



Review article

A Critical Review on Dissimilar Welding of Stainless Steels to Titanium Alloys: Technology and Metallurgy

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ABSTRACT

The jointment of titanium alloys to stainless steel poses significant challenges due to their substantially different physical, chemical, and thermal properties. The joint properties of 304 stainless steel and Ti6Al4V are highly important due to the extensive industrial application of 304 stainless steel and Ti6Al4V alloy. The formation of brittle intermetallic compounds such as Fe₂Ti and FeTi in the weld zone is a primary cause of decline in joint strength and failure.² This study investigates various welding methods, including solid-state and fusion weldings, and analyzes the impact of interlayer materials on improving the joint quality. Various welding methods have been used to join these two alloys among which, liquid-state weldings such as high energy beam welding, resistance welding, arc welding, and solid-state weldings like diffusion welding, friction stir welding can be mentioned. The results indicate the crucial role of welding process and parameter optimization for preventing the formation of intermetallic compounds and enhancing the joint strength. Diffusion bonding using niobium interlayer leads to the highest tensile strength (417.5 MPa) among the solid-state welding processes. Additionally, a combination of copper and vanadium interlayers in laser welding technique demonstrated significant strength of 350 MPa among the fusion welding techniques. In fusion welding processes, the use of copper as an interlayer not only reduced residual stresses but also prevented the formation of brittle phases, thereby, improving joint quality. This research highlights that the use of interlayers such as copper, nickel, silver, and niobium, combined with optimized welding processes, can effectively overcome the relevant challenges. These findings provide valuable guidance for designing welding processes and expanding industrial applications. The joint mechanical properties of the solid and liquid state weldings of stainless steels and Ti alloys were listed over the previous 3 decades.

1. Introduction

Welding titanium (Ti) alloys to stainless steel is a

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significant challenge in materials engineering due to the fundamental differences in their physical, chemical, and thermal properties. Titanium and its alloys are widely used in industries such as aerospace, chemical processing, and medical fields because of their high strength, low density, excellent corrosion resistance, and thermal stability [1]. On the other hand, stainless steel is preferred in industries like automotive, construction, and energy due to its mechanical properties, cost-effectiveness, and excellent formability. A combination of these two materials can result in joints with high strength and superior corrosion resistance; although, achieving such

joints is associated with great technical complexity [3].

One of the primary challenges is the formation of brittle intermetallic compounds such as Fe₂Ti and FeTi due to the limited solubility of iron and titanium. Particularly in fusion welding processes, these compounds significantly reduce the joint strength and increase susceptibility to cracking. Additionally, the substantial differences between the thermal expansion coefficients and thermal conductivity of titanium and stainless steel generate great residual stresses at the weld interface, often leading to the joint failure [2].

Early research in this field was focused on fusion welding methods, such as arc welding and electron beam welding. While these methods succeeded in forming initial joints, the brittle intermetallic phases and residual stresses limited their success [3]. In recent decades, advanced techniques like laser welding, diffusion bonding, and friction stir welding have been developed to address the challenges associated with the welding of these materials. Among these advancements, the use of interlayer materials such as copper, nickel, niobium, and silver has proven to be effective in reducing the formation of brittle phases and enhancing the joint strength [2, 3].

This study aims to provide a comprehensive overview on the technological advancements in welding titanium alloys to stainless steel. Various welding methods were explored and their advantages and limitations were compared. The impact of interlayer materials on the mechanical and metallurgical properties of the joints was also addressed. The findings of this research offer practical guidance for selecting optimal welding processes and parameters for these dissimilar materials, contributing to the development of industrial applications.

2. Phase Microstructure in Fe-Ti Phase Diagram

In the binary Ti-Fe phase diagram (Fig. 1), λ represents the Fe₂Ti compound. This phase has a C14 hexagonal Laves structure. In the ternary Fe-Cr-Ti phase

diagram, λ depicts a solid solution of Fe₂Ti and Cr₂Ti. The λ-Laves compound has a close-packed structure. Meanwhile, this phase shows a homogeneity range of 64.8–72.4 at% Fe. The base centered cubic (BCC) structure of βTi transforms to αTi and FeTi by a eutectoid reaction at equilibrium conditions. The FeTi compound has a BCC structure and exists only in the range of 47.5 and 50.2 at% Fe. αFe also has a BCC structure [1].

As depicted in Fig. 1. an eutectic reaction occurs on the Ti-rich side with the βTi and FeTi formation from the liquid. At the equilibrium, the formation of forementioned two compounds is in a lamellar structure with periodic βTi and FeTi plates. Each set plates of βTi and FeTi have a specific orientation relationship and the same crystal orientation to decrease the interfacial energy between two compounds. At high cooling rates, the directionality is discovered in the plates growth resulting in an aligned microstructure with the plates oriented in the heat flow direction [1].

