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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF TI-6AL-4V ALLOY FABRICATED BY WIRE ARC ADDITIVE MANUFACTURING

The paper presents a systematized analytical synthesis of the current body of experimental data regarding the arc additive manufacturing of Ti-6Al-4V titanium alloy, focusing on Wire Arc (WAAM) and Gas Tungsten Arc (GTAW-AM) technologies. WAAM is an arc-based additive manufacturing technology derived from conventional welding processes. The synthesis focuses on quantitative relationships between deposition parameters, thermal cycling effects, microstructural evolution, and anisotropy of mechanical properties. It is demonstrated that heat input control, interpass temperature, and deposition path strategy govern prior-β grain growth and α-phase morphology. Repeated thermal exposure inherent to layer-by-layer deposition promotes the formation of columnar prior-β grains aligned with the build direction and height-dependent α-lath coarsening, resulting in hardness gradients and anisotropy of tensile strength. Optimized GTAW-AM parameters ensure geometric stability of deposited beads and tensile strength exceeding 900 MPa. For the WAAM process under controlled interpass temperature conditions, the formation of refined Widmanstätten-type lamellar structures is characteristic, contributing to improved strength. In addition, comparative analysis of mechanical properties reveals pronounced anisotropy in ultimate tensile strength, yield strength, and elongation depending on specimen orientation relative to the build direction. Typical technological defects inherent to arc-based additive manufacturing, including porosity, residual stresses, and microstructural heterogeneity, are associated with heat input and cooling conditions. The findings define a consistent process–structure–property relationship for arc-based additive manufacturing of Ti-6Al-4V and provide a scientifically grounded basis for optimization of arc-based AM technologies for critical structural components.

Keywords: Additive manufacturing, Wire Arc Additive Manufacturing (WAAM), GTAW-AM, Ti-6Al-4V, microstructure, thermal cycling effects, prior-β grains, α-lath morphology, mechanical anisotropy, microhardness, process–structure–property relationship, material deposition.

INTRODUCTION

Titanium alloys, particularly Ti-6Al-4V alloy, are extensively employed in aerospace, biomedical, and energy sectors due to their high specific strength, excellent corrosion resistance, and biocompatibility. However, conventional subtractive manufacturing of titanium components is associated with high production costs and significant material waste, largely attributed to poor machinability and unfavorable buy-to-fly ratios. These limitations have stimulated the rapid development of additive manufacturing (AM) technologies for near-net-shape fabrication of high-performance titanium structures [1–2].

Among various AM processes, Wire Arc Additive Manufacturing (WAAM), an arc-based Directed Energy Deposition (DED-Arc) technique derived from conventional gas tungsten arc welding (GTAW) and plasma arc welding (PAW), has emerged as a promising approach for large-scale titanium components. WAAM offers high deposition rates (up to several kilograms per hour), high material utilization efficiency, and good scalability for structural applications. The process involves layer-by-layer deposition of metallic wire feedstock, where an electric arc serves as the heat source. Process parameters such as welding current, wire feed rate, travel speed, and interpass temperature govern heat input, molten pool dynamics, thermal gradients, and solidification conditions, thereby directly influencing the resulting microstructure and mechanical properties. WAAM systems typically integrate a motion control platform (robotic or CNC-based), an arc welding power source, and a wire feeding mechanism, enabling precise control of deposition path and layer geometry [3–5].

Various arc- and energy-based technologies have been adapted for metal additive manufacturing. Arc-based processes include Gas Metal Arc Welding (GMAW/MIG-MAG), Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), and Cold Metal Transfer (CMT), which differ in heat input characteristics, arc stability, and metal transfer mechanisms. In addition to arc-based approaches, other directed energy deposition technologies such as Direct Metal Deposition (DMD) and Electron Beam Additive Manufacturing (EBAM) have also been applied for the fabrication of metallic components. However, WAAM has gained particular attention due to its ability to produce large-scale structures with high deposition rates, high material efficiency, and relatively low equipment cost compared to laser- or electron-beam-based systems [2,17,18].

Previous studies have demonstrated that the repetitive thermal cycling inherent to WAAM leads to the formation of columnar prior-β grains aligned with the build direction, followed by the development of acicular α' martensite or lamellar $\alpha + \beta$ microstructures depending on cooling rate and heat accumulation [3, 6, 7]. The interplay between heat input, cooling rate, and subsequent thermal exposure significantly affects phase transformation kinetics, residual stress evolution, and defect formation, including porosity and lack of fusion. These microstructural features ultimately determine tensile strength, hardness distribution, and anisotropy of mechanical performance [6–8].

Previous studies have shown that the microstructure of WAAM-produced Ti-6Al-4V is strongly influenced by thermal history and layer building strategy, leading to variations in grain morphology and texture that affect mechanical anisotropy and phase distribution [8, 9]. Additionally, WAAM-manufactured titanium exhibits higher hardness and altered machinability characteristics compared to conventional wrought material, impacting cutting forces and chip formation during drilling operations [10].

