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Feasibility Studies on Welding of Titanium with Stainless Steel with Different Filler Material Combinations Using Electron Beam Welding

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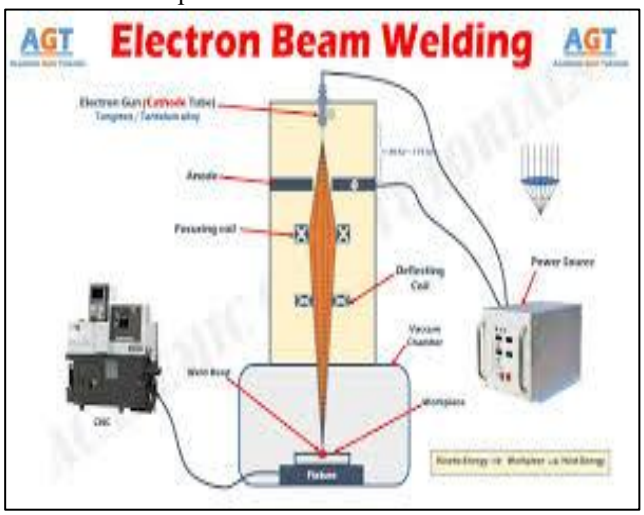
Abstract: ***This review paper highlights the essential role of machine learning models in improving weld quality and optimising welding processes, with a strong focus on ML's revolutionary applications in electron beam welding. By adopting these innovations, the industry can confidently unlock new levels of efficiency and excellence in welding technology. The formation of brittle Ti–Fe intermetallic compounds (IMCs) and thermal property mismatches make welding titanium and stainless steel difficult. Electron Beam Welding (EBW) can join these dissimilar metals under high vacuum, providing precise control and minimal contamination. The study investigates various filler and interlayer materials, including graded stacks and Nb, Ta, V, Mo, Cu, and Ni. The study assesses how well these materials strengthen joints, reduce IMC formation, and increase corrosion resistance. While Ni may promote brittle phases, refractory metals like Nb and Ta are predicted to perform best. The results will help determine workable welding parameters and filler materials. Brittle Ti–Fe intermetallic compound (IMC) formation and thermal-property mismatches make welding titanium and stainless steel difficult. This study investigates the viability of various filler and interlayer materials, including graded stacks and Nb, Ta, V, Mo, Cu, and Ni. The results will help identify workable filler materials and welding parameters for dependable Ti–SS joints. Furthermore, the study offers a comparative framework that businesses can use to guide dissimilar-metal joints in advanced engineering applications that are lightweight, corrosion-resistant, and mechanically dependable. Main objective statement: This project investigates the feasibility of welding titanium alloy (Ti-6Al-4V) to stainless steel (304L/316L) using electron beam welding and different filler materials (Ni, Cu, V). The study aims to analyse how filler materials affect weld quality, microstructure, and mechanical properties to identify the most suitable filler for high-strength applications. Main task: This project welds titanium alloy (Ti-6Al-4V) to stainless steel (304L/316L) using electron beam welding with different filler materials (nickel, copper, vanadium). The welds will be analysed for microstructure and mechanical properties to identify the most suitable filler material for producing strong, defect-free joints.***

Keywords: LBM, Machine Learning, Performance, Efficiency, Material Characterisation, Filler Material Selection, and Weldability Testing. Diffusion Barrier, Beam Offset, Heat Input, Microstructure, Mechanical Properties, Residual Stress, Titanium, Ti-6Al-4V, Commercially Pure Titanium, Stainless Steel, 304L 316L, 410/420, Intermetallic, Interlayer, Filler, Copper, Nickel, Vanadium, Niobium, Tantalum, Molybdenum, and Feasibility.

