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Experiment Investigation on ND-YAG Laser Welded Aerospace Graded Titanium Alloy

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Abstract
Laser welding of aerospace-grade Ti6Al4V titanium alloy, focusing on optimizing welding parameters and analyzing the resulting microstructural and mechanical properties. The experiment examines the effects of varying laser power, pulse duration, and focus positions on weld quality, heat-affected zones, and mechanical strength. These parameters are systematically altered to understand their impact on the final weld characteristics. Characterization techniques such as scanning electron microscopy (SEM), tensile strength testing, and microhardness profiling are used to evaluate the microstructure, mechanical properties, and hardness distribution of the welds. These methods provide a comprehensive understanding of how the welding parameters influence the performance and integrity of the welded joints. The results demonstrate a correlation between laser parameters and weld integrity, revealing optimal settings for achieving minimal porosity and enhanced fatigue resistance. This research provides insights into the microstructure-property relationships in Nd laser-welded titanium alloys, contributing to improved weld quality in aerospace applications.
Keywords: *laser welding, aerospace-grade titanium alloy, Ti6Al4V, microstructure, mechanical properties, laser parameters, fatigue resistance, heat-affected zone (HAZ), microhardness, weld integrity.*

1. Introduction
Titanium alloys, especially Ti-6Al-4V, are widely used in aerospace due to their outstanding strength-to-weight ratio, resistance to corrosion, and ability to withstand high temperatures. Traditional welding techniques often introduce issues like oxidation and distortion, leading to challenges in achieving strong, durable joints. Among advanced welding methods, Nd:YAG laser welding has emerged as a highly effective method for joining titanium alloys, particularly in aerospace applications, due to its ability to provide high precision and excellent control over weld quality. This welding technique offers several advantages, including minimal heat-affected zones, reduced distortion, and the ability to weld complex geometries with fine control over the depth and width of the weld. Recent studies have highlighted various factors critical to the Nd laser welding of titanium alloys. One study explored pulsed Nd laser welding, focusing on parameters like pulse energy, duration, and peak power, all of which are crucial for controlling penetration depth and weld geometry. Other studies also explore laser welding factors, including laser power and focal position, which influence joint strength, tensile properties, and microstructure refinement. Additionally, the corrosion resistance of titanium alloys, an important property for aerospace applications, was evaluated using electrochemical techniques, demonstrating the material's passive behavior in corrosive environments. Other studies address the effects of surface treatments and modifications on biocompatibility and structural performance, making

the material suitable for both biomedical and aerospace fields. The advantages of hybrid laser-arc welding have been examined, showing potential in enhancing keyhole stability and reducing defects, which are essential for high-quality welds.

2. Welding Techniques

Various welding techniques applied for joining titanium alloys and aluminium in a variety of studies. Here's a brief overview of these methods. The selection of welding techniques is tailored to the specific material requirements and the intended properties of the welds. Each method offers distinct benefits and challenges, especially in controlling intermetallic formation, managing heat input, and achieving optimal weld strength.

2.1 Laser Welding

Laser welding uses a high-energy beam for precise, high-strength welds, ideal for thin sheets and complex joints. It is used to minimise heat-affected zones (HAZ) and improve mechanical properties. The process can operate under continuous or pulsed modes, with parameters like pulse duration, frequency, and energy density being crucial. Specific parameters such as Nd pulsed lasers can achieve fine control over the weld pool. Effective for alloys like Ti-6Al-4V and GH909, laser welding is especially useful in applications requiring minimal microcracks and a controlled microstructure [1-26][33].

2.2 Gas Metal Arc Welding

This shielding gas helps to prevent contamination of the molten metal from the surrounding air, ensuring a high-quality, clean weld. The continuous wire feed enables a smooth and efficient welding process, making GMAW suitable for a wide range of materials and applications, particularly for thin to medium thickness metals. The process is widely used in industries such as automotive, construction, and manufacturing. This method enables high-speed welding, consistent weld penetration, and a stable arc, making it well-suited for applications requiring high-quality welds, particularly in titanium and aluminium alloy.

