

Effect of Solution Heat Treatment and Aging on the tensile Properties of Ti-6Al-4V Alloy Component Manufactured by Wire Arc Additive Manufacturing

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Abstract

Wire Arc Additive Manufacturing (WAAM) is a cost-effective technique for fabricating components from the Ti-6Al-4V alloy, known for its high strength and utility in demanding applications. To maximize its strength, the alloy undergoes Solution Treating and Aging heat treatment, comprising three key steps: (i) Solution Treating: The alloy is heated to 950°C (just below the β transus) and held for 1 hour, increasing the β phase proportion. This step sets the foundation for further strengthening in subsequent stages. (ii) Quenching: Rapid cooling in water preserves the β -favored phase from solution treatment. Without rapid cooling, the material would revert to a higher α phase content upon slow cooling. However, this quenching process can introduce residual stresses and unstable structures, like martensite. (iii) Aging: The alloy is held at 530°C for 8 hours, decomposing residual martensite and unstable β phase into stable α and β phases. This controlled transformation enhances the alloy's mechanical strength, by up to 3.13%.

Keywords: WAAM; Ti-6Al-4V; Solution Treatment and Aging (STA); Tensile Properties

INTRODUCTION

Titanium alloys are extensively utilized across various industries including aerospace, marine, chemical, and biomedical sectors due to their outstanding mechanical properties. These characteristics include superior corrosion resistance, low density, excellent fracture toughness, and high specific strength [1,2]. However, the widespread adoption of titanium components is hindered by the high cost of production, particularly in the aerospace industry where components often exhibit high buy-to-fly ratios. In response to the need for cost-effective manufacturing, alternative methods such as metal additive manufacturing (MAM) are gaining increasing attention.

Additive Manufacturing (AM) refers to a process where components are created layer by layer through material addition, as opposed to subtractive or formative traditional manufacturing techniques. The specific AM process used depends largely on the energy source and the form of the feedstock material. According to the ISO/ASTM 52900-15 standard, seven primary AM processes exist, but for metals, the most widely used are: (A) Directed

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Energy Deposition (DED) and (B) Powder Bed Fusion (PBF). In the PBF process, powdered metal is spread in layers and selectively fused using a heat source such as a laser or electron beam, forming a near-net shape. In contrast, DED utilizes either wire or powder as feedstock, which is melted by an energy source—laser, electron beam, or arc welding—as it is deposited. One notable DED technique is Wire Arc Additive Manufacturing (WAAM), which feeds a continuous wire into an electric arc where it melts and deposits material onto a substrate or previous layer [3]. This method resembles Gas Metal Arc Welding (GMAW) or Gas Tungsten Arc Welding (GTAW). WAAM is an innovative technique capable of producing fully dense, large, three-dimensional near-net shape metal components directly from wire feedstock. In this method, a metal wire is continuously fed into an electric arc, where it melts and deposits onto a substrate or previously built layer. Compared to many other metal additive manufacturing techniques, WAAM offers significantly higher deposition rates, often measured in kilograms per hour. It also boasts nearly complete material utilization, eliminating the need for powder handling, and comes at a lower cost compared to laser- or powder-based processes. Typically, parts manufactured using WAAM cost roughly an order of magnitude less than those made by laser powder bed fusion methods. This technology finds applications across diverse sectors including aerospace, automotive, military, tooling, nuclear energy, and marine industries. For example, aerospace manufacturing benefits from WAAM when producing complex titanium components, as traditional subtractive methods for such parts can be challenging and expensive. Titanium comprises approximately 93% of the structural weight of the Lockheed SR-71 Blackbird, with around 90% of the forging material typically removed during machining. Conventional fabrication techniques like forging or machining rely on removing material from a solid block to achieve the desired shape. In contrast, WAAM reverses this approach by progressively adding material to build near-net shapes, reducing waste and time. This process is guided by CAD/CAM software, which generates robot instructions for precise weld path control. The resulting components usually require minimal post-processing, and scrap rates are nearly eliminated. Additionally, WAAM's minimal tooling requirements allow for design modifications even after part completion through additional deposition or machining. In aerospace, the efficiency of material usage is often measured by the buy-to-fly ratio—the amount of raw material compared to the final part weight—with lower ratios being highly beneficial for costly and difficult-to-machine materials like titanium. Since the WAAM process directly influences both the dimensional accuracy and quality of the fabricated parts, significant attention must be given to controlling mechanical properties, residual stresses, and bead geometry to ensure optimal performance.

