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INFLUENCE OF WELDING AND HEAT TREATMENT ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF TITANIUM ALLOYS FOR MARINE APPLICATIONS

ВПЛИВ ПАРАМЕТРІВ ЗВАРЮВАННЯ ТА ТЕРМІЧНОЇ ОБРОБКИ НА МІКРОСТРУКТУРУ ТА МЕХАНІЧНІ ВЛАСТИВОСТІ ТИТАНОВИХ СПЛАВІВ ДЛЯ МОРСЬКИХ ЗАСТОСУВАНЬ

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Abstract. Welding of high-strength titanium alloys, particularly Ti-6Al-4V, poses significant challenges in marine engineering and shipbuilding due to the formation of heterogeneous microstructures and anisotropic mechanical properties. This study investigates the combined effects of welding energy, welding speed, and post-weld heat treatment (PWHT) on the microstructural evolution and mechanical performance of Ti-6Al-4V welds. Cross-sectional metallography, scanning electron microscopy (SEM), and stress-strain analysis were used to evaluate the weld zone, heat-affected zone, and base metal, as well as for quantitative assessment of yield strength, plasticity, and strain distribution. Results indicate that high welding energy and rapid cooling promote coarse martensitic α' formation in the fusion zone, increasing initial strength but reducing ductility. PWHT transforms α' into lamellar $\alpha+\beta$, narrows the heat-affected zone, and enhances microstructural uniformity. Mechanical testing results demonstrate that the solution-treated and aged (STA) condition provides a balanced combination of strength (~925–960 MPa) and ductility, with elongation increasing by 20–30% compared to the as-welded samples. Welding speed primarily determines initial microstructural features, whereas PWHT governs plasticity recovery and fatigue resistance.

The study provides the first integrative analysis linking welding parameters, PWHT, microstructural evolution, and mechanical performance in Ti-6Al-4V for marine applications. The findings offer practical guidance for optimizing welding and heat treatment to ensure reliable strength, ductility, and service life of titanium components in shipbuilding and offshore structures. Future research should focus on fatigue behaviour, residual stress management, and integration with additive manufacturing techniques to enhance microstructural control in welded titanium assemblies.

Key words: Ti-6Al-4V; welding parameters; post-weld heat treatment; microstructure; mechanical properties; process optimization; $\alpha' \rightarrow \alpha+\beta$ transformation; fusion zone; heat-affected zone.

Анотація. Зварювання високоміцних титанових сплавів, зокрема Ti-6Al-4V, становить значні труднощі в морській інженерії та суднобудуванні через формування гетерогенних мікроструктур та анізотропних механічних властивостей. У дослідженні

проаналізовано комбінований вплив енергії зварювання, швидкості зварювання та термічної обробки після зварювання (PWHT) на мікроструктурну еволюцію та механічну поведінку Ti-6Al-4V зварних з'єднань. Використовувалися металографічний аналіз поперечного перерізу, скануюча електронна мікроскопія (SEM) та аналіз напружень і деформацій для оцінки зони зварювання, зони термічного впливу та основного металу, а також кількісної оцінки межі текучості, пластичності та розподілу деформацій. Результати показують, що висока енергія зварювання та швидке охолодження сприяють утворенню грубих мартенситних α' у зоні зварювання, що підвищує початкову міцність, але знижує пластичність. PWHT трансформує α' у ламелярну структуру $\alpha+\beta$, звужує зону термічного впливу та підвищує мікроструктурну однорідність. Механічні випробування свідчать, що стан розчинного відпалу та старіння (STA) забезпечує збалансоване поєднання міцності (~925–960 МПа) і пластичності, при цьому відносне подовження зростає на 20–30% порівняно зі зварними зразками без термічної обробки. Швидкість зварювання визначає початкові мікроструктурні особливості, тоді як PWHT регулює відновлення пластичності та стійкість до втоми.