Nomenclature:
FSW: Friction Stir Welding
EBM: Electron Beam Melting
LBM: Laser Beam Melting
SEM: Scanning Electron Microscopy
ML: Machine Learning
HAZ: Heat-Affected Zone
TIG: Tungsten Inert Gas
MIG: Metal Inert Gas
FSW: Friction Stir Welding
RSM: Response Surface Methodology
DoE: Design of Experiments
SEM: Scanning Electron Microscopy
EDS: Energy-dispersive X-ray Spectroscopy
XRD: X-ray Diffraction

I. INTRODUCTION

Electron beam machining (EBM) is a crucial technique in non-conventional manufacturing and precision engineering. This technology uses a focused electron beam to perform a range of material-processing operations. EBM uses a high-energy electron beam to remove or modify material layers on a workpiece surface. It achieves this through processes such as ablation, vaporisation, or melting. LBM leverages the unique properties of electron light, including its coherence, monochromaticity, and high intensity, to remove material with remarkable precision and control.



[Fig.1: Electron Beam Welding]

Microoperations excel in precision engineering, enabling accurate drilling of tiny holes, meticulous carving of intricate designs, detailed engraving of markings, and

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sophisticated sculpting of complex curves. This versatile technique works on a wide range of materials, including metals, polymers, ceramics, and composites, making it essential in advanced manufacturing and craftsmanship.

Electron beam machining (EBM) represents a groundbreaking advancement in manufacturing technology. It provides a non-contact process that greatly reduces thermal distortion and damage. By eliminating the tool wear and damage common in traditional machining, EBM improves operational efficiency and delivers exceptional precision. This state-of-the-art technique is reshaping industries and setting new benchmarks for machining quality and reliability.

EBM's broad applicability across sectors underscores its significant influence. Industries such as aerospace, automotive, electronics, and medical device manufacturing leverage EBM's advantages to drive innovation and excellence.

In the aerospace sector, Electron Beam Melting (EBM) is a crucial technology for manufacturing lightweight components with intricate geometries. This advanced production process not only enhances design flexibility but also reduces heat-affected zones, protecting component performance and structural integrity. By employing EBM, engineers can create parts that are reliable, efficient, and designed to meet the demanding specifications of contemporary aerospace applications. This ability is critical to guaranteeing the longevity of critical parts. In the medical industry, Laser Beam Melting (LBM) enables precise fabrication of intricate medical devices and implants while supporting patient safety and biocompatibility.

Titanium and stainless steel are widely used in aerospace, nuclear, chemical processing, and biomedical engineering because of their exceptional mechanical properties and corrosion resistance. However, titanium and stainless steel cannot be joined directly because they are chemically incompatible. As a result, brittle Ti–Fe intermetallics (TiFe, $TiFe_2$) form, drastically reducing joint ductility and toughness. Moreover, differences in melting points and thermal expansion coefficients increase residual stresses and distortion.

Electron Beam Welding (EBW) is a high-tech fusion welding process that uses a concentrated electron beam to create deep penetration and high energy density under high vacuum. Its advantages include precise heat-input control, low contamination, and small heat-affected zones. These features make EBW a promising method for welding titanium to stainless steel when combined with the appropriate filler or interlayer materials. Interlayers such as Nb, Ta, V, and Mo act as diffusion barriers to suppress Ti–Fe intermetallics. At the same time, Cu can buffer the interface, and graded stacks can further tailor the transition between the two metals. To create mechanically reliable, sound, and defect-free Ti–SS joints, this study aims to determine whether EBW with different interlayer combinations is practical.

A. Literature Review

Ahmad Naseem et al. [2] experimentally investigated electron beam welding of low-nickel, nitrogen-strengthened austenitic stainless steel to assess its mechanical properties. They found a 90% improvement in strength compared to the base alloy, while microhardness decreased by 12.9%. Additionally, they noted that impact energy decreased by 50% compared to the base material.

Dutilleul T et al. [3] also explored electron beam welding, focusing on its application in high-productivity welding of thick-section components within the nuclear industry. Their research highlighted using small modular reactors to join thick-section pressure vessel components. They identified the Pro-Beam K 2000 system, which operates within a chamber for electron beam applications, at the Nuclear Advanced Manufacturing Research Centre.

