A Comprehensive Feasibility Investigation of Titanium–Stainless Steel Dissimilar Welding Using Electron Beam Welding with Multiple Filler/Interlayer Materials

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***Abstract*—The primary goal of this research project is to determine whether electron beam welding (EBW) can successfully join the titanium alloy Ti-6Al-4V with austenitic stainless steels 304L and 316L using various filler materials, particularly nickel (Ni), copper (Cu), and vanadium (V). Due to their significant differences in melting temperature, thermal conductivity, and chemical affinity—all of which can result in the formation of brittle intermetallic compounds—dissimilar metal welding between titanium and stainless steel is extremely difficult. In order to create joints with dependable mechanical performance, it is crucial to choose the right filler materials and optimize the welding parameters. The purpose of this study is to examine the effects of each filler material on the morphology of the weld beads, the evolution of the microstructure, and the overall integrity of the weld when high-strength application requirements are met. With its narrow heat-affected zone, high energy density, and deep penetration capability, electron beam welding offers a promising method for creating high-quality dissimilar welds with little distortion. In order to determine phase formation, grain behavior, and elemental distribution throughout the fusion zone and heat-affected regions, a thorough microstructural characterization will be conducted using optical microscopy, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS). The performance of the joints made with Ni, Cu, and V fillers will be assessed mechanically using tensile strength, hardness profiling, and bend tests. The findings will assist in determining the best filler material to use in order to achieve strong, flawless Ti-6Al-4V to stainless steel welds. The project's ultimate goal is to gain a thorough understanding of filler metal interaction, weldability problems, and performance results. This will help with high-strength engineering, aerospace, and biomedical applications where dissimilar metal joining is essential.**

***Index Terms*—mechanical characteristics, residual stress, titanium alloy, Ti-6Al-4V titanium alloy, commercial grade titanium, stainless steel.**

I. INTRODUCTION

Electron beam machining (EBM) is a transformative technology in the field of manufacturing. EBM provides a non-contact process that greatly reduces damage and thermal distortion. Another important technology is electron beam melting (EBM), which is used by the aerospace industry to manufacture lightweight parts with complex geometries. The advanced manufacturing method improves design flexibility and ultimately reduces the heat-affected zone during part manufacturing, maintaining component performance and structural integrity (4-8). The EBM process enables engineers to fabricate components that are reliable and efficient, as well as specifically engineered to meet requirements associated with the high demands of modern aerospace applications. This capability is essential in order to ensure the life of critical components. In the medical field, laser beam melting (LBM) promotes the safe and accurate fabrication of complex implants and medical devices while ensuring patient safety and biocompatibility. The scheme of the EBW of CP-Ti and Ti64 plates is presented in Figure 1.[3]

Aerospace, nuclear, chemical processing, and biomedical engineering heavily utilize titanium and stainless steels because of their excellent mechanical properties and resistance to corrosion. However, titanium and stainless alloys cannot be directly joined because of their chemical incompatibility. Consequently, brittle Ti–Fe intermetallic (TiFe, $TiFe_2$)

are created, severely reducing ductility and toughness of joints.

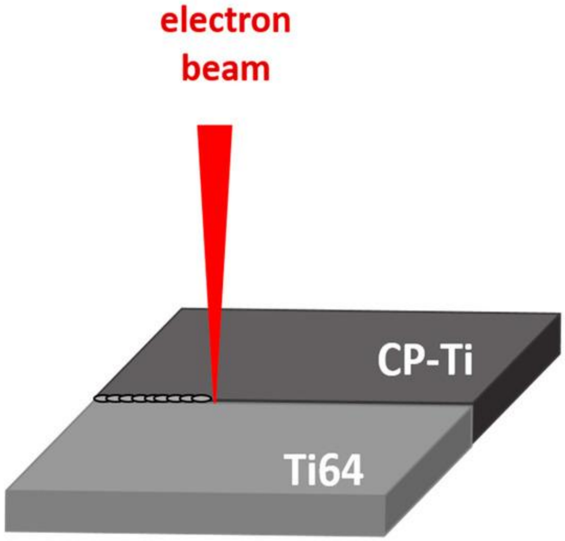

Figure 1. Schematic of the process of EBW of CP-Ti and Ti64.

