the Ti-17 alloy cut surface primarily arises from the rapid heating and cooling inherent to the WEDC process. This temperature fluctuation induces thermal gradients within the material, creating localized expansions and contractions that

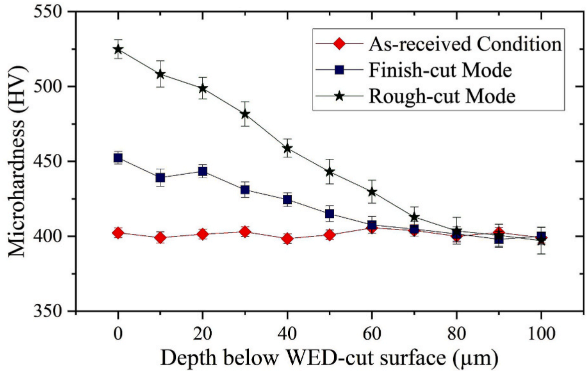

Fig. 10. Evaluation of subsurface microhardness of WED cut surface of Ti-17 alloy under different cutting condition.

generate residual stresses upon cooling. Further, the α (hcp) and β (bcc) phases of Ti-17 alloy are highly sensitive to temperature changes [35]. Under high temperatures electrical discharges during rough cutting, α-phase regions may transform into the high-temperature β-phase. Upon rapid cooling, some of these regions revert to α-phase, but not uniformly. This inconsistent transformation generates phase boundaries where stress concentrations develop due to mismatched thermal contractions between α and β phases. As illustrated in Fig. 11, the rough-cut condition leaves high tensile residual stresses (approximately 540 MPa) on the Ti-17 alloy surface. The rapid cooling following rough cutting causes uneven contraction, especially near phase boundaries, where residual tensile stresses accumulate. These tensile stresses penetrate up to a depth of about 120 μm, creating potential points of weakness that can degrade the fatigue life [33] and overall structural integrity of the aero-engine component. The higher tensile residual stresses are especially concerning for aerospace applications where cyclic loading is expected, as they can exacerbate crack initiation and propagation.

As seen in Fig. 11, residual stresses in the finish-cut condition are significantly lower (~305 MPa) compared to the rough-cut condition. The finish-cut process employs a lower energy input, which results in less aggressive heating. This controlled heating avoids extensive phase transformations, preserving the stability of the α and β phases. The gradual cooling rates and reduced thermal impact prevent abrupt temperature gradients, thereby minimizing residual stress formation. Additionally, the reduced heating in finish cutting avoids inducing substantial tensile stresses, leaving the alloy surface with more balanced and stable internal stresses. Study by Yakout et al. [36] corroborates that controlled thermal processing in aerospace alloys significantly reduces residual stress and improves material stability.

3.6. Metallurgical analysis

The XRD pattern of the as-received Ti-17 alloy surface shows prominent α (hcp) and β (bcc) phases (refer to Fig. 6). These phases represent the stable microstructure of the alloy before machining, providing a baseline for comparison. The XRD pattern of the cut surface of the Ti-17 alloy is displayed in Fig. 12 which indicates notable shifts in peak intensities, suggesting significant structural changes in Ti-17 alloy. This change in peak intensity can be attributed to the high thermal stress experienced during the roughing process. The elevated localized temperature in this condition induces phase transformations, particularly in the Heat-Affected Zone (HAZ). Here, α-phase titanium partially transforms into the β-phase due to the bcc structure's stability at higher temperatures, similar to observations reported by Shehata et al. [37]. Upon rapid cooling, however, some of this β-phase may revert to α-phase. This cycle of transformation and partial reversion results in a refined and altered grain structure, evident from the changes in XRD peak intensity.

In contrast, the XRD pattern for the finish-cut surface shows minimal variation in peak intensities for α and β phases. This stability implies that the finish-cut condition generates lower thermal stress, which minimizes phase transformations and preserves the original microstructure of the alloy. This limited transformation suggests that the finish-cut process effectively controls the HAZ and induce minimum microhardness alteration on the machined surface as shown in Fig. 10. This aligns with findings in prior studies on the impact of machining conditions on phase transformation in titanium alloys [31].