Some elements like Cr, W, V, Ta, Nb, Fe, and Mo are β-stabilizer elements, whose presence decreases the α-β transus. Some other elements like O and Al are α-stabilizer elements with the opposite influence. The overall influence of these elements can be measured by the calculating %Mo equivalent which as follows:

$$\begin{aligned} \%Mo \text{ Equivalent} = & 0.67 (\%V) + 1.0 (\%Mo) + 0.44 \\ & (\%W) + 0.22 (\%Ta) + 0.28 (\%Nb) - 1.0 (\%Al) + 1.6 \\ & (\%Cr) + 2.9 (\%Fe) \end{aligned} \quad \text{Eq.(1)}$$

It is supposed that a β-alloy will form when %Mo-equivalent values exceed 10 %. In the Fe-Ti pair, a few amount of mixing is needed to surpass the 10% Mo equivalent threshold. The expanded solubility of iron in βTi has been detected at elevated cooling rates. This permits the formation of βTi(Fe) phase at composition levels apart from the equilibrium range [1].

3. Application of Ti-SS Joints

Thanks to their proper stiffness and high-temperature

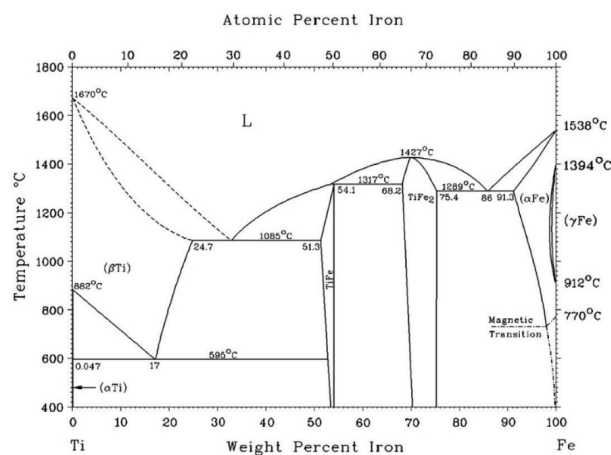


Fig. 1. Ti-Fe binary phase diagram [2].

mechanical properties, elevated strength, great corrosion resistance, stability in aqueous media, high specific strength, and enhanced oxidation resistance, titanium alloys have found extensive applications in astronautics and aeronautics for civil and military purposes. However, their high costs is a serious challenge [3]. Commercial pure (CP) titanium is roughly 10 and 100 times more expensive than the stainless steel (SS) and plain steel, respectively [4-6]. Austenitic SSs are utilized in applications requiring high levels of the workability [4, 5, 7].

Owing to its attractive characteristics like elevated toughness at ambient temperature, and proper high-temperature creep resistance, Ti6Al4V (equivalent to TC4) is recognized as the most commonly used Ti alloy, covering 60% of the Ti global market. It has found a broad range of applications in chemical and aerospace industries [8].

High strength joints of SSs and Ti alloys offer extensive advantages for medical, chemical, cryogenic, petrochemical, microelectronics, as well as heat exchangers for thermal power station, nuclear, aerospace, aeronautics, astronautics, and spacecraft industries. Meanwhile, weight and cost reduction are highly demanded for car bodies to enhance fuel efficiency and decrease the air pollution [4, 5, 9-12].

4. Difficulties of Direct Welding of Ti-SS

4.1. Brittle Intermetallics Formation

The direct joining of SS and Ti alloys suffers from two main challenges. The first one is the formation of brittle intermetallic compounds (IMCs) like brittle Fe_2Ti and Cr_2Ti compounds due to the limited solubility of Fe and Ti. Intermetallic phases form at the interface between two metals, in this case, titanium and stainless steel. These phases usually arise due to chemical reactions between the elements of different metals, significantly influencing the mechanical and metallurgical properties of the weld [5]. Based on the binary Ti-Fe phase diagram (Fig. 1.), the solubility of iron in titanium is very low (0.1% at room temperature), beyond which, the fragile IMCs TiFe (600 HV) and then $TiFe_2$ (1000 HV) start to form [1, 6].

4.1.1. Factors Affecting the Formation of Intermetallic Compounds

The following factors influence the formation of intermetallic compounds:

- **Welding temperature:** The welding temperature and process parameters, such as welding speed, can affect the type of intermetallic phases.
- **Chemical composition:** The ratios of different elements in titanium and stainless steel impact the formation and stability of intermetallic phases [6].

4.1.2. Effects of Intermetallic Compounds on the Weld Properties

Some weld properties may be affected by the intermetallic compounds:

- **Hardness and Brittleness:** Intermetallic phases may increase the hardness of the weld but can simultaneously induce brittleness.
- **Alteration of Physical Properties:** These phases can modify physical properties such as thermal expansion and thermal conductivity [7].

4.2. Difference in Thermal Expansion

The second challenge of Ti-SS welding is the formation of residual stresses and then cracks, due to the huge differences between thermo-physical properties of Ti alloy and SS. Regarding the extensive application of Ti6Al4V and 304 SS, their physical and mechanical characteristics are shown in Table 1. The thermal expansion coefficients of 304 SS and Ti6Al4V are $17.3 \times 10^{-6} K^{-1}$ and $8.6 \times 10^{-6} K^{-1}$, respectively. After the welding process, assuming that the two alloys are initially at the same temperature, the titanium will undergo a lower contraction than the stainless steel during the cooling. As the two alloys are welded, this dissimilarity leads to the tensile stress on the stainless steel side and also compressive stresses on the titanium side [1].