Дослідження надає перший інтегративний аналіз взаємозв'язку параметрів зварювання, PWHT, мікроструктурної еволюції та механічної поведінки Ti-6Al-4V для морських застосувань. Отримані результати пропонують практичні рекомендації щодо оптимізації зварювання та термічної обробки для забезпечення надійної міцності, пластичності та довговічності титанових компонентів у суднобудуванні та нафтогазових морських конструкціях. Подальші дослідження повинні зосередитися на поведінці при втомі, керуванні залишковими напруженнями та інтеграції технологій адитивного виробництва для покращення контролю мікроструктури зварних титанів.

Ключові слова: Ti-6Al-4V; параметри зварювання; післязварювальна термічна обробка; мікроструктура; механічні властивості; оптимізація процесу; перетворення $\alpha' \rightarrow \alpha+\beta$; зона зварного шва; зона термічного впливу.

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Problem Statement. Titanium alloys, especially Ti-6Al-4V, are widely employed in aerospace, biomedical, and industrial applications due to their high specific strength, corrosion resistance, and biocompatibility. In addition to these sectors, welded titanium alloys are increasingly considered for marine and offshore structures, where high corrosion resistance, damage tolerance, and strength-to-weight efficiency are critical for long-term structural integrity. Welding and welding-based additive processes, such as wire arc additive manufacturing (WAAM), are essential technologies for producing and joining titanium components. However, the welding of titanium alloys is inherently challenging because of their strong affinity to atmospheric gases, the risk of brittle intermetallic phase formation, and the development of residual stresses. These factors significantly affect the microstructure, defect formation, and mechanical properties of welded joints [1].

Recent reviews have demonstrated that welding parameters, including heat input, welding speed, shielding conditions, and cooling rate, exert a decisive influence on grain morphology, phase transformations, and tensile performance of titanium alloys [2–4]. Variations in thermal cycles during welding often lead to pronounced microstructural heterogeneity between the fusion zone, heat-affected zone, and base metal, resulting in anisotropic mechanical behaviour and reduced structural reliability. To address these issues, post-weld heat treatment (PWHT) has been increasingly investigated as an effective strategy for relieving residual stresses, reducing anisotropy, and improving ductility and service performance of welded titanium structures [3].

Despite substantial progress, the reported effects of PWHT remain highly dependent on the initial welding conditions, alloy composition, and applied thermal regimes. Grain coarsening, in-

complete decomposition of martensitic α' phase, and the persistence of microstructural gradients across the welded joint continue to limit fatigue resistance and damage tolerance. Furthermore, process parameters such as heat input and welding speed strongly influence defect formation, including porosity, lack of fusion, and microcracking, which cannot always be fully mitigated by subsequent heat treatment [4].

For marine engineering and shipbuilding-related applications, where welded joints are frequently subjected to cyclic loading, variable thermal exposure, and aggressive environments, the absence of a unified framework linking welding parameters, post-weld heat treatment, and resulting structure–property relationships presents a significant challenge. Current studies tend to address individual aspects of welding or heat treatment in isolation, while a systematic analytical synthesis of their combined influence on microstructural evolution and mechanical behaviour remains limited [5].

Therefore, there is a clear need for a comprehensive analytical assessment that correlates welding parameters and post-weld heat treatment conditions with microstructural development and mechanical response of Ti-6Al-4V alloys. Such an approach provides a scientific basis for defining optimal processing windows and improving the reliability and performance of welded and additively manufactured titanium components intended for demanding structural applications.

Analysis of Recent Research and Publications. Titanium alloys, particularly Ti-6Al-4V, are widely used in aerospace, biomedical, and industrial applications due to their high strength-to-weight ratio, corrosion resistance, and biocompatibility. Welding and subsequent post-weld heat treatment (PWHT) significantly influence their microstructure and mechanical performance. Contemporary studies have provided valuable insights into the relationships

between welding parameters, PWHT, and the resulting properties of Ti-6Al-4V joints.

In the study by Springer (Yu Lu, 2024), the impact of PWHT on electron beam welded joints was investigated. The study demonstrates that controlled heat treatment promotes the decomposition of martensitic α' into equilibrium $\alpha + \beta$ phases, refines grain morphology, and reduces residual stresses, thereby enhancing tensile strength and ductility [6].