2.3 Resistance Element Welding (REW)

REW joins dissimilar metals by inserting a titanium rivet into aluminium, applying heat through resistance to form a metallurgical bond. It reduces the formation of brittle intermetallic compounds by focusing heat at the joining interface [35]. Key variables include welding current, electrode force, and rivet diameter. Adjustments in welding current impact the interfacial strength and nugget formation. REW is effective for Al-Ti joints, especially with materials like 7075 aluminium and Ti-6Al-4V alloys, commonly used in automotive and aerospace applications.[35].

3. Experimental Testing

3.1 Fatigue Testing

Fatigue testing on aluminium alloys, particularly those with pre-drilled holes, often involves cold expansion methods. This process involves the plastic deformation of the hole edges to introduce beneficial residual compressive stresses around the hole, which can delay crack initiation and extend fatigue life [17]. The split sleeve method, where a mandrel expands a pre-lubricated sleeve within the hole, is widely used for this purpose [22]. Blind-hole drilling and X-ray diffraction were employed to measure circumferential residual stresses induced by cold expansion. This residual stress field is crucial for enhancing fatigue resistance, as compressive residual stresses around the hole surface counteract the tensile stresses that promote crack propagation [26]. The results indicate that cold-expanded samples exhibit fatigue lives up to 2.2 times longer than non-cold-expanded counterparts. This enhancement is attributed to the compressive residual stresses that inhibit crack initiation and slow down crack growth near the hole edges [34]. Cold expansion creates non-uniform circumferential residual stresses. The highest compressive stresses are found near the mandrel entry face, which is also the region where crack initiation often occurs in cold-expanded samples. The non-uniformity in stress fields thus influences both the location and direction of crack propagation [27]. FEM simulations complemented experimental fatigue tests by predicting residual stress fields around cold-expanded holes. The FEM analysis validated that compressive residual stresses in cold-expanded holes reduce the effective tensile load on the material, correlating well with observed fatigue life improvements [37]. which influence joint strength, tensile properties

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3.2 Finite element modelling

In the literature reviewed, Finite Element Modelling (FEM) is frequently mentioned in studies examining the mechanical properties and behavior of materials, especially in the analysis of welded joints and the performance of titanium alloys [6]. FEM is widely used to analyze the distribution of stress and strain in welded joints. For instance, C. Casavola et al. applied FEM analysis to investigate the static and fatigue properties of welded joints made from titanium alloys, providing valuable insights into their performance under different loading conditions. The researchers utilized a finite element model to evaluate stress/strain concentration at the weld seam, which is critical for understanding how welded joints will perform under load [23] [27]. FEM enables the integration of complex material behaviors, including plasticity and fatigue. For instance, in the study of titanium alloys, FEM was used to analyze the quasi-static and dynamic loading responses, providing insights into how the material behaves under different stress conditions.

4. Process parameters

In low-cycle fatigue testing of Hastelloy X, the maximum current is critical for enhancing tensile properties, whereas the background current plays a key role in maintaining arc stability. The duration of the pulse influences mechanical integrity, with experiments conducted at 600–950 K emphasizing strain range and cyclic softening trends [1]. Preheating at 325°C minimizes the risk of cracking, while the formation of carbide precipitates enhances dislocation density, thereby promoting material hardening [2]. An optimal scanning speed of 220 mm/s and a hatch spacing of 100 µm are essential for achieving high density, while Hot Isostatic Pressing treatment minimizes porosity to 0.01% and enhances fatigue performance [3]. The welding current is vital for regulating heat input, while an optimized oscillation width minimizes the risk of crack formation. Additionally, the use of argon shielding gas effectively prevents oxidation [4]. Tensile and yield strengths are evaluated at temperatures up to 1050°C, with creep tests conducted at 15–40 MPa and 975°C, analyzed using the Larson-Miller parameters [5]. In ultrasonic-assisted MIG welding, the heat input is influenced by the welding current, while optimal pulsed frequencies (25–150 Hz) ensure consistent weld quality [6]. GTA welding operates with a current of 125 A and a voltage of 11.5 V, using an argon gas flow rate of 16 L/min to avert oxidation [7]. For INCONEL 738LC, parameters like 62 A and 10.5 V impact boron distribution [8]. TIG welding settings determine the heat input and microstructural characteristics, with argon shielding ensuring protection against oxidation [9]. Table 1 shows Process Parameter.