Min Cheng et al. [4] conducted an experimental study on electron beam welding, focusing on the joining of a novel high-temperature titanium alloy powder compact. They also investigated how annealing treatments affect the microstructure and mechanical properties of the EBW joints.

Meanwhile, Konrad Kerber et al. [5] explored the critical welding speeds that distinguish conduction (low welding speeds) from non-conduction (higher welding speeds). Their study used several methods, including optical microscopy, electron backscatter diffraction, ultrasonic testing, in situ thermal imaging, electrical resistance measurement, and tensile tests. The joints achieved up to 98% of the specific electrical conductivity of the international annealed copper standard.

Zbigniew Wencel et al. [6] conducted an experimental study of the welding process by exploring two electron-beam de-bunching values, each with a different width, while considering various welding parameters. The subsequent heat treatment involved tempering at 520°C for 3 hours, followed by a single freezing step at -84°C for 3 hours, along with another single-temperature treatment at 520°C for 3 hours.

Bauer A. et al. [7] also conducted experimental studies, demonstrating that tailored processing parameters—such as electron-beam preheating or beam oscillation during welding—facilitated defect-free joining with very thin weld seams and a minimised heat-affected zone. Nonetheless, despite the chosen welding parameters, some specimens formed smaller grains within the former fusion zone.

Marta Lipinska et al. [8] conducted experimental studies to reduce energy input during welding, which in turn minimises the heat-affected zone and limits the evaporation of elements with high saturated vapour pressure. The weld efficiency for the CG alloy was 80%, whereas for the UPG sample it was 68%, or 82% of the CG base material efficiency.

Vadim S. Tynchenko et al. [9] developed a mathematical model that employs machine learning techniques to predict effective process parameters. This research used regression algorithms, such as ridge regression and the random forest regressor, because predicting process parameters requires a regression model. All models successfully addressed the task, achieving at least 89% forecasting accuracy. The weld depth followed a second-degree polynomial relationship with a regularisation of 10^-5, while the weld width followed a third-degree polynomial relationship with a regularisation of 10^-4.

Jia Tao et al. [10] conducted an experimental study comparing FEM simulations using a 2D Gaussian heat source. They performed an EBW experiment on niobium sheets to validate the simulation results. The

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mechanical findings indicate that the peak longitudinal stress in the weld centre, the peak transverse stress in the weld centre, longitudinal distortion, and transverse distortion predicted by the designed model deviate from the experimental results by only -4.88%, -4.03%, -9.32%, and -5.98%, respectively.

In Tynchenko V.S. et al. [11], the authors examine various algorithms for addressing the regression problem. Implementing these algorithms is expected to improve the quality of regression models. Additionally, assessment methods and forecasting techniques will reduce the time and labour required to search for, develop, and refine the process. This proposed approach aims to help electron beam welding specialists make informed technological decisions when developing processes and introducing new product types into production.

Ariel Rokem et al. [12] examined one challenge of ridge regression: setting a hyperparameter (alpha) that controls the level of regularisation. This process can become cumbersome when analysing large datasets. This work addresses these issues with an innovative approach to ridge regression. We present an algorithm that efficiently implements this approach, called fractional ridge regression, along with open-source software implementations in Python and MATLAB (https://github.com/nrdg/fracridge).

Vasundhara Singh et al. [13] conducted an experimental study by manipulating the magnetic lens aligned with the electron beam to investigate the oscillating beam diameter (OD) and its impact on weld quality. They varied the OD between 0.5 mm and 2 mm. They used a comprehensive array of tests, including X-ray diffraction, scanning electron microscopy (SEM), electron backscattered diffraction, and assessments of hardness, wear, and tensile properties, to characterise weld quality. Although the weld strength was lower than that of the base metal, introducing BO improved the welds' ductility and strength.