To examine the thermal stress during the Ti6Al4V-304 SS laser welding, the coefficient of thermal expansion (CTE) and Young's modulus of 304 SS and Ti6Al4V were investigated [13]. The thermal stress can be calculated by:

$$\sigma = \alpha \cdot E \cdot \Delta T \quad \text{Eq.(1)}$$

Where E, ΔT , and α are Young's modulus, temperature gradient, and CTE, respectively. For the Ti6Al4V and 304 SS:

$$\sigma_{Ti6Al4V} = E_{Ti6Al4V} \cdot \alpha_{Ti6Al4V} \cdot \Delta T_{Ti6Al4V} \quad \text{Eq.(2)}$$

$$\sigma_{304 SS} = E_{304 SS} \cdot \alpha_{304 SS} \cdot \Delta T_{304 SS} \quad \text{Eq.(3)}$$

For both Ti6Al4V and 304 SS, assuming constant temperature gradient:

$$\Delta T_{Ti6Al4V} = \Delta T_{304 SS} = \Delta T \quad \text{Eq.(4)}$$

CTE and the Young's modulus of 304 SS and Ti6Al4V are:

$$\alpha_{Ti6Al4V} = 8.7 \times 10^{-6} 1/K \quad \text{Eq.(5)}$$

$$\alpha_{304\text{ SS}} = 16 \times 10^{-6} \text{ 1/K} \quad \text{Eq.(6)}$$

$$E_{\text{Ti6Al4V}} = 110 \text{ GPa} \quad \text{Eq.(7)}$$

$$E_{304\text{ SS}} = 193 \text{ GPa} \quad \text{Eq.(8)}$$

Thus:

$$\sigma_{304\text{ SS}} = 3.22 \sigma_{\text{Ti6Al4V}} \quad \text{Eq.(9)}$$

Based on Eq.(9), the thermal stress in the 304 SS is 3.22 times higher than the TC4 alloy without contemplating the formation of compounds at the interface. Regarding the formation of the brittle IMCs in the Ti-SS joints, the residual stresses and then cracking can occur due to the difference in thermal stresses of Ti6Al4V alloy and SS [15].

4.3. Differences in the Thermal Diffusivity and Heat Conductivity

The coefficients of the heat conductivity of TC4 alloy and 304 SS are 6.7 W/m.K and 16.2 W/m.K, respectively. The samples spontaneously crack at sufficient contents of intermetallic compounds. Consequently, prevention from the formation of brittle intermetallic compounds promotes the formation of strong joints between SSs and Ti [9, 11, 15-20]. The difference in the heat conductivity can be the principle reason for the propagation of the cracks. Therefore, the induced heat spreads twofold quicker in the 304 SS compared to TC4 [20]. The audible rupture occur during the solidification of welds [1].

The Ti thermal diffusivity, $6.9 \times 10^{-6} \text{ m}^2/\text{s}$, is almost twice that of SS, $4.08 \times 10^{-6} \text{ m}^2/\text{s}$. In the meanwhile, Ti also has a greater melting temperature, 1665 °C vs 1375 °C. Thus, more heat should be provided for the titanium to assure it attains its melting temperature which is executed through the heat source offset (like a laser beam) toward the Ti [1]. The temperature in the SS plate is bigger than that in the Ti plate because the efficiency of the heat dissipation of the SS side is greater than that of the Ti side due to the higher heat conductivity of SS [5].

5. How to Prevent Brittle IMCS Formation

The Ti-Fe phase diagram shows the insufficient solid solubility between Ti and Fe. Also, the formation of IMC depends on the temperature-time profile of both alloys. Due to the dependence of the formation of IMCs on the diffusion of elements from the parent alloys towards each other and then the reaction of elements with together, an increase of the temperature-time cycles enhances the mobility of metallic elements and thus, the formation of different intermetallics. The direct Ti-SS weldments are too brittle with weak joining strength due to the formations of brittle σ phase and IMCs. Two approaches can be adopted to prevent the formation of brittle IMCs:

- The control of the welding process (adjusting the heat input).
- Welding metal engineering (utilizing of other metals as interlayers to modify the composition of the weld zone) [22].

6. Interlayer Engineering

The mechanical properties of the SS-Ti alloy welds can be enhanced by insertion of the intermediate foils to modify the interaction character of the melted zone (MZ), and promote the formation of compounds other than Fe-Ti-rich IMCs [17]. The most common of these intermediate foils are Cu, Ni, Mg, Al, and Ag capable of forming intermetallic compounds with titanium. These foils hinder the diffusion of atoms between Fe and Ti, Ni, or Cr [16]. Zr, V, Mo, Nb, Hf, and Ta are another group of candidates for the welding SSs to Ti alloys which do not produce IMCs with Ti. Pure vanadium is the most favored of these elements which can create solid solutions with titanium. The melting temperature of V (1914 °C) is close to Ti (1670 °C) [23]. It is well recognized that Ti does not produce IMCs with pure Nb, Zr, Ta, Mo, Hf, or V. The weldability of these metals with SS, and also their high-cost result in the utilization of low-cost and more available metals like Ni, Cu, and their alloys [17]. These intermediate layers have been applied to prohibit the formation of Fe-Ti IMCs during the welding [14]. The mechanical strength of such joints could be increased by adding an interlayer to modify the composition of the final compound [9].