Despite extensive investigations, a systematic understanding of region-dependent microstructural evolution along the wall height — particularly the influence of repeated thermal cycles on phase morphology and property heterogeneity — remains incomplete. Therefore, further synthesis of experimental findings is required to establish robust correlations between welding parameters, microstructure formation mechanisms, and mechanical behavior of WAAM-fabricated Ti-6Al-4V components [8–10].

LITERATURE REVIEW AND PROBLEM STATEMENT

Early systematic investigations of arc-based additive manufacturing of Ti–6Al–4V were conducted by Wang et al. (2013) [11], who demonstrated that WAAM processing leads to epitaxial growth of prior β grains along the build direction due to directional heat flow and repeated thermal cycling. The authors were among the first to experimentally confirm the formation of columnar prior β grains and heterogeneous lamellar α structures across the build height, establishing the fundamental relationship between thermal history and microstructural evolution in WAAM-fabricated titanium alloys.

In subsequent work, Wang et al. (2018) [8] further investigated the influence of interpass temperature and heat accumulation on phase morphology and mechanical performance. Their study showed that variations in thermal gradients significantly affected α-lath thickness, grain refinement, and hardness distribution along the wall height, thereby reinforcing the critical role of process-induced thermal conditions in controlling structure–property relationships in WAAM Ti–6Al–4V components.

Thermal history modelling has been demonstrated to be crucial for microstructural control. Murgau et al. (2019) [12] applied a coupled process simulation and microstructural model for GTAW-based deposition of Ti-6Al-4V, quantifying the evolution of α lath thickness and predicting the graded microstructure along the build height. Their findings emphasized that heat accumulation and local thermal gradients govern α/β morphology and ultimately influence mechanical properties. In addition, the authors employed finite element thermal simulation coupled with microstructural modelling and validated the predicted α-lath morphology through quantitative microstructural characterization.

Recent review studies have also explored advanced strategies for improving the performance of WAAM-fabricated components. A comprehensive analysis of nanoparticle-reinforced WAAM processes demonstrated that the incorporation of ceramic nanoparticles (carbides, nitrides, and oxides) can significantly enhance microstructural refinement and mechanical performance of deposited alloys. The authors systematically classified nanoparticle incorporation approaches and reported that appropriate nanoparticle additions improve yield strength and ultimate tensile strength, although excessive concentrations may lead to particle agglomeration and deterioration of properties. These findings highlight the potential of nano-scale reinforcement as a promising approach for microstructural control and performance enhancement in arc-based additive manufacturing systems [20].

Experimental investigations by Wu et al. (2018) [13] confirmed that interpass thermal histories during WAAM lead to variations in grain size, phase distribution, and hardness along the wall height, highlighting the importance of interpass thermal control for achieving homogeneous mechanical performance.

Machinability implications have also been reported. Alonso et al. (2020) [10] demonstrated that differences in as-built microstructure and residual stress states directly affect cutting and thrust forces during drilling, linking microstructural heterogeneity from WAAM to post-processing behavior. Similarly, Liu et al. (2023) [3] applied response surface methodology (RSM) to systematically investigate GTAW-AM thin-walled Ti-6Al-4V components. They showed that welding current, wire feed, and torch speed influence deposition geometry and graded α phase morphology, which correlates with height-dependent microhardness variations (~362 HV top, ~353 HV middle, ~341 HV bottom), demonstrating a strong process–structure–property relationship.

Further insights into practical machining were provided by Hoye and Cuiuri (2018) [14], who reported that additively manufactured Ti-6Al-4V thin walls exhibit lower milling forces but higher drilling resistance compared to wrought counterparts. This indicates that arc-based AM affects surface integrity and tool wear, emphasizing the need to consider microstructural gradients when planning post-processing.

In addition to studies focusing on thermal cycling and process parameter effects, recent investigations have explored variations in deposition strategy and their influence on both microstructure and mechanical behavior. Zhou et al. (2020) [15] examined WAAM Ti-6Al-4V specimens fabricated with different deposition paths and demonstrated that deposition route significantly affects prior-β grain orientation, surface waviness, and tensile performance by modifying local thermal histories and solidification patterns. Moreover, a recent study by Kim, Kam, and Lee (2025) [16] systematically characterized the microstructure and mechanical properties of Ti-6Al-4V produced via wire-arc additive manufacturing, showing that fine Widmanstätten α-lath structures formed during WAAM lead to enhanced strength compared to wrought alloys and that microstructural features strongly correlate with deformation resistance mechanisms.

Recent review studies on WAAM technologies highlight their potential for large-scale metallic component fabrication, while emphasizing the importance of controlling heat input, microstructural evolution, and residual stresses during deposition [19].