Scanning electron microscopy (SEM) was performed on a “LYRA I XMU” scanning electron microscope for the investigation of the microstructure of the welded specimens. This analysis was performed in order to gain knowledge on the resultant microstructure as a function of the used beam power. All images included in this paper were taken using the back-scattered electrons mode. The accelerating voltage during the experiments was 20 kV. In addition, energy dispersive X-ray spectroscopy was performed in order to obtain information on the chemical composition of the studied samples [2,4].

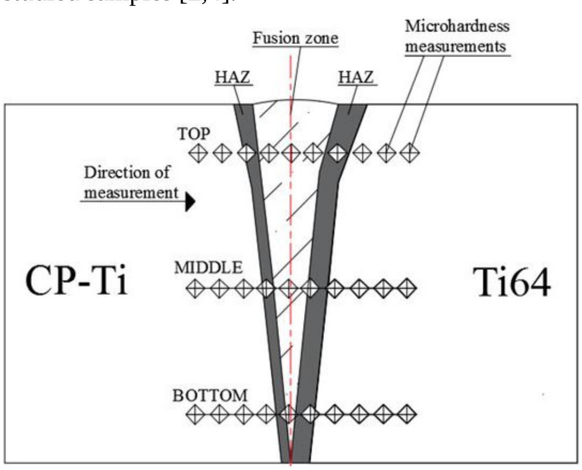

Figure 2. Scheme of the Vickers hardness experiments.

A Bruker D8 Advance X-ray diffractometer was used to analyze the investigated samples’ phase. The method used was Coupled Two Theta. The radiation of the X-ray tube was CoKα with a wavelength 1.78897 Å. The range of the research was from 35° to 115°, the X-ray generator current was 40 mA, and the used voltage was 35 kV. The tests were performed with a 0.05° step with a 0.25 s time for each step. [1,6] The tensile tests were performed on a machine for static and dynamic tests (a ZWICK Vibrophore 100) in accordance with the requirements of the ISO 6892-1 Method B, with a constant rate of stresses in the elastic region of 30 MPa/s. The microhardness measurements were performed in a semi-automatic mode. A visual representation of the method is shown in Figure 2.[6]] During the experiments, 40 measurement of the Vickers hardness were performed[3,7]. For each measurement a force of 0.5 N was employed along with a test time of 10 s.