Table 1. The physical and mechanical properties of pairing materials and pure Cu [21].

Alloy	Thermo-physical properties					Mechanical Properties				
	Melting temperature (°C)	Thermal conductivity (W.m-1.K-1)	Density (g/cc)	Linear expansion coefficient (10^{-6} K^{-1}) 20°C	Specific heat capacity ($\text{J.Kg}^{-1}.\text{K}^{-1}$)	Hardness (V)	UTS (MPa)	Shear modulus (GPa)	Y.S. (MPa)	Elongation at Break (%)
Ti6Al4V	1604-1660	6.7	4.43	8.6	526.3	349	950	44	880	14
304 SS	1400-1455	16.2	8.00	17.3	500	129	505	86	215	70
Pure Cu	1083	385	7.764	16.4	385	50	210	46	33.3	60

7. Interlayer for Ti-SS Welding

The mutual solubility of Fe and Ti with the other elements in a binary system are depicted in Fig. 2. Titanium almost reacts with the most elements to produce brittle intermetallic compounds, except for some elements such as Zr, V, Ta, and Nb. Ti creates the most brittle Fe-Ti IMCs with the iron exists in SS [24].

7.1. Single Interlayer Suggestion

A proper intermediate layer for the welding 304 SS to Ti6Al4V should possess enough solubility in both Ti and Fe. Okamoto et al. [2] extensively addressed this topic whose results are listed in Table 2. which presents the elements with maximum solubility in Fe and Ti.

Accordingly, V and Cr showed the highest solubility in both Ti and Fe.

7.2. Composite interlayer suggestion

The use of a single intermediate layer between two alloys suffers from high cost of V and Cr and also low resistance to corrosion of Cr in SS-Ti alloy joints. Meanwhile, the selection area for the suggestion of a single interlayer is more limited than that of the composite interlayers. Consequently, the composite interlayers comprising two different interlayers are needed. Elmi Hosseini et al. [14] suggested a topological diagram (Fig. 3.) to illustrate the elementary transition lines between some elements with the maximum solubility at room temperature, based on the binary phase diagrams [2].

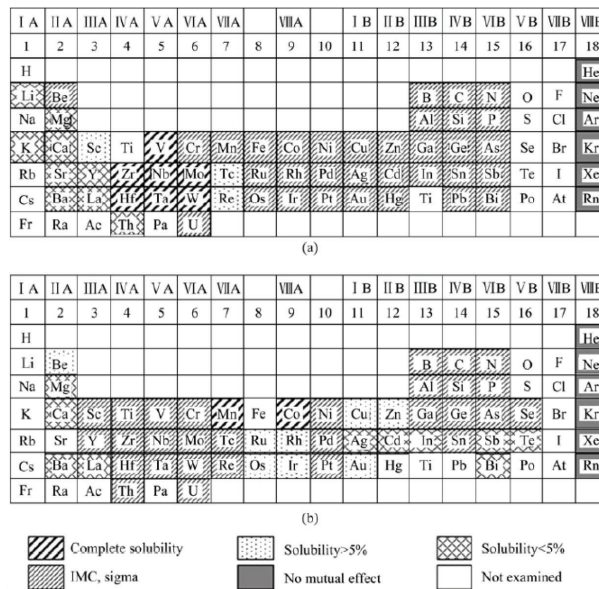


Fig. 2. Mutual solubility of (a) titanium and (b) iron with the other elements in the binary periodic system (up to 1200 °C) [24].

Table 2. Elements with the highest solubility in Ti and Fe at the single interlayer condition.

Element	The elements with maximum solubility
Fe	V, Ni, Cr, Ir, La, Mn, Ag, Pd, Ph, Au, Co, Cu
Ti	Mo, Gd, V, Nd, W, Sc, Zr, Ce, Cr, Nb, Y, Er, Ta, Th

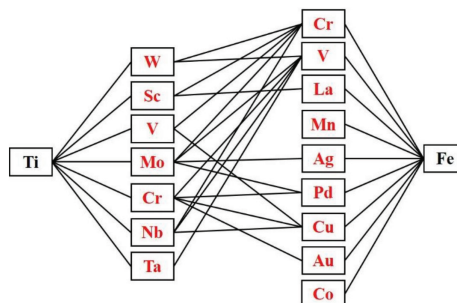


Fig. 3. The elements topological diagram with the maximum solubility in Ti and Fe with no IMC formation [2].

Based on Fig. 3. Ti does not form brittle IMCs with W, Sc, V, Mo, Cr, Nb, or Ta. Furthermore, Fe cannot form brittle intermetallics with elements such as Cr, V, La, Mn, Ag, Pd, Cu, Au, and Co. Considering the composite interlayers containing two metallic layers, either interlayer next to Ti and SS sides with enough solubility in each other are connected by dark lines in the topological diagram. Consequently, all combinations of two columns of elements such as Nb-Cu, V-Cu, and W-V can be considered as composite interlayers to join Ti alloy and SS, especially Ti6Al4V-304SS pair.