A recent review by Dwivedi (2025) [21] comprehensively analyzed the principles, process steps, and key challenges associated with Wire Arc Additive Manufacturing (WAAM). The authors highlighted that WAAM offers several advantages over conventional manufacturing techniques, including high deposition rates, improved material efficiency, reduced lead times, and enhanced production flexibility. However, they also emphasized that excessive heat input during deposition can lead to critical processing defects such as residual stresses, porosity, cracking, and delamination. The study provides a systematic overview of process planning strategies and defect mitigation approaches, illustrating how careful control of deposition parameters is essential for achieving high-quality metallic components. Importantly, the review underscores the relevance of WAAM for aerospace applications, where titanium alloys like Ti-6Al-4V require precise microstructural control and mechanical performance for load-bearing structures. This work establishes a foundational understanding of WAAM performance and challenges, serving as a basis for further research aimed at optimizing the technology for industrial-scale aerospace manufacturing.

Despite these advances, several limitations remain:

1. Few studies integrate thermal modelling, microstructural evolution, and experimental mechanical characterization into a unified framework.
2. Comparative analyses of different arc-based AM processes (e.g., GTAW-AM vs WAAM) are limited, complicating generalization of process–property relationships.
3. Systematic correlations between deposition conditions and machining loads for precision thin-walled components are scarce.

Therefore, the problem addressed in this work is the insufficient understanding of how arc welding-based additive manufacturing affects microstructure, mechanical properties, and machinability of Ti-6Al-4V alloys. The study aims to experimentally investigate the influence of process parameters on bead formation, microstructural evolution, hardness profiles, and machining performance, with the goal of defining strategies for improved structural and functional performance of titanium components.

RESEARCH AIM AND OBJECTIVES

The primary aim of this study is to critically analyse the influence of arc-based additive manufacturing (WAAM and GTAW-AM) on the microstructure, mechanical properties, and machinability of Ti-6Al-4V alloy. Special attention is given to the relationships between process parameters, thermal history, and residual stresses, as these factors directly affect structural performance and post-processing behaviour of additively manufactured titanium components.

To achieve this aim, the following objectives are addressed:

1. To summarise recent experimental and numerical studies on arc-based additive manufacturing of Ti-6Al-4V, focusing on deposition strategies, thermal management, and resultant microstructural characteristics.
2. To evaluate the mechanical properties (tensile strength, hardness, ductility) and machinability of Ti-6Al-4V parts produced by arc-based additive manufacturing.
3. To analyse the effects of thermal cycles and residual stresses on the integrity and performance of deposited layers.
4. To identify gaps in current knowledge and suggest directions for future research aimed at optimising arc-based additive manufacturing processes for high-performance titanium alloys.

Arc-based additive manufacturing technologies, such as Wire Arc Additive Manufacturing (WAAM) and Gas Tungsten Arc Welding Additive Manufacturing (GTAW-AM), are highly relevant to the aerospace industry due to the critical demand for large, load-bearing Ti-6Al-4V components. Precise control of thermal cycles, microstructural evolution, and mechanical properties is essential to ensure structural integrity, minimize anisotropy, and meet stringent safety standards in aircraft applications. Therefore, understanding the process–structure–property relationships in these technologies provides a scientifically grounded basis for optimizing additive manufacturing methods in aerospace structural elements.

RESULTS OF THE STUDY

3.1 Influence of Arc-Based Deposition Parameters on Geometry and Thermal History

Experimental studies on GTAW-based additive manufacturing demonstrate that welding current predominantly governs molten pool size and penetration depth, while torch travel speed controls heat input distribution and solidification rate. Wire feed rate exerts a secondary influence, affecting layer height and material deposition per unit area [3]. These parameters collectively determine the thermal history of deposited layers, including localized melting, rapid solidification, and repeated thermal cycling. Such thermal regimes directly affect microstructural development and, consequently, mechanical behavior and machinability.

3.2 Microstructural Evolution in WAAM and GTAW Processes

Both WAAM and GTAW-based additive manufacturing of Ti-6Al-4V result in epitaxial growth of prior-β grains and formation of basket-weave α structures, with martensitic α′ occasionally present in the β matrix due to repeated thermal cycling [3, 10]. WAAM-produced walls generally exhibit more uniform hardness along the build height, whereas GTAW-AM thin-walled components display height-dependent microstructural gradients caused by localized control of heat input and layer-by-layer solidification. The microstructure is therefore strongly linked to process parameters and deposition strategy, demonstrating a clear process–structure–property relationship.

Under optimized GTAW-AM process parameters (I = 90 A, wire feed speed Vf = 900 mm/min, and travel speed Vs = 200.18 mm/min), a thin-walled Ti-6Al-4V structure was successfully fabricated using a reciprocating deposition strategy. The deposited wall exhibited stable geometry with smooth side surfaces and no evident collapse at arc initiation or termination points (Figure 1a) [3], indicating adequate control of heat input and melt pool stability.