Zagornikov V.I. et al. [14] examined the need to repair the cathode unit after imported insulators showed defects, specifically a 0.5 to 1.0 mm thickness deviation in the metal flange at the brazed joint with the insulator. It was essential to address the repercussions of improper mechanical treatment of the insulator collar following brazing. The repair technologies used circumferential insert bandages in two scenarios, aimed at rectifying welding defects through both localised edge repairs and repairs of more extensive areas.

Jozef Beata et al. [15] conducted an experimental study on the thickness of 25.4 mm for AW 2099-T83 aluminium-lithium alloy, utilising electron beam welding with an accelerating voltage of 55 kV to produce welded joints. The welded joints underwent inspection through computed tomography, macroscopic and microscopic analysis, tensile strength tests, and microhardness measurements. Fracture occurred in the weld metal during tensile testing.

Mohamed M. Jameel et al. [16] conducted an experimental investigation of the electron beam welding process, in which a high-speed stream of electrons is precisely focused on the weld spot. This method is widely used in the aerospace and defence industries because it creates a narrow fusion zone, melting less metal during the joining process. Consequently, it reduces distortion and minimises heat input. Electron beam welding is inherently complex and influenced by a variety of parameters. Welding input parameters are crucial in determining weld quality and include accelerating voltage, beam current, depth of penetration, beam focal diameter, and welding speed.

Oleksii Fedosov et al. [17] conducted experiments showing that electron beam welding can effectively join 40 mm-thick VT23 and VT3-1 titanium alloys, overcoming the deep-penetration challenges of conventional welding methods. To achieve high strength (exceeding 1250 MPa) and impact toughness (48-50 J/cm^2) in these titanium alloys after electron beam welding, post-weld heat treatment is crucial. Additionally, advances in welding modelling have improved reproducibility, quality, and efficiency, yielding welded joints with properties comparable to the base metal.

Rai et al. [18] conducted an experimental study of three-dimensional heat transfer and fluid flow during keyhole electron beam welding, accounting for variable keyhole wall temperature. They applied the model to 304L stainless steel welds produced with different power-density distributions, achieved by varying the focal spot radius while keeping the input power fixed. Their findings highlight the importance of convective heat transfer in the weld pool during electron beam welding.

Zenin A.A. et al. [19] conducted an experimental study on how temperature affects the structure of brazed titanium-alumina joints. Their research used electron beam brazing with a plasma-cathode source. They found that brazing below the titanium alpha-beta transition temperature enhances joint performance. As a result, they achieved a robust, tight metal-ceramic joint between titanium and alumina ceramic.

Nesterenkov V.M. et al. [20] 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 joins complex structures across industries and restores and repairs components, such as gas turbine engine parts.

Shapovalov et al. [21] experimentally investigated the mechanical properties of steels subjected to highly concentrated energy sources, such as plasma. Research on nitrogen's role in metal melts during the plasma-slag process remains scarce. At partial nitrogen pressures below 0.1 atm above the melt, temperatures ranging from 1823 to 2323 K have minimal impact on the nitrogen content in steel. Conversely, at higher partial pressures, the nitrogen content in steel tends to decrease as the temperature rises. Under the experimental conditions, the melt temperature was 2385 K. The nitrogen distribution coefficient between the metal and slag remained relatively stable, at 1.1-1.2 for partial nitrogen pressures up to 1 atm.

Skryabinsky et al. [22] experimentally studied the mechanical properties of joints and the hardness distribution in the heat-affected zone (HAZ) of 2219 alloy plates. They quenched these plates before welding and then subjected them to artificial ageing. They observed an improvement in

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the ultimate strength of the joints, increasing from 300-315 MPa to 385-395 MPa, along with a rise in hardness of both the weld and HAZ metal by 5-10 HRB. By measuring the welding process thermal cycles, the maximum heating temperature in this region reached approximately 590°C. At a welding speed of 20 mm/s, metal hardness decreased by 2-3 HRB, with an HAZ width of about 8 mm.