4. Conclusion

The conclusions derived from the experimental analysis are as follows:

- Pure brass wire, due to its superior thermal conductivity, enhances heat dissipation, achieving smoother surfaces (~1.01 μm roughness) in finish-cut by minimizing crater formation and preserving surface integrity of Ti-17 alloy, critical for fatigue-resistant applications.
- Utilizing low discharge energy in finish-cut reduces crater sizes and micro-cracks, resulting in a fine microstructure with thinner, defect-free recast layers. This significantly improves the fatigue strength and corrosion resistance of Ti-17 alloy.
- Controlled thermal input in finish-cut limits microhardness enhancement to 5–10 μm, maintaining ductility and flexibility. It also preserves the α and β phases, ensuring the mechanical consistency and durability of the alloy under demanding aerospace conditions.
- High discharge energy in rough-cut mode results in coarse grains, thick recast layers, and microcracks, leading to surface roughness of ~2.54–2.68 μm. These defects compromise the alloy's durability, increasing the risk of crack initiation under cyclic aerospace loading.
- Rough cuts induce martensitic-like hardening up to 80 μm depth, enhancing wear resistance but introducing brittleness. The α-to-β phase transformation, driven by high thermal stress, results in ~540 MPa tensile residual stresses, making the alloy prone to crack propagation.
- Lower discharge energy in finish cuts maintains phase stability and reduces tensile residual stresses to ~305 MPa, minimizing phase transformations and microstructural alterations. This approach enhances the fatigue resistance of Ti-17 alloy, ensuring durability in advanced aero-engine components.

The research does not include corrosion resistance testing of the machined components, which may be critical for aerospace application. The current study's findings are based on controlled laboratory experiments. Real-world testing in actual aerospace component manufacturing is needed to validate the practical applicability of the results.

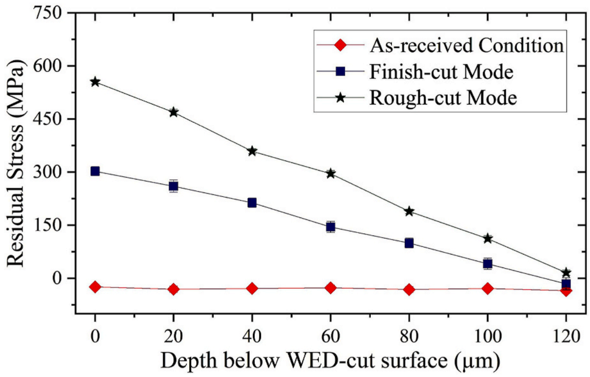

Fig. 11. Evaluation of residual stresses of WED cut surface of Ti-17 alloy under different cutting condition.

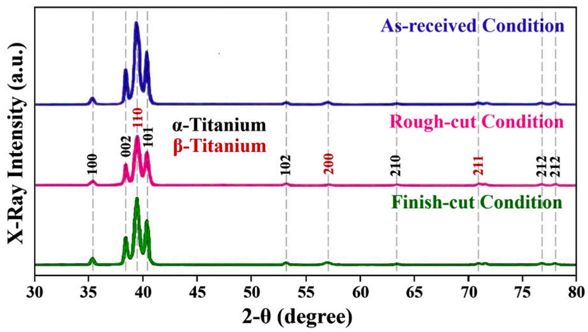

Fig. 12. Evaluation of metallurgical changes of WED cut surface of Ti-17 alloy under different cutting condition.

CRediT authorship contribution statement

Ramatenki Chinna: Methodology, Investigation, Data curation, Conceptualization. **Priyaranjan Sharma:** Writing – original draft, Visualization, Supervision, Resources. **Filipe Fernandes:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors declare no financial or personal conflicts of interest related to this research. All funding sources and potential influences have been disclosed to ensure transparency and maintain the integrity of the study.