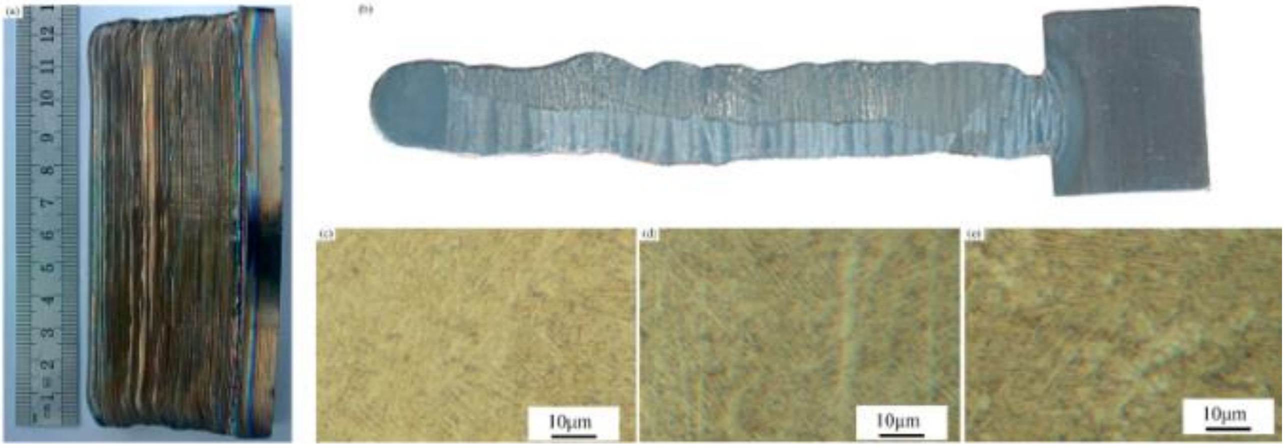

Figure 1. Optical microscopy of the TC4 titanium alloy RSM thin-walled part: (a) overall morphology, (b) macrostructural features, and (c–e) microstructural characteristics at different wall heights (top, middle, bottom). [3]

Metallographic examination revealed a pronounced layer-wise architecture resulting from repeated thermal cycling (Figure 1b). Distinct interlayer boundaries were observed in the middle and lower regions, manifested as light–dark contrasts, whereas such features were significantly less pronounced in the top region due to the absence of subsequent reheating cycles. The microstructure was dominated by coarse prior-β columnar grains extending nearly through the entire wall height, confirming directional solidification under a steep thermal gradient. Higher magnification observations $(500\times)$ demonstrated a typical basket-weave $\alpha+\beta$ morphology across all regions (Figure 1c–e).

However, a clear gradient in α-phase morphology was identified along the build direction. The top region (Figure 1c) exhibited finer α lamellae, attributed to rapid heat dissipation and the absence of secondary thermal exposure. In contrast, the middle region (Figure 1d) showed relatively coarsened α plates due to repeated reheating [3]. The bottom region (Figure 1e) presented the coarsest α phase together with short β columnar grains and partially equiaxed structures, reflecting prolonged heat accumulation and heat transfer toward the substrate.

This microstructural gradient confirms the strong dependence of phase evolution on local thermal history and demonstrates a clear process–structure relationship inherent to arc-based additive manufacturing of Ti-6Al-4V.

Figure 1. Schematic representation of microstructural features along the wall height. Top regions show finer α-phase due to rapid cooling and limited thermal cycling, middle regions exhibit coarser α-phase due to reheating, and bottom regions contain coarser α-phase with short columnar β grains reflecting prolonged heat accumulation.

3.3 Mechanical Properties and Machinability Correlations

Microstructural characteristics directly influence mechanical performance and machining behavior. Areas with finer acicular α-phase and limited martensitic α′ generally correspond to higher hardness and tensile strength, whereas regions with coarser grains show relatively lower hardness. This vertical gradient necessitates consideration of layer orientation and thermal management to ensure uniform mechanical performance. Machinability is similarly affected: increased hardness and α′ content lead to higher cutting forces and torque, while regions with coarser microstructure are easier to machine. Knowledge of these microstructural gradients allows optimization of post-processing and machining strategies for additively manufactured titanium components [10].

3.4 Comparative Analysis of WAAM and GTAW-AM

- WAAM: Higher material throughput and more uniform mechanical properties along wall height; broader layer-to-layer uniformity in hardness.
- GTAW-AM: Finer control of layer geometry, pronounced height-dependent mechanical gradients, and localized microstructure control suitable for precision thin-walled components.

Both technologies emphasize the critical role of thermal cycles, residual stress, and process parameters in defining mechanical performance, highlighting the importance of integrating deposition strategy with microstructure management in titanium additive manufacturing [3, 10].

3.5 Practical Implications

Understanding the process–structure–property linkages in WAAM and GTAW-AM enables:

- Optimization of deposition strategies for desired microstructure and mechanical performance.
- Prediction of machining behavior and adaptation of cutting parameters to local hardness variations.
- Design of load-bearing components with controlled anisotropy and improved reliability for aerospace, biomedical, and other high-performance applications.