Akhonin et al. [1] conducted experimental studies on melting low-grade nickel scrap to produce semi-finished products, including hot- and cold-formed seamless pipes, capillarity pipes, thin- and thick-walled pipe variants, rings, squares, and hexagons. To assess quality, the study conducted comprehensive research on manufacturing semi-finished products in the form of elongated soft rods with a diameter of 40 mm and wire with a diameter of 3 mm. The study found that the mechanical properties of EBM nickel semi-finished products fully comply with standard requirements.

Radoslav Vandzura et al. [24] conducted an experimental study on electron beam welding in collaboration with First Welding Company Inc. The objective was to create a weld joint between aluminium alloys prepared using additive and conventional methods. They aimed to evaluate the base materials, heat-affected zone, and weld joint microstructure, and to measure and assess microhardness.

Maksymov S.Yu et al. [25] experimentally investigated cooling rates in different weld-metal regions during both wet underwater welding and air welding. They determined how the volumetric fractions of phase components such as ferrite, austenite, and excess phases changed in the heat-affected zone (HAZ) microstructure as a function of cooling rate. Phase transformations primarily occurred in the high-temperature heat-affected zone (T = 1300-800°C), while the low-temperature heat-affected zone (T = 800-500°C) contributed negligibly to changes in phase components.

Korotynskyi O.Ye et al. [26] conducted an experimental study on pulsed welding currents of regulated shape. Such currents are needed primarily to meet the objectives of pulsed technologies, where the load-current shape ensures the required timing of power input into the technological object. Notable applications include pulsed laser welding, laser heat hardening, and laser piercing. Special pulsed current generators are needed to create such energy profiles.

Sihui Yang et al. [27] conducted an experimental study on the superalloy GH4169, widely used in the aero-engine industry. They evaluated the hardness, microstructure, and tensile properties of electron-beam-welded GH4169 joints. They also analysed the high-temperature creep properties of these joints with residual height. They also tested the fatigue performance of the welded joints, comparing those with and without residual height; the results indicated that joints without residual height had a fatigue life approximately 10 times greater than those with residual height.

Beata Simekova et al. [28] tested pure titanium Ti grade 2, 2 mm thick, welded to 2 mm thick nickel alloy 201 using electron beam welding. The authors used various welding parameters to create the butt-welded joints, with welding currents ranging from 40 to 70 mA and welding speeds of 20 to 50 mm/s. The study examined two beam offsets: 100-300 µm toward the nickel side and 200 µm toward the titanium side. The beam offset significantly affected weld joint strength.

Georgi Kotlarski et al. [29] investigated how different electron beam welding conditions affect the microstructure and mechanical properties of joints between the dissimilar alloys Ti6Al4V and AL6082-T6. In all experiments, we preheated the plates to 300°C. We explored various welding strategies, including the electron beam current-to-welding-speed ratio and a beam offset toward the aluminium side. The highest observed ultimate tensile strength was 165 MPa, with a yield strength of 80 MPa and an elongation of 18.4%.

Reisgen et al. [30] highlight that, due to its high energy intensity and deep-penetration capability, electron beam welding is particularly effective for welding steel plates with substantial wall thicknesses. Such plates are commonly utilised in offshore wind power systems. In their study, they tested three different parameters with varying energy inputs on three types of steel, using plates with an 80 mm wall thickness. The resulting top and bottom beads of the welds conformed to the DIN EN ISO 13919-1 standard. The parameters used resulted in an energy input per unit length ranging from 9.5 kJ/mm to 15.5 kJ/mm.

Egoitz.Aldanondo. et al. [31] The feasibility of friction stir welding (FSW) surface-treated AA2099-T83 aluminium extrusions with AA2060-T8E30 aluminium sheets in the overlap configuration and using a sealant at the interface was investigated in this work. We produced FSW welds using several combinations of surface treatments and sealant application, with no significant influence on FSW process stability or performance.