8. Cu Interlayer

Wang et al. were the first scientists to execute the liquid state welding of Ti alloy to stainless steel with the 1 mm Cu interlayer [4]. The weldment was achieved by two pass electron beam (EB) welding. Furthermore, the MZ was depicted to contain Fe₂Ti IMCs dispersed in the Cu medium. The mechanical strength of the weld was 224 MPa. Meanwhile, brittle fracture occurred within the intermetallic layer near the MZ/titanium interface [17]. Among the mentioned elements, copper is considered a proper choice to meet the industrial requirements due to the following reasons [23]:

- 1- Copper is compatible with iron and does not form brittle IMCs with Cr, Fe, C, or Ni. The copper interlayer refines the metallurgical reactions within the weld pool and leads to the formation of Cu-Ti IMCs by decreasing the proportion of TiFe and TiFe₂ intermetallic compounds. The formation of Ti_xCu_y compounds is compensated by high toughness of Cu and leads to acceptable joint strength. Moreover, copper-containing IMCs are tougher with lower hardness compared to Ti-Fe IMCs [17, 18, 22]. The Cu-Ti binary phase diagram is exhibited in Fig. 4.
- 2- Copper is a soft metal which can be easily deformed

to decrease inner stress concentrations during the liquid state welding and lighten the residual stresses created by linear expansion mismatch [4]. According to Zhang et al. [5], lateral and the maximum longitudinal residual tensile stresses decreased from 88 and 260MPa to 57 and 194 MPa, respectively after the copper sheet addition. This indicates that the Cu metal is a proper choice for welding Ti alloy to SS in terms of residual stress [5].

3- The copper melting point is greater than that of Mg or Al, signifying high corrosion resistance and high-temperature performance of the joint with copper interlayer [15].

4- The copper melting point is not very high, therefore, the copper filler is completely melted while partial Ni and V fillers remain in the weld due to their higher melting points [4, 15].

5- The copper is also less expensive than Ni and Ag, decreasing the production costs [14, 25].

6- Clearly, the Fe/Cu/Ti joint temperature is less than that of the Fe/Ti joint. The copper heat conductivity is greater than SS or Ti alloy. Therefore, the Cu filler metal could be considered a “cold source”. Consequently, the temperature is declined in both sides [5].

Some disadvantages of Cu as the interlayer are:

- 1- The properties of Ti-Cu-Fe systems express that the joint temperature durability is much inferior to that of Ti alloys and steels according to low temperature transformations of the copper containing compounds [9].
- 2- Copper is occasionally welded by the laser welding due to elevated reflection of the laser beam which reduces the process efficiency and durability [15].

9. Solidification of MZ

The large surface area which connects the molten metal to the both interface sides as well as limited proportion of molten metal would increase the cooling rate

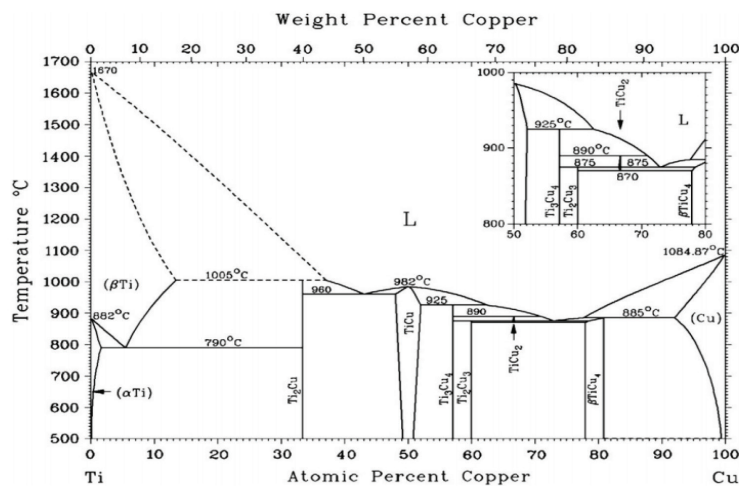


Fig. a2. Ti-Fe binary phase diagram [19].

Fig. 4. Ti-Cu binary phase diagram [2].

of this region and also non-equilibrium compounds and microstructures formation [1]. Since titanium has the greatest melting temperature (1725 °C), the solidification starts on the interface between Ti6Al4V and the molten bath. The 2nd area that starts to be solidified is the stainless steel melted zone (T_m of Fe = 1538 °C). High Cu content besides its gamma type character as well as high cooling rate stabilizes γ_{Fe} to room temperature [26].

Regarding the Ti-Fe equilibrium diagram, the formation of Fe₂Ti phase is initiated at 1427 °C and the FeTi compound appears at the nodular inclusions edge at 1317 °C, on the titanium alloy/molten bath interface as well as in the copper-rich liquid regions [26]. After that, the Fe(Cr)-Ti phases nucleated firstly in the weld pool, and Fe(Cr) and Ti contents in the residual liquid declined quickly. As the temperature achieved the Cu melting point, a solid-solution of the copper appeared in the residual liquid [27]. The solidus temperature of the Cu-rich solid solution (near the 1085 °C) is greater than the melting temperatures of Ti-Cu IMCs which is about 890 °C for Cu₃Ti₂. Consequently, it solidifies in the shape of large dendrites [17].