3.6 Key Experimental Data (Quantitative Findings)

Quantitative evaluation of arc-based additive manufacturing of Ti-6Al-4V demonstrates direct correlations between deposition parameters, thermal cycling effects, microstructural evolution, and mechanical performance. In GTAW-AM thin-walled components, optimization via response surface methodology (Liu et al., 2023) [3] identified 90 A welding current, 900 mm/min wire feed speed, and 200.18 mm/min torch travel speed as conditions ensuring stable wall formation and controlled penetration geometry. Increased current and wire feed enlarged penetration depth and layer width, whereas higher travel speed reduced these dimensions. The resulting microstructure exhibited a height-dependent α-phase gradient governed by cumulative thermal exposure: fine α at the top (362.7 HV), coarser α in the middle (352.7 HV), and the coarsest morphology at the bottom (340.5 HV). Correspondingly, horizontal tensile strength reached 926 MPa with 12.2% elongation, while vertical strength increased to 938 MPa with 14.4% elongation, indicating limited anisotropy under optimized conditions.

In WAAM-fabricated walls, deposition at a rate of 2 kg/h and an interpass temperature of 600 °C (Alonso et al., 2020) [10] produced columnar prior-β grains and acicular α structures with gradual coarsening along the build height due to repeated thermal cycling. Hardness remained relatively uniform compared to laminated material, while machinability was characterized by shorter chips and reduced burr formation despite elevated cutting forces.

The influence of deposition path was further confirmed (Zhou et al., 2019) [15], where co-directional strategies enhanced vertical tensile strength, whereas reciprocating paths increased β-grain waviness and surface irregularity. Recent results (Kim et al., 2025) [16] demonstrate that cyclic thermal exposure in WAAM promotes refinement of Widmanstätten (α_w) α-laths, leading to higher tensile strength relative to conventionally processed alloys and emphasizing the governing role of solidification kinetics and interpass temperature control.

Collectively, these data establish quantifiable process–structure–property relationships in Arc-AM Ti-6Al-4V. Welding current, wire feed rate, travel speed, deposition path, and interpass temperature define molten pool dynamics and thermal history, which in turn regulate α-morphology, β-grain evolution, hardness gradients, tensile performance, and machining response.

3.7 Comparative Mechanical and Microhardness Data

Table 1 presents the comparative mechanical and microhardness data of Ti-6Al-4V components fabricated using WAAM and GTAW-AM techniques. The data indicate that the ultimate tensile strength (UTS) and yield strength (YS) exhibit anisotropic behavior depending on specimen orientation in the WAAM-fabricated walls, with the oblique direction demonstrating the highest UTS, whereas elongation at break shows an opposite trend, being maximal in the vertical direction (Table 1) [3,10,12,16]. Microhardness values remain relatively consistent across wall height for WAAM components, indicating uniform hardness distribution despite columnar prior-β grains and acicular α structures.

GTAW-AM-fabricated components, optimized via response surface methodology (RSM), show a height-dependent α-phase gradient with top α-phase finer (362.7 HV) and coarser α at the bottom (340.5 HV), reflecting the influence of repeated thermal exposure and controlled interpass temperature on microstructural evolution (Table 1). Similar observations have been reported [12], demonstrating that coupled thermal simulation and microstructural modelling can predict α-lath thickness and graded morphology along the build height, validated through microstructural characterization.

Comparative analysis demonstrates that microstructural refinement in both WAAM and GTAW-AM components significantly affects tensile performance and mechanical anisotropy, corroborating the quantitative process–structure–property relationships discussed in Section 3.6.

Table 1. Comparative mechanical properties and microhardness of Ti-6Al-4V components fabricated by WAAM and GTAW-AM [3,10,12,16]

Method / Deposition	Specimen Orientation	Ultimate Tensile Strength (UTS, MPa)	Yield Strength (YS, MPa)	Elongation at Break (%)	Microhardness (HV)	Microstructural Features
PAW-WAAM [10]	Horizontal	981 ± 36.3	917 ± 19.3	11 ± 0.9	301 ± 8	Columnar prior-β grains, acicular α structures
PAW-WAAM [10]	Vertical	925 ± 18.2	864 ± 22.8	15 ± 1.3	304 ± 5	Columnar prior-β grains, uniform hardness
PAW-WAAM [10]	Oblique	1094 ± 35.5	1020 ± 20.2	10 ± 0.5	294 ± 4	Highest UTS, slight anisotropy in elongation
GTAW-AM [3]	Horizontal	926	900	12.2	362.7–340.5	α-phase gradient along height, optimized parameters
WAAM [16]	—	—	—	—	—	Refined Widmanstätten α-laths, improved tensile performance
GTAW Wire-Feed AM [12]	Vertical / Horizontal (simulated)	~920–940	~880–900	12–14	350–365	Columnar prior-β grains; α-laths (Widmanstätten) with graded thickness along build height

3.8 Statistical Modeling of Process Parameters in GTAW-AM

Statistical modeling of GTAW-AM deposition using response surface methodology (RSM) demonstrates that welding current represents the dominant factor governing geometric stability and melt pool characteristics (Table 2). For deposition layer width, current and travel speed were statistically significant, whereas wire feed rate exhibited negligible influence. Layer height was strongly affected by all three primary parameters, with current showing the highest F-value. Penetration depth was primarily controlled by welding current, with additional contribution from travel speed and $A \times C$ interaction effects.