Neves. Manuel. et al. [32] investigated the influence of tool geometry, material position in the joint, and welding speed on the temperature and torque developed. The study also analysed weld quality in dissimilar and tri-dissimilar T joints. The aluminium alloys used were

AA2017-T4, AA6082-T6, and AA5083-H111. These factors showed that tools with a progressive pin produce sound dissimilar and tri-dissimilar welds, unlike single-pin tools.

Mohamed I. A. Habba. Et al. [33] This work aims to investigate the effect of applying different welding techniques, tungsten inert gas (TIG) and metal inert gas (MIG), as fusion welding processes compared to friction stir welding (FSW), a solid-state joining process, on the joint performance of the produced 5 mm thick similar AA5083-H111 butt weldments at different welding conditions.

1 Mahendra K. C. et al. [34] reviewed different materials, including ferrous, non-ferrous, and dissimilar materials, using a process-based methodology. The study highlights the parameters that

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influence the process and their effects on mechanical behaviour in the respective categories of material intermixing. Further recommendations indicate that FSW can also be used effectively for polymeric materials.

Ambati Hemanth Sai Kumar et al. [35]. These models investigate discrepancies between experimental and predicted results. Researchers developed random forest regressor and artificial neural network techniques using experimental data. Moreover, they compare analysis-of-variance results with machine-learning predictions to assess variance.

Rami Alfattani et al. [36] Aluminium (Al) alloy is a suitable material for weight reduction in vehicles because it is highly ductile and lightweight. The two specimens (AA6061 and AA8011) and the weld region are suspended in a salt spraying chamber, and a 5 wt.% NaCl solution is continually sprayed using the circulation pump for 60 h, with the specimens being weighed every 15 h to determine the corrosion rates.

Jin Feng Li . et al. [37] All MGs can be welded in the air by the ns-pulsed laser, and the crystallisation of the welding joints can be avoided by proper control of the laser parameters. Mechanical strength is closely linked to the welding-joint profile, suggesting a simple method for evaluating welding quality.

Aniekan Essienubong Ikpe et al. [38]. Key issues that need to be addressed to improve arc welding for industrial applications include limited understanding of the process, limitations of current welding equipment, and the need for skilled welders. Additionally, rising demand for high-quality welded products across industries has pressured manufacturers to improve welding processes to meet market requirements.

Ivan S. Zuiko et al. [39] This work presents an in-depth investigation of the early stages of abnormal grain growth (AGG) in a friction-stir-welded (FSWed) 2519-T820 aluminium alloy. We studied microstructural evolution during the heating stage of solution heat treatment (SHT). This reduced precipitation-pinning forces, promoting rapid grain coarsening.

Won-Ik Cho*et al. [40] Maintaining these facilities is more economical through in-space welding rather than supplying parts from Earth. Therefore, this review focuses on the technologies needed to adapt laser welding to space environments while accounting for these unique conditions.

Varimadugu Sandhya et al. [41] show that Machine Learning (ML) improves process parameter optimisation in manufacturing. They used machine learning to forecast weld bead geometry in electron beam welding. The input weld process parameters considered were accelerating voltage (kV), beam current (mA), and welding speed (m/min).

P N Siddharth and C Sathiya Narayanan et al. [42] Electron Beam Welding is an unconventional manufacturing technique widely used in the Aerospace and Defence industries. It offers advantages such as less metal melting, less distortion, and less heat input than TIG and Arc welding. This paper reviews various optimisation methods researchers have applied to electron beam welding.

Sihui Yang et al. [43] reported that superalloy GH4169 and related welded structures were widely used in the aero-engine industry. The study focuses on the properties of electron-beam-welded GH4169 joints. Welded joints without residual height have a fatigue life about 10 times longer than joints with residual height.

Darina Kaisheva et al. [44] studied electron beam welding of copper and AI6082T6 aluminium alloys. Beam scanning geometries influence the structure and mechanical properties of the welded joints. The experiments used a circular oscillation mode with oscillation radii of 0.1 mm and 0.2 mm.