WAAM stands out for its high deposition rates, scalability, and efficient material use, making it a cost-effective approach for producing titanium alloy parts compared to other metal AM methods. The microstructure of Ti-6Al-4V is significantly influenced by chemical composition, processing conditions, thermal history, and cooling rates. Rapid cooling from just below the β transus temperature can produce a needle-like, acicular α phase via martensitic transformation. Conversely, slower cooling leads to a plate-like Widmanstätten microstructure. Primary α phase may retain a globular morphology, while transformed β phases may become elongated or acicular. The volume and morphology of these phases directly affect mechanical properties.

In WAAM, the layer-by-layer deposition process introduces complex thermal gradients. Each layer undergoes distinct cooling rates and thermal cycles due to accumulated heat. For instance, the bottom layers are cooled primarily by conduction through the substrate, whereas the upper layers dissipate heat through convection and radiation. This uneven thermal history leads to variations in microstructure throughout the build height, potentially resulting in anisotropic mechanical properties. Typically, vertically built specimens display 20–30 MPa lower ultimate tensile strength (UTS) and yield strength (YS) compared to horizontally built ones, though they often exhibit greater elongation due to the formation of large columnar β grains through epitaxial growth. Several post-processing techniques have been studied to improve the mechanical performance of WAAM-built parts by modifying their microstructure. These include inter-pass cold rolling, controlled cooling between layers, surface peening, ultrasonic impact treatments, hot isostatic pressing (HIP), and various heat treatments. Among these, heat treatment is particularly effective in refining microstructure and enhancing mechanical

properties. Heat treatments are applied to relieve residual stresses (typically around 600°C), improve ductility and machinability (annealing at ~800°C), and tailor phase composition and morphology for improved mechanical behaviour. Specific treatments can also be designed to enhance properties such as fracture toughness, fatigue resistance, and creep strength at elevated temperatures. A commonly employed post-treatment for $\alpha+\beta$ and β titanium alloys is Solution Treating and Aging (STA). This approach is used to maximize strength, particularly in alloys like Ti-6Al-4V. The STA process involves heating the material to a temperature near the β transus, followed by rapid quenching and subsequent aging. The treatment promotes a high volume fraction of β phase, which is retained through quenching, resulting in enhanced strength. The solution treatment phase typically involves heating just below or slightly above the β transus and holding for about an hour. The subsequent water quench locks in the desired phase distribution. Aging, conducted at 480–595°C for 4–8 hours, decomposes any residual martensite and metastable β phase formed during quenching, leading to improved strength and mechanical stability. Heat treatments at temperatures below 800°C increase ductility slightly, while higher temperatures coarsen the microstructure and improve elongation at the cost of strength [4]. Ti-6Al-4V is typically used in applications requiring high strength, and heat treatments like quenching and aging can increase strength by 30-50% by altering the balance of α and β phases.