The high R^2 values (>0.89) confirm strong predictive capability of the regression models, establishing quantitative relationships between process parameters and geometric responses. These findings provide a statistical foundation for the process–structure–property correlations discussed in Sections 3.6–3.7.

Table 2. Summary of statistically significant process parameters affecting geometric responses in GTAW-AM (after Liu et al., 2023 [3])

Response	Dominant Factor	Secondary Significant Factors	R^2
Layer Width	Welding current	Travel speed	0.8966
Layer Height	Welding current	Wire feed rate, travel speed	0.9665
Penetration Depth	Welding current	Travel speed, $A \times C$ interaction	0.9360

DISCUSSION OF RESULTS

Analysis of the studies by Liu (2023), Alonso (2020), Murgau (2019), Zhou (2019), and Kim (2025) [3,10,12,15,16] demonstrates a clear process–structure–property relationship governing arc-based additive manufacturing of Ti-6Al-4V. The following analytical synthesis evaluates the influence of process parameters, thermal history, and microstructural characteristics on mechanical behavior and machinability.

Influence of Process Parameters on Geometric Stability and Thermal History

Liu (2023) [3] quantitatively demonstrated that welding current, wire feed speed, and torch travel speed directly control deposition geometry through modulation of heat input. Increased current enhanced penetration depth and layer width, while higher travel speed reduced melt pool dimensions. These findings confirm that geometric stability in GTAW-AM is fundamentally heat-input-driven.

A recent investigation by Kim, Kam, and Lee (2025) [16] further advances the understanding of microstructural evolution in WAAM-fabricated Ti-6Al-4V. The authors demonstrated that the formation of fine Widmanstätten α-lath structures, induced by cyclic thermal exposure and rapid solidification, significantly enhances tensile strength compared to conventionally processed alloys. Their findings reinforce the concept that heat accumulation, solidification kinetics, and α-morphology refinement are key factors governing the structure–property relationships in arc-based additive manufacturing. These results align with earlier studies emphasizing thermal history as the dominant mechanism controlling mechanical performance in WAAM components.

Zhou (2019) [15] extended this understanding by showing that deposition path strategy (reciprocating vs co-directional) significantly influences surface waviness and prior-β grain orientation. This suggests that not only scalar process parameters but also spatial deposition strategies dictate solidification behavior and thermal gradients.

Collectively, the analyzed studies indicate that heat input control and thermal cycling effects constitute the primary mechanisms governing arc-based deposition.

Similar conclusions regarding the dominant role of thermal history were reported by Murgau et al. [12], who demonstrated through coupled thermal simulation and microstructural modelling that temperature evolution during GTAW-based additive manufacturing governs α-lath morphology and microstructural refinement.

Quantitative microstructural analysis indicates that the average α-lath thickness in GTAW-deposited Ti-6Al-4V remains relatively stable across different bead configurations (~1.0–1.1 μm), although a slight increase in α-lath thickness with increasing number of deposited beads has been observed due to additional thermal cycles promoting diffusional growth of the α phase [12]. A reduction in α-lath thickness is generally associated with increased strength but reduced ductility, highlighting the importance of thermal control during additive deposition. In contrast, the fraction of grain boundary α shows considerable variation, which is attributed to differences in prior-β grain size and crystallographic orientation within the deposited structure.

Microstructural Evolution: Prior-β Grain Growth and α-Phase Morphology

Across all studies, the dominant microstructural feature is columnar prior-β grains aligned along the build direction, reflecting directional solidification under steep thermal gradients.

Liu (2023) [3] observed progressive α-phase coarsening from top to bottom, correlated with decreasing microhardness. Similarly, Zhou (2019) reported a vertical gradient from fine basket-weave to coarse α morphology, while Kim (2025) identified Widmanstätten α-lath structures formed by rapid cooling and layer-by-layer reheating [15, 16].

The formation of Widmanstätten α-lath morphology is associated with the diffusion-controlled decomposition of the β phase during cooling. Nucleation of α plates typically initiates at prior-β grain boundaries and subsequently propagates into the β grains in a lamellar arrangement. Under rapid cooling conditions characteristic of arc-based additive manufacturing, repeated thermal cycling may also promote martensitic α formation, further influencing microstructural refinement and mechanical response [12].

The convergence of reported findings suggests that repeated thermal cycling inherent to WAAM and GTAW-AM leads to α-lath coarsening, anisotropic grain morphology, and microstructural heterogeneity along the build height.

However, Kim (2025) [16] demonstrated that compared to wrought material, WAAM produces finer α-laths and lower β fraction, contributing to higher strength but reduced ductility. This highlights a key trade-off in additive processing.

Recent review studies further emphasize that microstructural heterogeneity in WAAM-fabricated components is strongly influenced by process parameters such as heat input, wire feed speed, torch travel speed, and interlayer temperature. Excessive heat accumulation and unstable deposition conditions may lead not only to microstructural coarsening but also to technological defects including porosity, residual stresses, and humping phenomena, which negatively affect structural integrity and mechanical performance. As highlighted in recent systematic reviews, careful optimization of process parameters and thermal management strategies is therefore essential to achieve a refined microstructure and stable mechanical properties in WAAM-produced metallic components [20,21].