Taylor & Francis (Vamsi Krishna K., 2023) evaluated how variations in welding speed combined with PWHT affect grain size, phase distribution, and defect formation. Results indicate that optimized welding parameters together with appropriate heat treatment improve both fatigue resistance and impact toughness, illustrating the critical interplay between process parameters and post-processing [7].

MATEC (2020) explored localized PWHT via a defocused laser, demonstrating effective stress relief and partial decomposition of α' martensite. The study emphasizes the importance of controlled heat input and its effect on microstructural uniformity and mechanical performance [8].

ScienceDirect (2020) examined the influence of different PWHT regimes on hardness, tensile strength, and ductility. The findings confirm that proper selection of PWHT parameters significantly enhances mechanical properties of welded joints, highlighting the potential of heat treatment to mitigate adverse effects of welding [9].

MDPI (2024) investigated the effect of various heat treatment temperatures on the phase composition and mechanical properties. The study demonstrates that controlled thermal cycles allow optimization of α/β phase distribution, leading to improved performance in welded components [10].

Recent research has predominantly focused on the welding behaviour and post-weld heat treatment of titanium alloys, particularly Ti-6Al-4V, due to its widespread use in aerospace and biomedical applications (Yu Lu et al., 2021; Ferro, 2019) [6, 9]. These works clearly demonstrate that post-weld heat treatment (PWHT) can significantly refine the microstructure, reduce residual stresses, and enhance mechani-

cal properties. Complementary investigations into related alloy systems further highlight the importance of process selection and microstructural control. For instance, Tolvanen et al. (2025) [12] systematically studied Ti-6Al-4V welds produced using different welding and additive processes. The authors investigated how process route influences fusion zone morphology, phase distribution, and mechanical performance, providing the first comparative insight into process-dependent microstructural evolution and its effect on tensile and fatigue behaviour. This study demonstrates that selecting appropriate welding or additive manufacturing techniques is critical for achieving a balanced combination of strength, ductility, and structural integrity in titanium components.

Together, these insights underline that both process parameters and subsequent heat treatment strategies must be carefully controlled to achieve optimal microstructural stability and performance in welded titanium structures.

Collectively, these studies provide a detailed understanding of how welding parameters and PWHT affect the microstructure and mechanical behavior of Ti-6Al-4V alloys. While substantial progress has been made, existing literature indicates a need for further systematic analyses of combined welding and heat treatment effects to define optimal process windows. Such work is essential for producing high-performance, reliable titanium components across aerospace, biomedical, and industrial applications.

Unresolved Issues in the Field. Despite significant progress in understanding welding and post-weld heat treatment (PWHT) of Ti-6Al-4V, several critical challenges remain. Microstructural heterogeneity between the fusion zone, heat-affected zone, and base metal often leads to anisotropic mechanical properties and reduced structural integrity. Control of grain coarsening and formation of brittle phases in the HAZ is still difficult, affecting fatigue performance.

Furthermore, variations in welding energy, speed, and shielding conditions strongly influence defect formation, including porosity, lack of fusion, and microcracks. While PWHT can mitigate residual stresses and improve ductili-

ty, its effectiveness varies with thermal history, alloy composition, and process parameters, and systematic guidelines are lacking.

These unresolved issues indicate the need for integrated studies linking welding conditions, PWHT, and resulting microstructure–property relationships, particularly for applications requiring high reliability such as marine and aerospace structures.

Research Objective. The study aims to systematically analyse the influence of welding parameters and post-weld heat treatment (PWHT) on the microstructure and mechanical properties of Ti-6Al-4V alloys. Special focus is placed on understanding how fusion zone, heat-affected zone, and base metal evolve under different welding energies and thermal cycles, and how these microstructural changes affect strength, ductility, and overall performance. The ultimate goal is to provide a scientific framework for optimizing welding and PWHT strategies, with relevance to high-performance applications, including marine and aerospace engineering.