Numerous studies have concentrated on how heat treatment influences the properties of Ti-6Al-4V alloy. For instance, Morita et al. [5] explored the impact of a short-duration duplex heat treatment—comprising solution treatment followed by water quenching and aging—on the alloy’s microstructure and mechanical performance. They observed enhancements in both strength and ductility, attributing these improvements to the formation of martensitic structures during quenching and the precipitation of fine α -phase particles within the retained β -phase during aging. Similarly, Oh et al. [6] investigated the interrelation between heat treatment, microstructural changes, and mechanical properties in Ti-6Al-4V produced via vacuum arc remelting (VAR). Their heat treatment involved solution treating at 950°C for 30 minutes, followed by water quenching and subsequent aging at 450°C, 550°C, and 650°C. Their findings revealed that strengthening occurred due to the precipitation of α -phase within the β -matrix. Venkatesh et al. [7] examined how strain rate influenced the mechanical properties of heat-treated extra-low interstitial (ELI) grade Ti-6Al-4V. Their results showed that aging reduced the continuity of the α -phase, thereby enhancing strength but reducing ductility. Carreon et al. [8] focused on the effect of aging on the thermoelectric power (TEP) of Ti-6Al-4V and reported increased TEP values in aged samples. This increase was associated with the formation of fine, coherent α_2 (Ti₃Al) precipitates within the α -phase during aging. Yu et al. [9] studied the mechanical response of Ti-6Al-4V sheet following solution treatment and aging. They found that higher aging temperatures led to an increase in both primary and secondary α -phase grain sizes, which in turn caused a reduction in hardness. Gheysarian et al. [10] evaluated how aging influences microstructure, mechanical properties, and formability of the alloy. Their study demonstrated that aging increased hardness while reducing ductility and formability in quenched samples. However, introducing an annealing step prior to aging improved both hardness and formability, while reducing strength—an outcome they linked to martensite decomposition during annealing. Typically, stress-relieving heat treatments are carried out below 800°C and result in minimal microstructural changes, with only modest improvements in ductility (around 1–2%). In contrast, annealing at temperatures above 800°C promotes microstructural coarsening, which significantly improves elongation but compromises strength. Aging, even when conducted at elevated temperatures, tends not to drastically reduce strength due to precipitation hardening from Ti₃Al formation. The goal of the study is to analyse how STA heat treatment affect the strength of Ti-6Al-4V parts produced using WAAM, focusing on how these treatments can help to improve material properties and optimize the use of Ti-6Al-4V in high-performance applications.

Experimental Procedure

Ti-6Al-4V (ELI Grade 5) wall has been deposited using WAAM technique. The WAAM process used a Fronius TPS 370i power source and an ABB robot (IRB 1520ID) with an IRC5 controller. Ti-6Al-4V wire (1.2 mm diameter) was used as the feedstock, with an initial composition of 5.95 wt.% aluminium, 4.02 wt.% vanadium, and 0.07 wt.% oxygen. The substrate was kept in a chamber supplied

with Argon gas to prevent exposure to atmospheric oxygen during deposition, as excessive oxygen can increase strength but reduce ductility. The process used pulsed mode for metal transfer with specific parameters: welding current of 152 A, arc voltage of 21.5 V, travel speed of 12 mm/s, and wire feed speed of 6 m/min. A high-purity Argon shielding gas (99.99% pure) was used at a flow rate of 20 l/min. RAPID programming language was employed for controlling the robot's movements. The deposition was done using a zigzag strategy, with each layer being deposited bi-directionally, and the nozzle height was increased by 2 mm after each layer. After deposition, the walls were milled to refine the surface.



Figure 1. Robotic WAAM setup

Solution heat treatment was performed at 950°C for 1 hour, followed by water quenching. Aging treatment was carried out at 530°C for 8 hours, followed by air cooling. After the STA heat treatment process, samples were prepared for tensile testing according to ASTM standards using a wire EDM machine. The tensile properties of the material were evaluated using a tensile testing machine. This process aims to enhance the material's mechanical properties, particularly its strength and ductility, through careful control of deposition and heat treatment procedures (Figure 1).

RESULTS AND DISCUSSION

The solution treatment temperature (relative to the β transus) determines the β -phase content and influences mechanical properties like strength and ductility. STA heat treatment performed slightly above the β transus temperature ($\sim 980^\circ\text{C}$) in the β region or slightly below in the α - β region. Heating above the β transus temperature increases β phase, leading to higher strength but lower ductility. For a balance of strength and ductility, solution treatment is typically done at 20–30°C below β transus, i.e., at $\sim 950^\circ\text{C}$. To retain a high β phase, rapid cooling (e.g., water quenching) is used after solution treatment at 950°C. Rapid quenching is critical for retaining β -phase at room temperature. Aging below 550°C precipitates strengthening phases (Ti_3Al), while higher temperatures mainly reduce residual stresses. Aging at 530°C promotes the precipitation of Ti_3Al particles, enhancing the mechanical properties. Aging at $\geq 600^\circ\text{C}$ primarily serves as a stress-relief treatment and does not precipitate Ti_3Al . Aging below 550°C precipitates strengthening phases (Ti_3Al), while higher temperatures mainly reduce residual stresses.