10. Computational Thermodynamics

While the ternary and binary phase diagrams are favorable for understanding the influences of 2 or 3 main components on the compounds created during the welding, they are not capable of considering more than 3 constituents. Computational thermodynamics methods are usually utilized to describe the influence of more components. The fundamental of the phase prediction by computational thermodynamics is investigated by the calculation of the Gibbs free energy of different compounds of a material as a function of composition, X; pressure, P; and temperature, T. At a mechanical mixture of two pure constituents, the Gibbs free energy could be given as:

$$G^M = X_A H_A + X_B H_B - T(X_A S_A + X_B S_B) \quad \text{Eq.(1)}$$

Where S_i , H_i , and X_i show the entropy, enthalpy, and mole fractions of the corresponding constituents (A and B), respectively. As a solution is formed, the Gibbs free energy can be determined by:

$$G^S = X_A \bar{H}_A + X_B \bar{H}_B - T(X_A \bar{S}_A + X_B \bar{S}_B) - T\Delta S_M \quad \text{Eq.(2)}$$

Where barred quantities indicate values in the solution, ΔS_M denotes the entropy of mixing that accounts the solution configurational entropy. For the dilute solutions, the configurational entropy is given by:

$$\Delta S_M = -R(X_A \ln X_A + X_B \ln X_B)_M \quad \text{Eq.(3)}$$

For the non-ideal solutions in which the properties of the pure form and solution are different, the Gibbs free energy can be calculated by:

$$G_S = G_M + X_A(\bar{H}_A - H_A) + X_B(\bar{H}_B - H_B) - T[X_A(\bar{S}_A - S_A) + X_B(\bar{S}_B - S_B)] + RT(X_A \ln X_A + X_B \ln X_B) = G_M + \Delta H^{XS} - T\Delta S^{XS} - T\Delta S_M \quad \text{Eq.(4)}$$

Where X_s are the difference of the values relative to the ideal solution.

Eq.(4) indicates the Gibbs free energy of a distinct compound as a function of composition and temperature but constant pressure. As the mentioned relationships are recognized for each compound, the equilibrium phase diagram could be generated by plotting the compound with minimum free energy at each temperature and composition. This is the base of the CALPHAD (the abbreviation of CALculation of PHase Diagrams) [1].

11. Welding Processes for Ti-SS Joining

11.1. Liquid State Weldings

Liquid state welding processes, which are extensively employed in industry, are accompanied by a challenge in the welding of Ti alloys to steels. Liquid state welding involves melting the materials by heat followed by their joining. This method is typically used to bond metals or other materials at high temperatures. In this process, the workpieces are heated to their melting temperature, such that the material is liquified in the welding zone. After cooling, a strong and cohesive bond is formed. The molten zone of steel-titanium mixture could be hardly managed in traditional arc welding due to metallurgical incompatibilities, and the formation of long-lasting MZs with a complete mixing of the elements. Therefore, IMCs are formed during the welding. The instability of electric arc hinders the continuous energy supply, leading to local variations of the MZ content. Elevated power beam techniques like electron beam and laser weldings have made the liquid state welding of stainless steel to titanium alloy possible as they obtain accuracy in the weld realization, rapid cooling/heating gradients, and a local heat supply [4, 9, 16-18, 28].

The development of liquid state welding methods for the welding of Ti alloy to stainless steel by using the interlayer opens fascinating alternatives for the solid state weldings as it enables easy preparation of the junction surfaces, a fast-welding technique, and high flexibility in the geometry of welds [17].

Principles of liquid state welding can be listed as [17]:
1. Heat generation: To perform liquid state welding, the

workpieces must first be heated to their melting point (depending on the material type). This could be achieved by various heat sources such as gas torches, electric arcs, lasers, or hot plasma.

2. Formation of the molten pool: Once the metals reach their melting temperatures, a molten pool is created where the metal is liquified. This molten pool is the area where two metal pieces melt and fuse together.

3. Alloying and mixing: During welding, additional filler metals or materials may be introduced into the molten pool, leading to the formation of alloys or mixing. This helps to enhance the strength and properties of the weld.

4. Cooling and Solidification: At the end of the welding process, the molten metal gradually cools and solidifies. This is a critical step as the cooling rate and the type of material welded can significantly affect the mechanical and physical properties of the weld.

11.1.1. Cold metal transfer

Cold metal transfer (CMT) process is also used for the welding of SS to Ti. This technique is suggested not only for its flexibility but also for its low heat input. This method does not require the furnace and could be utilized for different types of joints. Meanwhile, CMT could be adapted for many paths or designs of the joint when compared with other welding processes such as explosion welding and infrared brazing. A CuSi_3 wire with a diameter of 1 mm was deposited between the SS and Ti plates by using the CMT process as depicted in Fig. 5 [22].