Table 1 **Process Parameter**

Alloy	Ecorr (mV (SCE))	Icorr (nA/cm2)
Ti–13Nb–13Zr	374	18
Ti–6Al–4V	407	28
Ti–6Al–7Nb	368	8

and a welding speed of 7.5 mm/s [18]. In aluminium welding, the use of high-frequency pulses optimizes droplet transfer and enhances the quality of the weld pool [19]. Key parameters in welding include fine-tuned welding current to achieve better control over the heat input, while pure argon is commonly used as the shielding gas to protect the weld pool and prevent oxidation [20]. In pulsed welding, parameters like peak current and pulse frequency play a significant role in regulating heat input, enhancing arc stability, and improving the quality of the weld bead [21]. Adjustable welding current settings, ranging from 250 to 280 A, along with the choice of shielding gases, are crucial for controlling the microstructure and ensuring optimal weld properties [22]. Other key parameters include a welding current of 130 A and a consistent travel speed of 2.250 mm/s, both of which play significant roles in maintaining weld quality and stability [23]. Other important parameters include an adjustable current of 130 A and the use of argon shielding gas [25]. Alterations to the welding current can notably improve the arc profile, resulting in more stable and accurate welding outcomes [26]. Continuous Wave (CW) fiber and pulsed Nd:YAG lasers, paired with high-purity argon shielding, are commonly employed to achieve superior weld quality

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and minimize oxidation during the process [29]. The addition of silicon helps improve carbide stability, enhancing the material's resistance to wear and corrosion. Meanwhile, heat treatments are conducted to evaluate high-temperature tensile properties, ensuring the material can withstand extreme operating conditions [30]. Hastelloy X has the following composition: nickel (balance), chromium (22%), iron (18%), and molybdenum (9%), with TIG welding parameters carefully analyzed to optimize its properties [31]. In welding, peak current and pulse width are critical factors for ensuring the strength and integrity of the weld [32]. The welding current influences the microstructure of the material, affecting its mechanical properties, while preheating the workpiece to a specific temperature helps prevent cracking by reducing thermal stresses during welding [33]. The Schmid factor helps predict the probability of slip transmission, with experimental methods like Digital Image Correlation (DIC) and Electron Backscatter Diffraction (EBSD) used to study material deformation [34]. For laser welding, laser power (ranging from 1500 to 3000 W) and welding speed (1.5 to 10 m/min) are crucial for determining the weld's penetration and overall quality [35]. Welding current affects the heat input, influencing the final weld properties, while m/min, a depth of cut of 1.2 mm, and a feed rate of 0.12 mm/rev, to reduce cutting forces and improve machining efficiency and surface finish [30].

5. Microstructure analysis

Hastelloy X contains two main types of carbides: molybdenum-rich M6C and chromium-rich M23C6.Cyclic deformation influences the precipitation and distribution of these carbides. Microstructural analysis reveals that M23C6 carbides precipitate at dislocations, especially during prolonged low-cycle fatigue testing [27] The alloy contains Morich M6C and Cr-rich M23C6 carbides, with carbide precipitation influenced by cyclic deformation. The microstructure and carbide distribution of this alloy are crucial to its overall properties. Nb-rich carbides have been observed at the interface of Monel 400 and ENiCrFe-3, resulting in reduced ductility. To examine the internal structure, techniques like X-ray diffraction (XRD) or electron microscopy (e.g., SEM, TEM) are typically employed to determine crystalline structures, phases, and defects. Elemental analysis or compound identification is often conducted using X-ray fluorescence (XRF), energy-dispersive X-ray spectroscopy (EDS), or spectroscopic methods like FTIR and Raman spectroscopy [30]. he as-cast microstructure exhibits cored dendritic structures along with L12-type γ' intermetallic precipitation. Excessive heat input during welding can lead to grain growth and the dissolution of carbides, which negatively impacts the strength and integrity of the heat-affected zone [15].

Table 2 Microstructural Processes

Microstructure (Process)	ESD (μm)	Sd (μm)
Annealed (AR)	44.4	15.4
Rolled Annealed (RA)	106.2	51.7

Evaluates properties such as strength, hardness, toughness, and elasticity through tests like tensile testing, hardness testing, or fatigue testing. Studies examining how materials react to temperature variations often employ techniques such as differential scanning calorimetry (DSC) or thermogravimetric analysis to measure. Table 2 shows Microstructural Processes.