Mohamed M. Jameel et al. [1]. An experimental study on the electron beam welding process, which involves accurately directing a stream of electrons at high speed onto the weld location, was reported by This welding process is often used in the aerospace and defense industries since it is capable of producing a narrow fusion zone, thereby reducing the amount of metal melted during the welding process, which also reduces distortion and heat affected zone. Multiple factors influence the inherent complexity associated in the electron beam welding process. The welding input parameters—depth of penetration, beam focal diameter, welding speed, accelerating voltage, and beam current—are crucial for assessing the quality of the weld. Oleksii Fedosov et al. [2]. The difficulties with deep penetration in traditional welding techniques can be overcome by using electron beam welding to fuse 40 mm thick titanium alloys, such as VT23 and VT3-1, according to tests done by. These titanium alloys require post-weld heat treatment following electron beam welding in order to achieve high strength (above 1250 MPa) and impact toughness (48-50 J/cm2). Furthermore, improvements in welding modeling have improved efficiency, quality, and reproducibility by creating welded joints with characteristics similar to the base metal. Rai et al. [3] experimentally investigated fluid flow and three-dimensional heat transfer during keyhole electron beam welding to account for the variable temperature of the keyhole walls. 304L stainless steel welds with varying power density distributions produced by varying the focal spot radius while keeping the input power constant were subjected to the model they developed. The importance of convective heat transfer in the weld pool during the electron beam welding process is highlighted by their findings. Zenin A.A. et al. [4] investigated experimentally how temperature affects brazed titanium-alumina joint structure. They used a plasma-cathode source and electron beam brazing in their study. They discovered that joint performance is improved by brazing below the titanium alpha-beta transition temperature. These investigations led to the successful creation of a strong and secure metal-ceramic bond between titanium and alumina ceramic. Nesterenkov V.M. et al. [5] also conducted experiments at the Paton Electric Welding Institute, which focuses on advancing technology and equipment for electron beam welding, surfacing, and prototyping, particularly for modern structural alloys. The equipment developed is employed for joining complex structures across various industries, as well as for the restoration. Shapovalov et al. [6] experimentally investigated the mechanical properties of steels exposed to plasma and other intense energy sources. The function of nitrogen in metal melts during the plasma-slag process is remarkably poorly understood. Temperatures between 1823 and 2323 K have no discernible effect on the amount of nitrogen in steel at partial nitrogen pressures below 0.1 atm above the melt. However, as the temperature rises at higher partial pressures, steel's nitrogen content tends to decrease. It was discovered that the melt temperature under experimental conditions was 2385 K. Skryabinsky et al. [7] carried out experimental investigations of the mechanical characteristics of joints and the distribution of hardness in the heat-affected zone (HAZ) of 2219 alloy plates. Before being welded, these plates were quenched and then artificially aged. They found that the joints' ultimate strength increased from 300–315 MPa to 385–395 MPa, and that the hardness of the HAZ and weld metal increased by 5–10 HRB. It was discovered by monitoring the welding process's thermal cycles that the highest heating temperature in this area was roughly 590°C. With a HAZ width of roughly 8 mm, a 2-3 HRB decrease in metal hardness was observed at a welding speed of 20 mm/s. Akhonin et al. [8] melted low-grade nickel scrap to create semi-finished products such as rings, squares, and hexagons, capillarity pipes, and different types of thin and thick-walled pipes and seamless pipes that are formed both hot and cold. A thorough investigation into the production of semi-finished goods in the shape of long, pliable rods with a diameter of 40 mm and wire with a diameter of 3 mm was carried out in order to evaluate quality. According to the study, the semi-finished products made from EBM nickel have mechanical qualities that completely meet all accepted standards. Radoslav Vandzura et al. [9]. Creating a weld joint between aluminum alloys produced by additive and conventional methods was the aim of this experiment. They sought to measure and evaluate microhardness in addition to the microstructure of the base materials, the heat-affected zone, and the weld joint.

II. METHODOLOGY AND MATERIALS

2.1. Materials

A concentrated beam of high-velocity electrons is used in electron beam welding (EBW), a high-precision fusion welding technique, to fuse materials together. The material melts and forms a weld when the electron beams kinetic energy hits the workpiece and is transformed into heat. EBW is usually carried out in a vacuum chamber to guarantee deep penetration with little contamination and to stop electrons from scattering in the air it is particularly well suited for joining refractory and reactive metals, including titanium, stainless steel, and nickel-based alloys. The method creates extremely deep, narrow welds with high strength and little distortion, making it perfect for use in nuclear, automotive, and aerospace applications.

2.2. Process Overview:

In order to handle the significant differences in physical and chemical properties (melting point, thermal conductivity, and propensity to form brittle intermetallic), proton beam welding (EBW) for joining titanium to stainless steel starts with careful material preparation and selection as well as joint design. To lessen the formation of brittle Ti–Fe intermetallic, choose the grade of titanium (such as Ti-6Al-4V), stainless steel (such as AISI 316L), and potential filler materials or interlayers (such as pure niobium, copper, vanadium, nickel-based fillers, or graded functionally-graded interlayers). Degrease chemically clean to remove oxides and impurities, control fit-up (root gap and alignment), and cut and machine mating surfaces to precise tolerances. Either butt, lap, or stepped-joint geometries should be prepared for EBW, depending on the filler feeding technique and mechanical needs fig 3 [5]