Georgi Kotlarski et al. [45]. This work investigates how different electron-beam welding conditions affect the microstructure and mechanical properties of joints between Ti6Al4V and Al6082-T6 dissimilar alloys. The authors varied the heat input to ensure full electron-beam penetration. The authors studied the macrostructure of the samples, and the results indicated that high beam power and high welding speed increase defect formation within the weld seam.

Urminský Ján et al. [46]. The paper analyses the mechanical properties of welded joints made from AW 2099 aluminium-lithium alloy by electron beam welding. The experimental material thickness was 3 ± 0.2 mm. We produced the welds using a PZ EZ 30 STU electron beam welding machine. The maximum accelerating voltage used in this study was 55 kV. We performed metallographic analysis, hardness testing, and static tensile testing.

Dr Rashmi Dwivedi et al. [47] reported that vibratory treatment during welding reduces residual stresses and improves mechanical properties in the weld joint. Optimal vibration parameters, including frequency, amplitude, and time, are essential to maximise joint strength improvement. We used a machine learning approach to identify optimal parameters for GMAW welding of SS304. We checked mechanical properties; tensile strength and hardness were within acceptable deviation ranges.

Luigi Panza et al. [48] showed that electrode condition affects RSW joint quality; electrode condition strongly affects resistance spot welding joints. They developed a machine learning tool to assess how electrode wear affects RSW weld quality automatically.

Luis Alonso Dominguez Molina et al. [49] showed that assessing resistance spot welding quality with a trained computer vision model is vital during manufacturing. The study presents a low-cost, non-destructive quality evaluation methodology that links welding input parameters to output visual quality.

A.S. Buang et al. [23] reviewed current trends in advanced welding processes and technologies used across various industries. Conventional welding processes include gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), resistance welding and friction welding.

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II. SELECTION OF MATERIALS

A. Metal Bases

Grades 2 and 5 of titanium (Ti-6Al-4V)
AISI 304 or 316L stainless steel

B. Materials for Fillers

Choose filler metals that help Ti and SS become more metallurgically compatible:
Ni-based filler, such as Inconel 625
Cu-based filler (Cu-Ni or pure Cu)
Tantalum or vanadium interlayers
Composites of Ti-SS graded alloys (if available)

III. ELECTRON BEAM WELDING (EBW) IS THE WELDING PROCESS.

A. Setup of EBW Equipment

Use an EBW machine with a high-vacuum chamber.
Level of chamber vacuum: less than 10^{-4} mbar

B. Process Elements to Be Improved

Current beam (mA)
Voltage of beams (kV)
Speed of welding (mm/s)
Position of focus
(If used) Beam oscillation
Rate of filler feed (for external filler use)
Preheating (optional; controls the temperature gradient)

C. Design of Experiments

Make use of Response Surface Methodology (RSM) or Taguchi Design of Experiments (DoE):
Change the filler type, speed, voltage, and beam current.
Depending on the number of parameters, use an L9/L16 orthogonal array.
Three trials at the very least per configuration

IV. WELDING TRIALS AND SAMPLE PREPARATION

A. Cooperative Design

Lap joint, butt joint, and dissimilar interface
Machining with strict tolerances

B. Welding Experiments

Use a variety of filler materials.
Take note of any flaws in the welding (porosity, cracks, lack of fusion).
If the machine permits, use real-time monitoring.