11.1.1.1. Principles of CMT Welding

The core principle of cold metal transfer is to reduce the heat applied to the workpiece by using a controlled, pulsed wire feed mechanism. The process is characterized by the following steps [22]:

1. Wire feed pulsing: In CMT, the welding wire is fed into the weld pool in a controlled and pulsed manner. The wire is advanced towards the weld pool and then briefly retracted. This controlled movement of the wire reduces the heat introduced into the weld zone.

2. Reduction in heat input: The key innovation of CMT lies in its ability to minimize the heat input into the workpiece, preventing the overheating of thin materials. The short-circuiting behavior (when the wire touches the workpiece) is also controlled in such a way that the energy delivered during the short circuit is limited. After the wire is retracted, it cools quickly and reintroduces a new drop of molten metal with a controlled amount of energy.

3. Stable arc behavior: Due to the precise control of the wire movement and the arc, CMT ensures a stable arc throughout the welding process. This results in significantly reduced spatter and better control over the weld pool, allowing for a higher-quality weld, especially on thin materials.

4. Minimal heat affected zone (HAZ): The heat-affected zone (HAZ) is minimized in the CMT process as it uses lower heat input. This is particularly advantageous for welding heat-sensitive materials such as aluminum and high-strength steels. The reduced HAZ helps prevent material deformation, oxidation, and changes in mechanical properties near the weld.

11.1.1.2. Advantages of CMT Welding

Some advantages of the CMT process are [23, 24, 32]:

1. Reduced heat input: The most significant advantage of CMT is its ability to weld with reduced heat input. This makes it ideal for welding thin materials or delicate parts where high temperatures could lead to distortion, warping, or other unwanted effects.

2. Low spattering: CMT produces significantly less spatter compared to conventional MIG welding, which results in

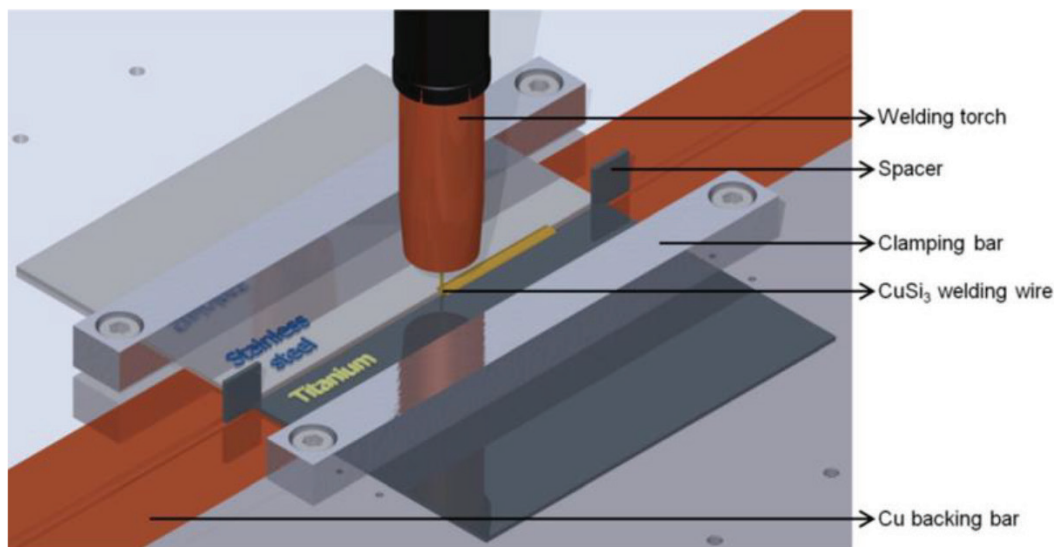


Fig. 5. A schematics of the CMT process used for Ti-SS welding [22].

cleaner welds requiring less post-weld cleanup. This is highly beneficial in terms of quality and efficiency.

3. Improved weld quality: The precision of the wire feed and the stability of the arc result in high-quality welds with smooth, uniform bead appearance. This method also enables proper control over the penetration depth and weld pool, ensuring a strong and durable bond.

4. Welding of thin materials: CMT is especially well-suited for welding thin materials (such as sheet metal or light-gauge materials) without burn-through or excessive distortion. This feature makes it highly effective in automotive, aerospace, and other industries where thin metals are common.

5. Versatility with different materials: While it is particularly popular for welding aluminum and high-strength steels, CMT is also appropriate for a variety of other metals, including stainless steel and mild steel. The process can be adjusted to handle a wide range of material types with various thicknesses.

11.1.1.3. Disadvantages of CMT Welding

Some disadvantages of the CMT process can be listed as [22]:

1. Equipment cost: CMT requires specialized equipment, including advanced power sources and wire feed systems, which can be more expensive than traditional MIG/MAG welding setups. However, this cost may be offset by the increased efficiency and reduced need for post-weld cleaning and rework.

2. Limited thickness range: While CMT excels at welding thin materials, it may not be as effective for thick samples, where traditional welding processes might be more suitable.

3. Need for skilled operators: The precision required for CMT welding means that operators need to be well-trained to fully utilize its capabilities to achieve the highest quality.

11.1.1.4. Applications of CMT welding

Some applications of the CMT process include [22, 27]:

1. Automotive industry: CMT is commonly used in the automotive industry for welding body panels, sheet metal, and other thin-walled components. The low heat input and minimal spatter are ideal for delicate parts requiring high-quality, precise welds.