Acknowledgement

Priyaranjan Sharma recognizes the seed money project 'KLEF/SRG/2023–24/ME/005′ for contributing funds for research and testing. Filipe Fernandes acknowledges the support of the UIDB/00285/2020 and LA/P/0112/2020 projects, which are funded by national resources from the Portuguese Foundation for Science and Technology (FCT), the Competitiveness and Internationalization Operational Program (COMPETE 2020), and FEDER Funds through Portugal 2020 (PT2020).

References

[1] Jr Campbell, C. F, Manufacturing Technology for Aerospace Structural Materials, Elsevier, 2011.
[2] I. Inagaki, T. Takechi, Y. Shirai, N. Ariyasu, Application and Features of Titanium for the Aerospace Industry, vol. 106, Nippon steel & sumitomo metal technical report, 2014, pp. 22–27. https://www.nipponsteel.com/en/tech/report/nssmc/pdf/106-05.pdf.
[3] E.O. Ezugwu, Z.M. Wang, Titanium alloys and their machinability—a review, J. Mater. Process. Technol. 68 (3) (1997) 262–274, https://doi.org/10.1016/S0924-0136(96)00030-1.

[4] K. Mouralova, J. Kovar, L. Klakurkova, P. Blazik, M. Kalivoda, P. Kousal, Analysis of surface and subsurface layers after WEDC for Ti-6Al-4V with heat treatment, Measurement 116 (2018) 556–564, https://doi.org/10.1016/j.measurement.2017.11.053.
[5] Y. Sun, Y. Gong, Y. Liu, M. Cai, X. Ma, P. Li, Experimental investigation on effects of machining parameters on the performance of Ti-6Al-4V micro rotary parts fabricated by LS-WEDT, Arch. Civ. Mech. Eng. 18 (2) (2018) 385–400, https://doi.org/10.1016/j.acme.2017.09.006.
[6] S.P. Arikatla, K.T. Mannan, A. Krishnaiah, Surface integrity characteristics in wire electrical discharge machining of titanium alloy during main cut and trim cuts, Mater. Today: Proc. 4 (2) (2017) 1500–1509, https://doi.org/10.1016/j.matpr.2017.01.172.
[7] P. Singh, V. Yadava, A. Narayan, Machining performance characteristics of Ti–6Al–4V alloy due to ultrasonic assisted micro-EDM using rotating tool electrode, J. Inst. Eng.: Series D 105 (1) (2024) 155–171, https://doi.org/10.1007/s40033-023-00460-3.
[8] P. Sivaprakasam, P. Hariharan, S. Gowri, Modeling and analysis of micro-WEDC process of titanium alloy (Ti–6Al–4V) using response surface approach, Engineering Science and Technology, an International Journal 17 (4) (2014) 227–235, https://doi.org/10.1016/j.jestch.2014.06.004.
[9] S. Ezeddini, W. Rajhi, M. Boujelbene, E. Bayraktar, S. Ben Salem, An investigation to achieve good surface integrity in wire electrical discharge machining of Ti-6242 super alloy, J. Mater. Eng. Perform. 33 (9) (2024) 4523–4537, https://doi.org/10.1007/s11665-023-08270-0.
[10] K. Veera Venkata Nagaraju, M. Joseph Davidson, G. Venkatesh, M. Manjaiah, K. Harikrishna, Machinability and pulse characteristics of Ti-16Al-14Nb (α/β) alloy in wire-electric discharge machining process: a surface integrity study, Proc. IME E J. Process Mech. Eng. (2024) 09544089241255942, https://doi.org/10.1177/09544089241255942.
[11] U. Elaiyarasan, C. Nandakumar, T. Arunkumar, Experimental study on parametric effect of wire electric discharge machining of titanium grade 2 alloy using cryogenic treated wire, J. Mater. Eng. Perform. (2024) 1–9, https://doi.org/10.1007/s11665-024-09976-5.