C. Treatment After Welding

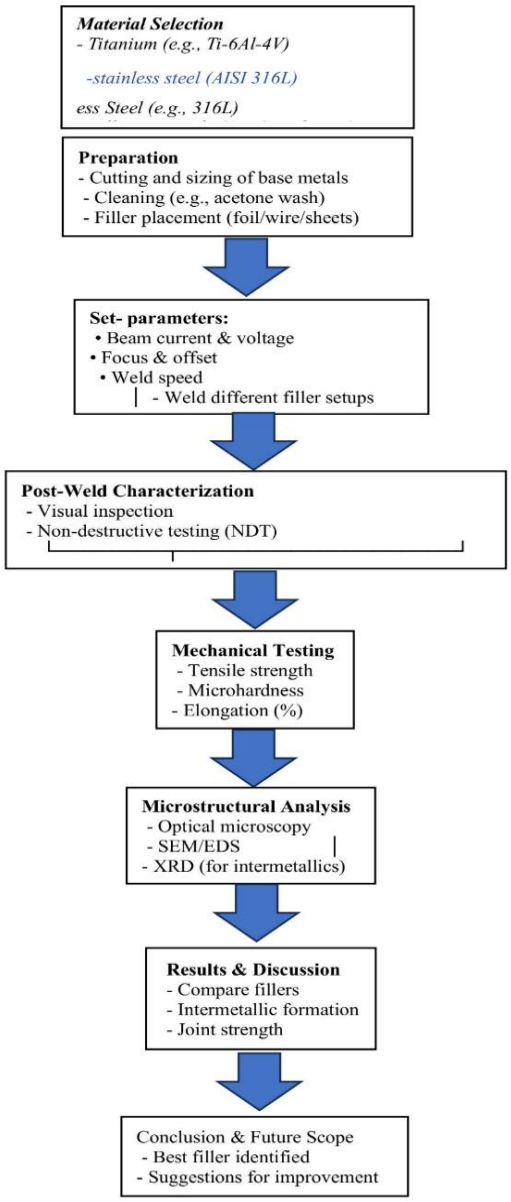
Weld cleaning and grinding
Post-weld heat treatment or controlled cooling are optional.

V. TESTING AND CHARACTERISATION

A. Microstructural and Macrostructural Analysis

To investigate the fusion zone, use optical microscopy (OM).
Interface and microstructural characteristics using scanning electron microscopy (SEM)
Elemental analysis using energy-dispersive X-ray spectroscopy (EDS)
Phase identification using X-Ray Diffraction (XRD) (intermetallics)

Methodology Flow Diagram



With a tensile strength of roughly 310 MPa, OSTI used copper as a filler to create a joint free of thermal-stress cracks during cooling.

Another study showed that copper's superior thermal conductivity improved mechanical properties, refined the microstructure, and produced a uniform temperature distribution. Among the filler materials compared, copper filler welds showed the highest elongation and improved residual stress profiles (MDPI).

VI. CONCLUSION

Vanadium, nickel, and other filler-based welds showed various interfacial intermetallics (e.g., Fe_2Ti, Ni_3Ti, $NiTi_2$, etc.). Tensile strengths differed and were closely related to the current trends and developments; review recent research on machine learning applications in welding processes, paying particular attention to electron beam welding (EBW). List the main conclusions of research that

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shows how machine learning affects the effectiveness and quality of welds. Examine the approaches and results of several machine learning models that have been successfully applied to welding applications.

Examine recent studies on machine learning applications in welding processes, with an emphasis on electron beam welding (EBW), to understand current trends and advancements. Enumerate the key findings of studies that demonstrate how machine learning impacts the quality and efficacy of welds. Examine the methods and outcomes of several machine learning models that have been effectively used in welding applications. Examine the benefits of using machine learning in electron beam machining, considering cost-effectiveness, speed, and accuracy. 5. Examine case studies that illustrate the useful advantages of combining machine learning and electron beam welding in various sectors, such as the production of medical devices and aircraft.

Because copper affects residual stresses and thermal gradients, improved heat-management techniques (such as thermal modelling, beam offsets, and cooling rates) may improve joint uniformity and reduce cracking. MDPI+1.

DECLARATION STATEMENT

After aggregating input from all authors, I, as the article's author, must verify the accuracy of the following information.

- **Funding Support:** This article has not been funded by any organisations or agencies. This independence ensures the research is conducted objectively, without external influence.
- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate, with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors' Contributions:** The authorship of this article is contributed equally to all participating individuals.

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