Methods, Object, and Subject of Study.

The study focuses on the microstructural evolution and mechanical behaviour of Ti-6Al-4V titanium alloy subjected to electron beam welding (EBW) and subsequent post-weld heat treatments (PWHT). The primary objective is to analyse the influence of welding parameters and thermal processing on phase transformations, grain morphology, and stress–strain response.

Experimental data were drawn from recent peer-reviewed investigations [6,7], providing cross-sectional metallography, scanning electron microscopy (SEM), and tensile testing results. The subject of the study includes the fusion zone (FZ), heat-affected zone (HAZ), and base metal (BM) of EBW Ti-6Al-4V welds under as-welded, aged, and solution-treated aged (STA) conditions.

The methodological approach integrates microstructural characterisation with thermodynamic modelling using the JMatPro database to interpret mechanical trends, allowing a systematic assessment of process–structure–property relationships without presenting new experimental data.

Main Material. The present section presents the main observations on the influence of welding parameters and post-weld heat treatment (PWHT) on the microstructure and mechanical behaviour of Ti-6Al-4V alloy, based on recent studies [6, 7].

Metallographic Characterisation of Weld Zones

Cross-sectional analysis of electron beam welded (EBW) Ti-6Al-4V revealed distinct regions: the fusion zone (FZ), heat-affected zone (HAZ), and base material (BM). Representative cross-sections at different welding energy densities (28 J/mm and 10 J/mm) and PWHT treatments demonstrated full weld penetration and defect-free geometry. Higher energy input produced wider and deeper weld pools, while PWHT did not significantly alter weld shape due to the solidification-fixed pool geometry (Fig. 1) [6].

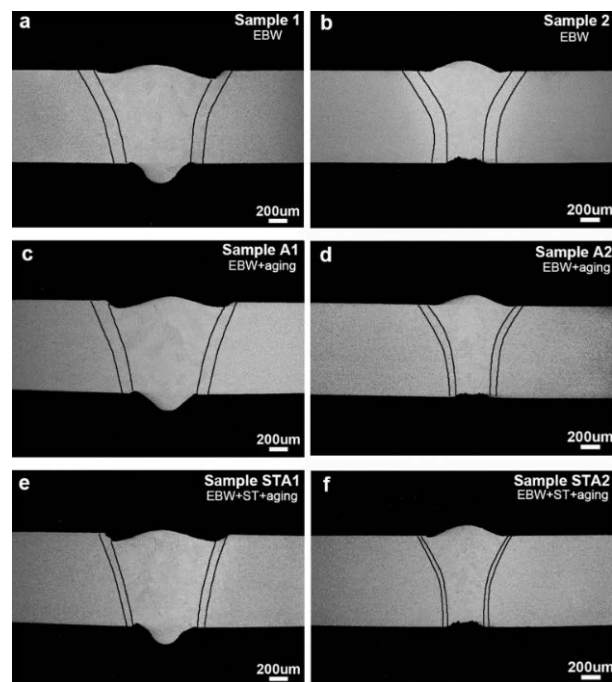


Fig. 1. Cross-sectional metallographic characterisation of EBW Ti-6Al-4V welds produced at different energy densities (28 J/mm and 10 J/mm) in the as-welded and PWHT conditions. Adapted from Yu Lu et al. (2023) [6]

Thermal cycling during PWHT contributed to stress relaxation and refinement of the HAZ. In solution-treated and aged (STA) samples, the HAZ width decreased, indicating improved microstructural homogeneity. Welding energy defined initial microstructural gradients, while PWHT promoted stress relief and phase stabilization [6, 7].

Microstructural Evolution in Different Weld Zones.

SEM analysis showed that the as-welded FZ contained coarse columnar β grains with fine martensitic α' laths. PWHT facilitated their transformation into a lamellar $\alpha+\beta$ structure. The HAZ experienced partial decomposition of metastable β into $\alpha+\beta$, and the BM retained a bimodal $\alpha+\beta$ microstructure. Microstructural differences were strongly influenced by both welding energy and PWHT. Representative micrographs of the FZ before and after PWHT are reported in the literature [7] but are not included here.