Therefore, understanding the relationship between thermal history, microstructural evolution, and process-induced defects remains essential for optimizing WAAM processing of Ti-6Al-4V alloys.

Mechanical Performance and Anisotropy

Liu (2023) [3] reported tensile strengths of 926–938 MPa with moderate elongation (12–14%), indicating compliance with structural requirements for load-bearing components.

Kim (2025) [16] confirmed that WAAM material exhibits higher ultimate tensile strength than wrought Ti-6Al-4V due to α-lath boundary strengthening and restricted slip transmission. However, ductility remains lower due to stress concentration at α/β interfaces.

Zhou (2019) [15] demonstrated that tensile strength varies depending on deposition path, with co-directional deposition yielding higher vertical strength, reinforcing the presence of anisotropy.

Therefore, mechanical anisotropy in arc-AM Ti-6Al-4V arises from columnar prior-β grain alignment, α-lath morphology, and deposition strategy.

Machinability and Post-Processing Implications

Alonso (2020) [10] introduced a critical industrial dimension: machinability. WAAM material exhibited higher hardness than laminated plate, resulting in increased cutting forces, serrated chip formation, and reduced burr height.

This confirms that microstructural refinement and hardness directly influence machining response. When considered alongside Liu (2023), it becomes evident that geometric control and thermal input optimization not only affect strength but also downstream manufacturing performance [3].

Knowledge Gaps and Research Perspectives

Despite significant progress, limited quantitative correlation between α-lath thickness and cutting force magnitude has been established. In addition, residual stress distribution under varying deposition paths remains insufficiently characterized. Integrated modeling approaches combining thermal simulation with mechanical anisotropy prediction are still underdeveloped, and scalability challenges persist for large structural components requiring uniform microstructure.

Future research should focus on multi-layer thermal modeling, hybrid heat treatments, and real-time monitoring strategies to minimize microstructural heterogeneity.

The comparative evaluation of GTAW-AM and WAAM studies confirms that arc-based additive manufacturing of Ti-6Al-4V is governed by heat-input-driven microstructural evolution. Optimized parameter selection enhances tensile strength while potentially increasing hardness and machining resistance, whereas deposition path strategy introduces additional anisotropy effects.

Collectively, these findings establish a comprehensive process–structure–property framework linking deposition parameters, thermal history, microstructure, mechanical performance, and machinability, providing a scientific basis for further advancement of arc-based titanium additive manufacturing technologies.

Analytical Evaluation of Reported Experimental Results

Within the framework of the analyzed studies, the synthesized data presented in Tables 1 and 2 further elucidate the process–structure–property interrelationships governing arc-based additive manufacturing of Ti-6Al-4V. The comparative analysis of mechanical performance and statistical process modeling reveals a consistent process–structure–property relationship in arc-based additive manufacturing of Ti-6Al-4V.

As demonstrated in Table 1, WAAM-fabricated components exhibit orientation-dependent tensile behavior characterized by moderate mechanical anisotropy. The highest ultimate tensile strength (UTS) is observed in the oblique direction, whereas elongation at break is maximized in the vertical orientation. This anisotropic response can be attributed to the formation of columnar prior-β grains aligned along the build direction and the development of acicular α or Widmanstätten α-lath morphologies. The repeated thermal cycling inherent to layer-by-layer deposition promotes epitaxial β-grain growth and progressive α-lath coarsening along the build height, thereby influencing strain distribution and crack propagation pathways.

In contrast, GTAW-AM specimens optimized through response surface methodology exhibit comparatively reduced anisotropy under controlled processing conditions. The statistically validated models summarized in Table 2 confirm that welding current represents the dominant process parameter governing deposition layer geometry and melt pool stability. The high coefficient of determination values $(R^2 > 0.89)$ indicate strong predictive capability of the regression models, establishing a quantitative link between process parameters and geometric responses such as layer width, height, and penetration depth.

The dominant influence of welding current on penetration depth and layer width directly affects heat input and solidification kinetics. Increased current enhances melt pool volume and thermal accumulation, promoting coarser α-lath morphology at lower regions of the build due to prolonged thermal exposure. Conversely, optimized travel speed and controlled interpass temperature mitigate excessive grain growth and contribute to more uniform microstructural distribution. The observed α-phase gradient in GTAW-AM components reflects height-dependent thermal history, with finer α near the top layers and coarser morphology near the substrate.

Hardness measurements further support this interpretation. While WAAM components show relatively uniform microhardness distribution, GTAW-AM specimens demonstrate measurable hardness gradients associated with microstructural refinement. These variations correlate with tensile performance, confirming that microstructural morphology—specifically α-lath thickness and prior-β grain size—governs strength–ductility balance.

The combined evaluation of Tables 1 and 2 therefore substantiates that geometric stability achieved through statistical optimization translates into controlled microstructural evolution and predictable mechanical response. Heat input control, welding current regulation, deposition path strategy, and interpass temperature management collectively define molten pool dynamics, solidification rate, β-grain growth behavior, and subsequent α-phase transformation.