Make an experimental matrix that varies key parameters like beam current/energy, speed, focus, vacuum level, filler type and feed rate, and joint geometry in order to map their effects on dilution, penetration, and intermetallic formation. Incorporate process monitoring (beam current log, vacuum pressure, thermocouples, or pyrometry if feasible) to correlate settings with outcomes. fig 4 [2]

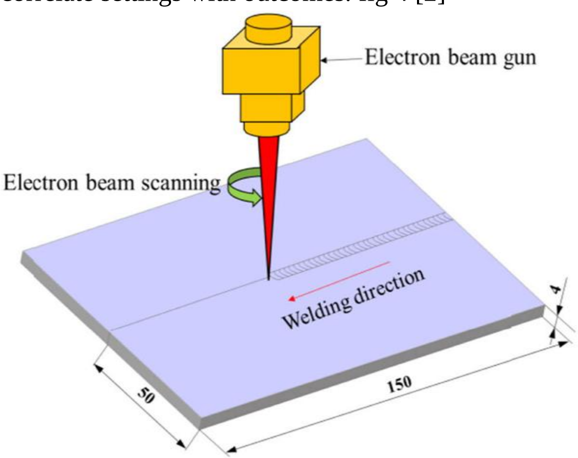

Figure 3 for of Electron Beam Welding

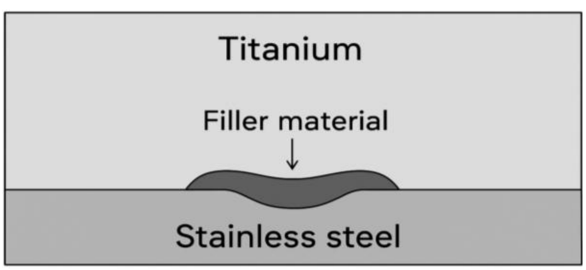

Figure 4 Titanium and Stainless-steel schematic diagram

2.3. Challenges in EBW Quality Assurance.

2.3.1.Welding of Dissimilar Metals:

Given the much lower melting point of titanium than stainless steels (temperature 1630–1660 °C), and considering their respective coefficients of thermal expansion and thermal conductivities. These characteristics create quite complicated metallurgical issues associated with dissimilar metal welding. Many times, this can result in potentially brittle intermetallic compounds that can detrimentally affect the ductility and mechanical properties of the weld joint, such as Ti–Fe phases.

2.3.2.Porosity and Vacuum Integrity:

It is important to maintain vacuum integrity when performing. Porosity in the weld can be caused by just a small amount of contamination by moisture, oil or entrapped gases. Porosity complicates quality control procedures and also reduces the strength of the weld.

2.3.3.Beam Alignment and Stability:

To ensure consistent heating and penetration, the electron beam must be accurately positioned and stable. Even minor displacement can lead to inconsistent weld profiles, penetration issues, or a lack of fusion, maintaining a consistent weld quality is difficult.

III. EXISTING QUALITY ASSURANCE METHODS

3.1. Turn off the auxiliary.

Turn off a small screw on the upper side of the switch frame. Open the key cover again and go to the key page. Turn off the auxiliary again. Please report back to one of the employees that you were able to fix the Code 152 issue.

3.2. Radiographic Testing (RT):

Radiographic Testing is commonly used to evaluate the internal soundness of EBW joints. RT exhibits capability to identify sub-surface flaws such as porosity, lack of fusion, and inclusions utilizing transmitted. RT is effective for identifying volumetric defects, but can be less effective in identifying small discontinuities, or very fine cracks, especially in dissimilar joints between titanium and stainless steel.

3.3. Ultrasonic Testing (UT):

Ultrasonic testing finds internal defects using sound waves of high frequency. It is particularly useful for identifying voids, cracks, and lack of penetration in thicker sections. Defect detection in Ti–SS welds can be difficult due to the reliance on operator skill and the acoustic properties of the dissimilar metals.