Mechanical Behaviour.

The mechanical response of EBW Ti-6Al-4V under different PWHT conditions was assessed experimentally and compared with thermodynamic predictions from JMatPro [6]. Stress-strain curves highlight the effect of PWHT on mechanical behaviour, showing increased ductility and moderated strength in solution-treated and aged conditions.

Mechanical behaviour and thermodynamic predictions.

The mechanical behaviour of electron beam welded Ti-6Al-4V under different post-weld heat treatment conditions reflects the combined influence of welding parameters and subsequent thermal processing. Experimental stress-strain curves obtained for the as-welded, aged, and solution-treated aged (STA) conditions reveal that heat treatment significantly affects the balance between strength and ductility, while noticeable differences between individual welds are also observed (Fig. 2).

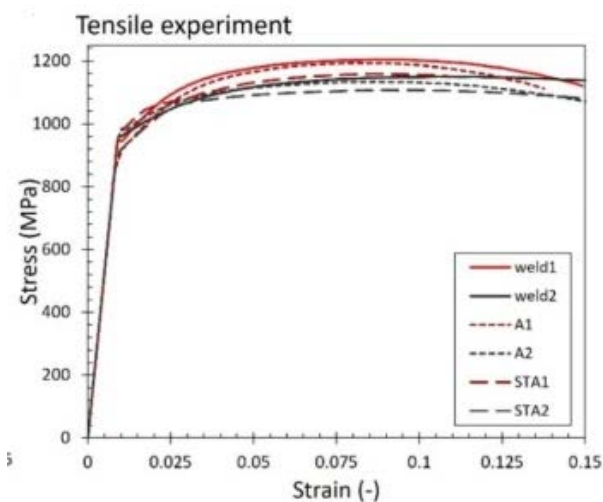


Fig. 2. Experimental stress-strain curves of electron beam welded (EBW) Ti-6Al-4V in the as-welded, aged, and solution-treated aged (STA) conditions at room temperature (strain rate 10^{-3} s^{-1}). Adapted from [6]

Comparative analysis reported in the original study indicates that thermodynamic predictions using the JMatPro database capture the general trend of yield strength evolution with PWHT; however, deviations between predicted and measured responses increase for welds produced under different thermal histories. In particular, the experimental data demonstrate that variations in weld thermal cycles exert a stronger influence on the stress-strain behaviour than heat treatment alone, suggesting that microstructural features formed during welding, such as grain size and cooling-rate-dependent transformations, play a decisive role in determining mechanical performance.

Variations in welding speed also affected yield strength and ductility. Welds produced at lower energy density displayed higher strength but lower ductility, while PWHT partially restored plasticity by relieving internal stresses and stabilising the $\alpha+\beta$ microstructure. These trends demonstrate that weld thermal history has a stronger influence on mechanical performance than PWHT alone. Stress-strain behaviour as a function of welding speed and PWHT is illustrated in Fig. 3 [7].

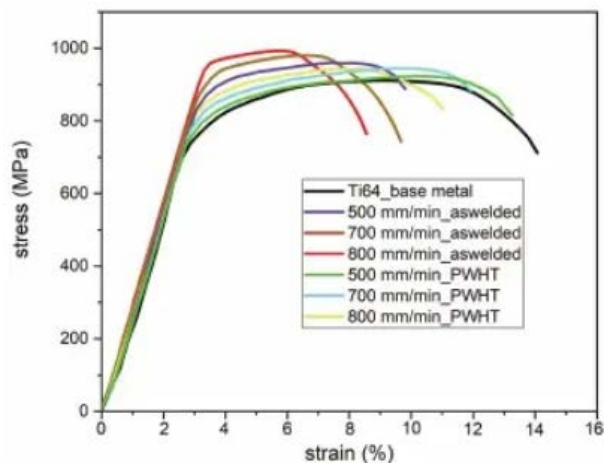


Fig. 3. Stress-strain curves of Ti-6Al-4V welds at different welding speeds and PWHT conditions (adapted from Krishna et al., 2023) [7]