Overall, the findings confirm that arc-based additive manufacturing of Ti-6Al-4V follows a deterministic process–structure–property pathway. Statistical parameter optimization enhances geometric accuracy and reduces variability, while thermal cycle management governs microstructural refinement and mechanical anisotropy. These results provide a robust framework for rational design and optimization of WAAM and GTAW-AM technologies for high-performance structural applications.

CONCLUSIONS

This analytical review provides a comparative evaluation of WAAM and GTAW-based arc additive manufacturing of Ti-6Al-4V, emphasizing the interrelation between deposition parameters, thermal cycling, microstructural evolution, mechanical anisotropy, and machinability.

The synthesized literature data indicate that arc-based deposition is predominantly governed by heat input and interpass thermal history, which control solidification behaviour, prior-β grain development, and α-phase morphology. Repeated thermal cycling inherent to layer-wise deposition promotes columnar prior-β grain growth along the build direction and height-dependent α-lath coarsening, resulting in microstructural gradients that influence hardness distribution and tensile response.

Comparative analysis of reported studies shows that mechanical performance is strongly process-dependent. Optimized GTAW-AM regimes reported in the literature ensure geometric stability and reduced anisotropy while maintaining tensile strengths exceeding 900 MPa. Similarly, controlled WAAM deposition conditions contribute to refinement of Widmanstätten α-structures and elevated strength levels relative to conventionally processed material, albeit with inherent directional dependence associated with grain alignment. Machinability trends reported across studies demonstrate a clear correlation between α-lath refinement, hardness increase, cutting force evolution, and chip morphology, confirming that process-induced microstructure affects not only structural integrity but also downstream manufacturing performance.

Comparative mechanical data reported in the reviewed studies further confirm the process-dependent variation of tensile strength, elongation, and microhardness in arc-deposited Ti-6Al-4V components.

Overall, the reviewed evidence supports a consistent process–structure–property–machinability framework for arc-based additive manufacturing of Ti-6Al-4V. Although anisotropy and microstructural heterogeneity remain intrinsic characteristics of arc deposition, the literature indicates that their magnitude can be moderated through precise control of welding current, travel speed, deposition strategy, and interpass temperature. These insights provide a scientifically grounded basis for further process optimization and industrial implementation of welding-derived additive manufacturing technologies.

The relevance of arc-based additive welding technologies is particularly significant for aerospace structural applications, where Ti-6Al-4V remains a critical load-bearing material, highlighting the practical importance of optimizing process parameters, microstructure, and mechanical performance for advanced aerospace components.

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Кирилаха С.В., Капустян О.Є. **Мікроструктура та механічні властивості сплаву Ti-6Al-4V, виготовленого за технологією Wire Arc Additive Manufacturing**

У роботі представлено систематизований аналітичний синтез сучасного масиву експериментальних даних щодо дугового адитивного виробництва титанового сплаву Ti-6Al-4V **з** фокусом на технологіях Wire Arc Additive Manufacturing (WAAM) та Gas Tungsten Arc Welding Additive Manufacturing (GTAW-AM). WAAM — це технологія дугового адитивного виробництва, що базується на процесах дугового зварювання. Синтез спрямований на встановлення кількісно обґрунтованих взаємозв’язків між параметрами наплавлення, характеристиками теплового циклу, кінетикою тверднення та фазових перетворень, еволюцією мікроструктури й формуванням анізотропії механічних властивостей. Показано, що тепловкладення, міжшарова температура та стратегія траєкторії наплавлення є визначальними чинниками, які контролюють ріст зерен попередньої β-фази (prior-β grains) і морфологію α-фази. Повторні термічні цикли, притаманні пошаровому формуванню, зумовлюють формування колонкових зерен попередньої β-фази, орієнтованих уздовж напрямку побудови, а також висотно-залежне укрупнення α-пластин, що призводить до формування градієнта мікротвердості та анізотропії межі міцності при розтягу. Встановлено, що оптимізовані параметри GTAW-AM забезпечують геометричну стабільність наплавлених валиків і тимчасовий опір розриву понад 900 МПа. Для WAAM-процесу за умов контрольованої міжшарової температури характерне формування подрібнених пластинчастих структур типу Відманштеттена, що сприяє підвищенню міцності. Характерні для дугового адитивного виробництва технологічні дефекти, зокрема пористість, залишкові напруження та мікроструктурна неоднорідність, пов’язані з величиною тепловкладення та умовами охолодження. Отримані результати формують узгоджену модель взаємозв’язку «процес – структура – властивості» для дугових технологій адитивного виробництва титанових сплавів і створюють науково обґрунтовану основу для оптимізації параметрів виготовлення відповідальних конструкційних елементів.

Ключові слова: Адитивне виробництво, Wire Arc Additive Manufacturing (WAAM), GTAW-AM, Ti-6Al-4V, мікроструктура, термічні цикли, зерна попередньої *β*-фази, морфологія *α*-пластин, механічна анізотропія, мікротвердість, процес – структура – властивості, осадження матеріалу.

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