[12] A. Kumar, C. Upadhyay, N. Kumar, A.V.S. Ram Prasad, D.S. Nagaraju, Soft computing based parametric optimization of cutting rate, surface roughness, and kerf width in wire electric discharge machining of high strength Ti-3Al-2.5 V, Exp. Tech. 48 (3) (2024) 537–558, https://doi.org/10.1007/s40799-023-00681-x.
[13] P. Sharma, D. Chakradhar, S. Narendranath, Effect of wire diameter on surface integrity of wire electrical discharge machined Inconel 706 for gas turbine application, J. Manuf. Process. 24 (2016) 170–178, https://doi.org/10.1016/j.jmapro.2016.09.001.
[14] M. Usman, K. Ishfaq, M. Rehan, A. Raza, J. Mumtaz, An in-depth evaluation of surface characteristics and key machining responses in WEDM of aerospace alloy under varying electric discharge environments, Int. J. Adv. Des. Manuf. Technol. 124 (7) (2023) 2437–2449, https://doi.org/10.1007/s00170-022-10608-2.
[15] I. Maher, A.A. Sarhan, H. Marashi, M.M. Barzani, M. Hamdi, White layer thickness prediction in wire-EDM using CuZn-coated wire electrode–ANFIS modelling, Transactions of the IMF 94 (4) (2016) 204–210, https://doi.org/10.1080/00202967.2016.1180847.
[16] M.T. Antar, S.L. Soo, D.K. Aspinwall, D. Jones, R. Perez, Productivity and workpiece surface integrity when WEDM aerospace alloys using coated wires, Procedia Eng. 19 (2011) 3–8, https://doi.org/10.1016/j.proeng.2011.11.071.
[17] L. Li, Y.B. Guo, X.T. Wei, W. Li, Surface integrity characteristics in wire-EDM of Inconel 718 at different discharge energy, Procedia CirP 6 (2013) 220–225, https://doi.org/10.1016/j.procir.2013.03.046.
[18] Y. Wang, Q. Wang, Z. Ding, D. He, W. Xiong, S. Chen, Z. Li, Study on the mechanism and key technique of ultrasonic vibration and magnetic field complex assisted WEDM-LS thick shape memory alloy workpiece, J. Mater. Process. Technol. 261 (2018) 251–265, https://doi.org/10.1016/j.jmatprotec.2018.06.006.
[19] P. Radhakrishnan, L. Vijayaraghavan, Assessment of material removal capability with vibration-assisted wire electrical discharge machining, J. Manuf. Process. 26 (2017) 323–329, https://doi.org/10.1016/j.jmapro.2017.03.002.
[20] S. Das, S.N. Joshi, Estimation of wire strength based on residual stresses induced during wire electric discharge machining, J. Manuf. Process. 53 (2020) 406–419, https://doi.org/10.1016/j.jmapro.2020.03.015.
[21] A. Pramanik, M.N. Islam, A.K. Basak, Y. Dong, G. Littlefair, C. Prakash, Optimizing dimensional accuracy of titanium alloy features produced by wire electrical discharge machining, Mater. Manuf. Process. 34 (10) (2019) 1083–1090, https://doi.org/10.1080/10426914.2019.1628259.
[22] A. Kumar, C. Upadhyay, V. Kukkala, C.S. Kumar, Effect of electrode material and hybrid metaheuristic optimization on die corner accuracy during wire electrical discharge machining on Inconel (625): a comparative study, J. Mater. Eng. Perform. (2024) 1–16, https://doi.org/10.1007/s11665-024-09649-3.
[23] P. Sharma, D. Chakradhar, S. Narendranath, Precision manufacturing of turbine wheel slots by trim-offset approach of WEDM, Precis. Eng. 71 (2021) 293–303, https://doi.org/10.1016/j.precisioneng.2021.03.018.
[24] D. Devarasiddappa, J. George, M. Chandrasekaran, N. Teyi, Application of artificial intelligence approach in modeling surface quality of aerospace alloys in WEDC process, Procedia Technology 25 (2016) 1199–1208, https://doi.org/10.1016/j.protcy.2016.08.239.