Results and Discussion

1. Microstructural Evolution in Welded and Heat-Treated Ti-6Al-4V

Cross-sectional metallography and SEM analyses indicate pronounced heterogeneity between the fusion zone (FZ), heat-affected zone

(HAZ), and base metal (BM) in electron beam welded Ti-6Al-4V [6,7]. In the as-welded state, the FZ exhibits coarse columnar β grains containing fine martensitic α' laths, while the HAZ shows incomplete $\beta \rightarrow \alpha$ transformation with metastable β and fine α precipitates. Post-weld heat treatment (PWHT) promotes the decomposition of α' into lamellar $\alpha + \beta$ structures, reduces HAZ width, and equilibrates phase distribution. The BM evolves into a bimodal $\alpha + \beta$ microstructure, reflecting improved phase balance and structural stability.

These trends are consistent across independent studies [6,7]. Optimized PWHT reduces anisotropy and suppresses excessive grain coarsening, resulting in more uniform microstructural features throughout the weld. The combination of controlled welding energy and heat treatment is critical for achieving a balanced α/β ratio and enhancing weld integrity.

2. Mechanical Performance under As-Welded and PWHT Conditions

Mechanical testing shows that as-welded specimens possess high yield strength (~ 970 MPa) but limited ductility due to the dominance of martensitic α' [6]. Aging treatments reduce yield strength slightly (~ 950 – 960 MPa) while improving strain accommodation, whereas solution-treated and aged (STA) specimens demonstrate lower yield (~ 925 MPa) but the most balanced strength–ductility profile. Stress–strain curves also reveal that welds produced at lower energy input or slower speed display higher ductility at the expense of ultimate tensile strength, confirming the critical influence of solidification dynamics and cooling rate on mechanical behaviour [7]. PWHT consistently enhances ductility and relieves residual stresses, although its effect on strength is moderate. Welding parameters primarily govern initial microstructural refinement and defect distribution, while PWHT fine-tunes mechanical performance through phase transformation and stress relief.

3. Comparative Assessment. Integration of microstructural and mechanical evidence confirms a clear relationship between welding parameters, PWHT regimes, and performance. High energy density and rapid cooling favor α'

formation, maximizing strength but reducing ductility. PWHT induces $\alpha' \rightarrow \alpha + \beta$ transformation, narrows HAZ, and stabilizes the microstructure, improving plasticity and fatigue resistance. The most homogeneous microstructure and stable mechanical response are achieved under STA conditions.

These findings highlight that optimal mechanical performance in EBW Ti-6Al-4V is attained through careful control of welding speed, energy input, and subsequent heat treatment. The results provide a practical framework for designing welding and post-weld processing strategies in aerospace, marine, and other high-performance engineering applications.

Conclusions

1. Welding parameters and post-weld heat treatment (PWHT) critically influence the microstructure and mechanical performance of Ti-6Al-4V, with high welding energy promoting coarse martensitic α' formation, increasing strength but limiting ductility.

2. PWHT transforms α' into lamellar $\alpha + \beta$, narrows the heat-affected zone, and stabilizes the base metal, resulting in a more homogeneous microstructure and improved mechanical balance.

3. Mechanical testing demonstrates that PWHT enhances ductility and toughness while moderately reducing strength, whereas welding speed and energy primarily define initial microstructural features.

4. Optimized combinations of welding conditions and PWHT enable a balanced trade-off between strength and ductility, providing a reliable framework for Ti-6Al-4V components in marine engineering and shipbuilding applications.

5. These findings extend previous knowledge by quantitatively linking microstructural evolution to mechanical response under conditions relevant for marine infrastructure, supporting predictive design of welded titanium structures.

6. Future work should explore scale-up and fatigue performance under service-like marine conditions to further validate welding and PWHT strategies for high-performance maritime components.

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