IV. ROLE OF AI IN EBW QUALITY ASSURANCE

Artificial Intelligence (AI) is emerging as a powerful tool to help improve quality assurance in electron beam welding (EBW) especially in complex applications such as welding titanium and stainless steel. AI techniques provide greater accuracy, less dependence on human intervention, and offer predictive quality assurance and real-time inspection.

4.1. Real-Time Process Monitoring:

The EBW process is fully monitored through capitalizing on AI algorithms and sensor data such as thermal imagery, acoustic emission signals, and electron beam settings. Deviations from the desired process such as beam instability, formation of porosity, or lack of welding penetration can be detected in real-time by observing trends with AI. This allows for corrective action during the welding process and before a defect arises.

4.2. Predictive Quality Assessment:

Machine learning models based on metrics of like, focus, and welding machine historic data are able to predict weld outcomes. Particularly for dissimilar metal systems such as Ti–SS, the use of predictive quality aids the selection of parameters for consistent weld quality and leads to the reduction of trial-and-error test methods.

4.3. Defect Detection Using Image and Signal Processing:

Defect detection may also be improved through AI-enabled signal analysis and image recognition in destructive and non-destructive testing. For example, computer vision algorithms can detect intermetallic phase regions, porosity, and microcracks in radiography or ultrasonic images that would be too difficult of an image for human inspectors to recognize.

4.4. Process Enhancement:

By using neural networks, fuzzy logic, or genetic algorithms, AI can be deployed to maximize numerous EBW parameters simultaneously. For Ti-SS dissimilar welding, this specifically helps to identify the best process window for maximizing joint strength and toughness while minimizing intermetallic.

V. COMPARATIVE ANALYSIS OF AI TECHNIQUES:

In scenarios where traditional trial-and-error approaches are costly and lengthy, artificial intelligence (AI) presents powerful tools for the improvement of Electron Beam Welding (EBW) of titanium and stainless steel with various filler material combinations. When datasets are small, traditional machine learning models such as regression and support vector machines are useful because they provide baseline predictions, and results are understandable. Nevertheless, they are not as trustworthy as modeling approaches for most complicated EBW studies because they will not account for the highly nonlinear interactions between welding parameters, filler properties, and joint performance. More complicated techniques like Bayesian approaches and tree-based ensembles (Random Forest, XGBoost) provide deeper insights and increased prediction performance.

VI. ADOPTION OF AI-DRIVEN EBW IN VARIOUS INDUSTRIES

AI is getting big in sectors that need stuff done right, reliably, and fast. It's being added to electron beam welding (EBW) a lot. Besides making sure the quality is better, AI also makes EBW smarter, simpler to change, and cheaper.

To make good welds on things like turbine blades and fuel systems, the aerospace biz really needs AI-controlled electron beam welding, especially when working with titanium and stainless steel. AI helps catch tiny cracks and stress in real-time, which keeps everything up to aerospace safety standards. Plus, AI can guess how welds will turn out, cutting down on test welds, so things get done quicker and cheaper.

6.1 Auto Industry:

EBW is getting more use in car making for exact parts like sensor cases, gear sets, and drive shafts.