The tensile properties are shown in table 1. As-deposited Ti-6Al-4V exhibits a yield strength of 807.52 MPa, UTS of 998.37 MPa, and elongation of 8.84%. After STA, the yield strength increased to 812.51 MPa, UTS to 1029.69 MPa, but elongation decreased to 8.38%. This change aligns with the expected increase in strength and slight reduction in ductility due to the preservation of the β phase at room temperature. Both strength properties increase slightly after STA, indicating that the heat treatment has enhanced the material's strength, particularly in terms of UTS. The yield strength and UTS increased by approximately 0.62% and 3.13% respectively after STA treatment. The increase in yield strength and UTS indicates that the STA treatment improved the material's strength, likely due to the precipitation hardening mechanism and the retention of β phase at room temperature. A decrease in elongation by approximately -5.20% after STA treatment is observed, which is typical for materials undergoing solution heat treatment followed by rapid cooling (preserving β phase). The decrease in

elongation aligns with the expected outcome when titanium alloys undergo solution heat treatment, where the material becomes stronger but less ductile. Figure 2 shows the Stress vs. Strain plot of the As-Deposited and STA heat treated Ti-6Al-4V alloy manufactured by WAAM.

Table 1. Tensile Properties of the as-deposited and aged WAAM manufactured Ti-6Al-4V.

Condition	Yield strength (MPa)	Ultimate Tensile strength (MPa)	Elongation (%)
Ref. [11]	820–850	960–980	9–10
As-deposited	807.52	998.37	8.84
STA	812.51	1029.69	8.38
Percentage Change	0.62%	3.13%	-5.20%

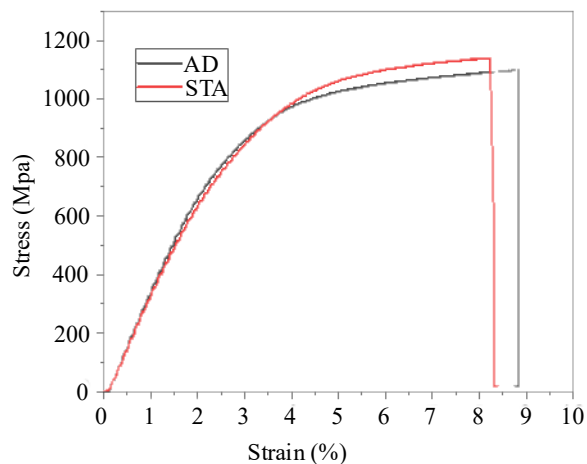


Figure 2. Stress vs. Strain plot of the As-Deposited and STA Ti-6Al-4V alloy manufactured by WAAM.

CONCLUSION

This study provides a detailed explanation of how STA heat treatment affects the microstructure and tensile properties of Ti-6Al-4V alloys deposited by WAAM process, particularly with respect to the β transus temperature and the β phase. Following STA process, the yield strength rose to 812.51 MPa, and the ultimate tensile strength (UTS) increased to 1029.69 MPa, while elongation declined to 8.38%. This behavior is consistent with the anticipated strengthening effect and the modest reduction in ductility, attributed to the retention of the β phase at room temperature. Both yield strength and UTS showed slight improvements after STA, demonstrating that the heat treatment effectively enhanced the material's overall strength, especially the UTS. Specifically, yield strength and UTS improved by about 0.62% and 3.13%, respectively, following the STA treatment. The study emphasizes the interplay between temperature, cooling rate, and aging in controlling the mechanical properties of Ti-6Al-4V alloys. By adjusting the solution heat treatment temperature (especially around 950°C), the strength and ductility of the material can be tailored to meet specific performance requirements, such as achieving high strength with adequate elongation.

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