[25] P. Sharma, D. Chakradhar, S. Narendranath, Analysis and optimization of WEDC performance characteristics of Inconel 706 for aerospace application, Silicon (2017) 1–10, https://doi.org/10.1007/s12633-017-9549-6.
[26] A. Kumar, C. Upadhyay, N. Kumar, A.V.S. Ram Prasad, D.S. Nagaraju, Soft computing based parametric optimization of cutting rate, surface roughness, and kerf width in wire electric discharge machining of high strength Ti-3Al-2.5 V, Exp. Tech. 48 (3) (2024) 537–558, https://doi.org/10.1007/s40799-023-00681-x.
[27] P. Sharma, H. Soni, S. Sethy, S.R. Das, M.Y. Tharwan, S. Al Sofyani, A. Elsheikh, Surface characterization of SAE 304 after WED cutting: an experimental investigation and optimization, J. Mater. Res. Technol. 23 (2023) 5723–5732, https://doi.org/10.1016/j.jmrt.2023.02.183.
[28] M.A. Karim, M.P. Jahan, Electrical discharge machining technologies in the aerospace industry, in: Modern Manufacturing Processes for Aircraft Materials, Elsevier, 2024, pp. 171–226, https://doi.org/10.1016/B978-0-323-95318-4.00007-0.
[29] P. Sharma, D. Chakradhar, S. Narendranath, Evaluation of WEDM performance characteristics of Inconel 706 for turbine disk application, Mater. Des. 88 (2015) 558–566, https://doi.org/10.1016/j.matdes.2015.09.036.
[30] S. Wang, B. He, H. Tang, Microstructure evolution of Ti17 titanium with ultrahigh strength and moderate plasticity fabricated by laser powder bed fusion, Mater. Sci. Eng., A 893 (2024) 146142, https://doi.org/10.1016/j.msea.2024.146142.
[31] A. Pramanik, A.K. Basak, G. Littlefair, S. Debnath, C. Prakash, M.A. Singh, R.K. Singh, Methods and variables in Electrical discharge machining of titanium alloy–A review, Heliyon 6 (12) (2020) e05554, https://doi.org/10.1016/j.heliyon.2020.e05554.
[32] P. Sharma, D. Chakradhar, S. Narendranath, Effect of wire material on productivity and surface integrity of WEDM-processed Inconel 706 for aircraft application, J. Mater. Eng. Perform. 25 (2016) 3672–3681, https://doi.org/10.1007/s11665-016-2216-z.
[33] A. Pramanik, A.K. Basak, C. Prakash, S. Shankar, S. Sharma, S. Narendranath, Recast layer formation during wire electrical discharge machining of Titanium (Ti-Al6-V4) alloy, J. Mater. Eng. Perform. 30 (12) (2021) 8926–8935, https://doi.org/10.1007/s11665-021-06116-1.
[34] K.P. Rajurkar, G. Levy, A. Malshe, M.M. Sundaram, J. McGeough, X. Hu, A. DeSilva, Micro and nano machining by electro-physical and chemical processes, CIRP annals 55 (2) (2006) 643–666, https://doi.org/10.1016/j.cirp.2006.10.002.
[35] A. Pramanik, A.K. Basak, Effect of wire electric discharge machining (EDM) parameters on fatigue life of Ti-6Al-4V alloy, Int. J. Fatig. 128 (2019) 105186, https://doi.org/10.1016/j.ijfatigue.2019.105186.
[36] M. Yakout, M.A. Elbestawi, S.C. Veldhuis, S. Nangle-Smith, Influence of thermal properties on residual stresses in SLM of aerospace alloys, Rapid Prototyp. J. 26 (1) (2020) 213–222, https://doi.org/10.1108/RPJ-03-2019-0065.
[37] M.M. Shehata, S. El-Hadad, M. Sherif, K.M. Ibrahim, A.I. Farahat, H. Attia, Influence of microstructure and alloy composition on the machinability of α/β titanium alloys, Materials 16 (2) (2023) 688, https://doi.org/10.3390/ma16020688.