VII. CHALLENGES IN AI-DRIVEN EBW

AI could be a game-changer for automating and checking quality in electron beam welding (EBW). Still, there are some big problems we have to fix before we can really use it. These problems hit us in tech, factories, and money, especially when we're welding tricky stuff like stainless steel to titanium.6.1 Data Problems: AI learns best with tons of good data. But EBW tests cost a lot and take forever, so getting enough data to trust the AI can be hard. If the data is bad or missing stuff, the AI might not guess right in the real world.6.2 Complicated Welding: EBW has tons of settings that all mess with each other, like beam power, speed, and vacuum. Trying to teach an AI all these tiny details is tough. Even a small switch in the metal or how thick it is can mess things up, so the AI has to be super adaptable.6.3 Old Machines: Lots of factories still use old EBW machines that can't even talk to AI. Upgrading these machines with AI sensors and cameras is expensive and not easy, which slows down how fast people start using AI.6.4 Real-Time Trouble: AI can look at data fast, but it's still tricky to get clear info in the vacuum of EBW. If there's interference such as the beam bouncing around or the room getting dirty, the AI might miss problems.6.5 No Rules: Right now, there aren't clear rules for using AI to check EBW quality. This is a headache for super important jobs, like building planes or reactors, because it's hard to prove the AI is safe, compare tests, and follow the law.

VIII. OPPORTUNITIES FOR ADVANCEMENT OF AI-BASED EBW

Putting artificial intelligence to work in electron beam welding could really change things, even if there are some problems to figure out first. When you're joining tricky stuff like titanium and stainless steel, AI could make welding way more exact, easy to change, and smart.7.1. Better Ways to Use Data: AI can learn how the settings on the EBW machine affect the final weld by looking at tons of data from tests and simulations. With smarter learning methods, we can find the best settings more easily, cut down on mistakes, and make sure everything's top-notch.7.2. Making Digital Copies: AI lets us build computer copies of the welding process. These copies let engineers see problems coming before they actually weld anything. The models can show how heat moves, how the metal changes, and where stress builds in real-time. This cuts down on the need for real-world tests, speeding things up and saving money.7.3. Welding Machines That Think: AI can power EBW machines that adjust themselves as they weld, changing things like the current, voltage, or speed. table 1 [5]

1.Experimental matrix (example):

Factor	Levels (example)
Filler / Interlaye	No interlayer; Ni foil (50–100 μm); Ti filler; Cu foil
Accelerating voltage	60 kV; 100 kV
Beam current	Low (15–25 mA); Medium (30–45 mA)
Welding speed	Slow (150 mm/min); Fast (600 mm/min
Joint type	Butt; Single-V

This table shows the different things we changed in our welding experiment (probably using electron beams). We looked at five main things that affect the weld: what kind of filler material we used (or if we used any), the voltage, the beam current, how fast we welded, and the type of joint. Each of these things had different settings. For example, for the filler, we tried no filler, nickel foil, titanium filler, and copper foil. The voltage went from 60 kV to 100 kV. We had low and medium current settings, and slow and fast welding speeds. We also tested butt joints and single-V joints. It looks like we're trying to figure out how these things change the weld quality, how deep the weld goes, or something like that – probably to improve the welding process or for research.

IX. CONCLUSIONS

Figuring out how to keep different metals nicely joined is tricky, as seen in the study about using titanium with different filler metals. Usual ways to check quality, like X-rays and stuff, are still important but can take a lot of work and might not catch all problems. Adding artificial intelligence (AI) to electron beam welding (EBW) quality control is a big change because it can predict issues, watch things as they happen, and adjust how things are done.

Machine learning and deep learning are good at finding problems, but comparing AI methods shows that things like fuzzy logic and genetic algorithms help tweak settings and control the process better. AI digital twins also help by letting people test things out without wasting materials, cutting down on trial-and-error costs. Even though there are challenges like getting enough data, needing a lot of processing power, and fitting AI into the mix, industries like aerospace, nuclear, medicine, cars, and energy could really benefit from using AI with EBW. So, using AI in EBW means welding key parts will be more accurate, reliable, and cheaper. As AI gets easier to understand, and as we get better at mixing AI models and controlling things in real-time, expect to see AI-driven EBW become really popular in factories. Pairing smart welding with intelligent systems could really change how we make sure things are well-made, leading to safer and better engineering next-generation systems.

Disclosure of Competing Interest:
The authors declare that there are no financial or personal conflicts of interest that could have affected this study.

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Statement of Data Availability:
If you want the data from this study, just ask the person in charge. We didn't use or make any public datasets for this research.

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