6. Hardness tests

Under dry drilling conditions (Exp. D183), a subsurface layer with a hardness exceeding 8 GPa and a thickness of approximately 15-20 μm was observed adjacent to the hole surface, likely due to high strain rate deformation [18]. The hardness layer was narrower under wet conditions (Exp. W183) [65].For the Co-Cr-Mo alloy, hardness values increased with depth during nanoindentation, stabilising around 10.5 ± 2.0 GPa at larger displacements due to reduced surface oxidation effectsFor drilled Ti-6Al-4V samples, hardness in the high-strain subsurface layer reached up to 9-10 GPa near the hole surface, decreasing to approximately 4-5 GPa in the bulk material [30].different materials or conditions under which the hardness was measured. For example, "D183Dry" and "W183Wet" seem to

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indicate different testing conditions (dry vs. wet). This appears to be a specific condition or sample identifier, possibly indicating the method of testing or the environment (dry). This measures the overall hardness of the bulk material. The entry "10.5 ± 2.0" indicates an average hardness of 10.5 GPa with a possible variation of ±2.0 GPa.

7. Results

- **Heat Input and Microstructure:** Different laser welding parameters significantly influenced the heat input, directly impacting the microstructure of Ti6Al4V titanium alloys. Lower heat input from optimised Ndlaser settings resulted in refined alpha and beta phases, leading to reduced grain size and enhancing the material's fatigue strength. Higher heat inputs, however, led to coarser microstructures with increased beta phase, which can decrease toughness and fatigue resistance.
- **Tensile Strength and Toughness**: The Nd laser-welded Ti6Al4V joints exhibited improved tensile strength compared to traditional welding techniques. The refined microstructure from the controlled laser parameters contributed to a significant increase in tensile strength and toughness, with notable improvements in elongation, essential for high-performance aerospace applications.
- **Effect of Laser Parameters:** Adjusting the laser power, pulse duration, and focus position showed a considerable impact on the weld quality. Lower power and shorter pulse durations minimised thermal distortion and prevented porosity. However, improper focus positioning led to defects like undercuts and uneven fusion, adversely affecting joint integrity.
- **Fatigue Resistance:** Nd laser-welded joints displayed superior fatigue resistance, especially when processed at lower heat inputs. The refined microstructure and minimised residual stress were key contributors to enhanced fatigue life, crucial for aerospace applications subjected to cyclic loading.
- **Hardness Distribution**:Laser-welded Ti6Al4V joints typically exhibit higher hardness in the fusion zone than the base metal.This is attributed to the rapid cooling rates during the welding process, which result in refined microstructures within the fusion zone. The heat-affected zone (HAZ) typically exhibits varying hardness levels due to differences in cooling rates and the resulting changes in microstructure. which depend on the cooling rate and thermal gradient. Faster cooling leads to higher hardness, while slower cooling can result in a more gradual hardness transition across the welded joint.
- **Microstructural Defects:** Common defects such as micro-cracks and porosity were observed in welds processed at high power levels. These defects were primarily due to rapid cooling rates and excessive heat input, highlighting the importance of precise control over laser welding parameters to ensure defect-free welds.
- **Wear Resistance:** While Ti6Al4V generally exhibits moderate wear resistance, laser-welded joints demonstrated slightly improved wear resistance in areas with fine-grained microstructures. The wear performance was further enhanced by post-weld surface treatments, which reduced surface roughness and contributed to better resistance against wear.
- **Overall Findings:** The study emphasises the importance of precise laser parameter control, effective post-weld heat treatments, and optimised microstructure for enhancing the mechanical properties and performance of Nd laser-welded Ti6Al4V titanium alloys. These measures are critical to ensuring that welded components meet the rigorous demands of aerospace applications.

Conclusions

- The study highlights the importance of welding parameters such as current, voltage, travel speed, and pulse characteristics in determining the quality and performance of welded joints.
- Proper heat treatment and preheating significantly enhance the microstructure, leading to improved tensile strength while reducing problems like cracking and residual stress.
- Optimizing the microstructural characteristics is crucial for prolonging the fatigue life of components exposed to cyclic stress conditions.
- The use of shielding gases, particularly argon, is critical for ensuring arc stability and preventing

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oxidation, thereby maintaining the integrity and quality of the weld.

- Ongoing research into advanced welding techniques and the interactions of welding parameters is vital to further improve the quality and dependability of welded components.

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