2. Aerospace industry: The aerospace industry benefits from CMT due to its ability to weld thin materials like aluminum alloys with minimal thermal distortion. The reduced heat input ensures the structural integrity of sensitive components.

3. Thin-walled products: CMT is extensively used for welding thin-walled metal products such as kitchen appliances, furniture, and various consumer goods where precision and minimal distortion are crucial.

4. Stainless steel and aluminum welding: This technique is especially advantageous for welding heat distortion-sensitive materials like aluminum as well as heat-sensitive samples such as stainless steel, where excessive heat input can alter material properties. The controlled arc and wire feed ensure minimal damage to properties of these materials.

11.1.2. Laser Welding

Laser welding is extensively utilized to weld 304 SS and Ti6Al4V. As one of the most advanced welding methods, laser welding employs a laser beam to melt and join the pieces. Thanks to its high precision, ability to focus energy on a small area, and high speed, it has been used in various industries such as automotive, aerospace, medical, and electronics. Laser welding utilizes laser technology to produce a high-energy light beam capable of raising the temperature of the materials in the welding area to their melting point. The schematic of the laser welding process is depicted in Fig. 6. [26, 40].

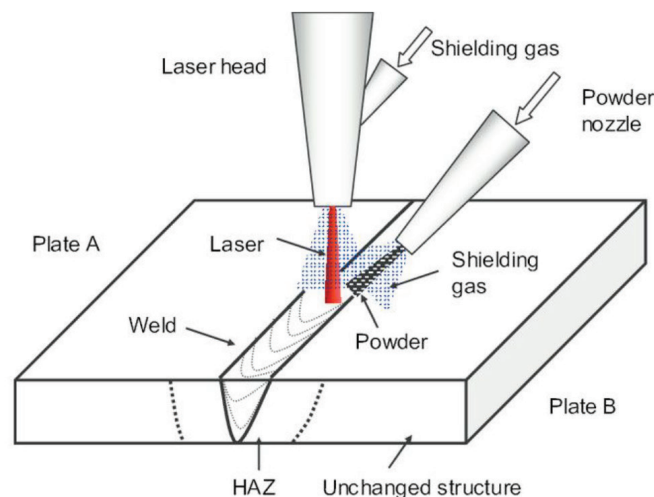


Fig. 6. The schematic of the laser welding process [26].

This process demonstrates the following advantages:

- Cost reduction with minimum destruction to the workpiece.
- Possibility of increasing the depth of the MZ under a constant pulse width by raising the pulse repetition rate.
- The quality of the welding has an acceptable standard in terms of cracking, strength, and microstructure.
- Elevated efficiency, great flexibility, and fantastic controllability,
- Applicability in various environments (vacuum and non-vacuum environment) [18, 20, 22].
- Minimum thermal deformation,
- High local heat concentration in the weld seam with high cooling and heating rates [29],
- Bright promises in welding dissimilar metals like Ti/SS, steel/Mg, Ti/Mg, Ti/Al, Al/steel, and Cu/steel [15],
- Safety and feasibility [30].

11.1.2.1. Principles of Laser Welding

In laser welding, the laser energy is focused onto a specific point on the surface of the materials. This energy causes the materials to melt. A strong bond is formed between the two pieces after cooling and solidification. This process is typically carried out in two different modes [18, 22]:

1. Laser pulsed welding:

In this method, the laser is applied in short and intense pulses. This type of welding is commonly used for thin materials or precise joints. The laser pulses transfer a large amount of energy in a very short time, allowing rapid

melting and the formation of clean and accurate welds.

2. Continuous laser welding:

In this method, the laser beam is continuously applied to the surface of the workpiece. This method is suitable for high-speed welding of thicker materials. The continuous energy from the laser allows deep penetration and formation of stronger bonds in the materials.

11.1.3. Laser Arc Welding

The laser arc hybrid welding process is employed to weld SS and Ti alloy to avoid the high reflection of the laser beam. This method has received much attention due to its dominances acquired from the arc and laser like:

- Elevated welding speed,
- Process stability,
- Useful bead appearances,
- Fantastic mechanical properties,
- Appropriate ability of the gap bridging [15].

The process is schematically illustrated in Fig. 7.

11.1.4. Electron beam welding

Electron beam welding is recommended as a liquid state welding process for welding dissimilar alloys due to its narrow heat-affected zone, accurate control of the heating position and area, vacuum atmosphere, and high energy density [4]. This process should be executed in vacuum, limiting its utilization. The schematic of this process is shown in Fig. 8. [18, 31].

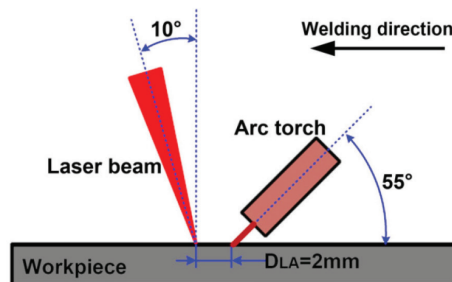


Fig. 7. A schematic diagram of the hybrid laser-arc welding [15].

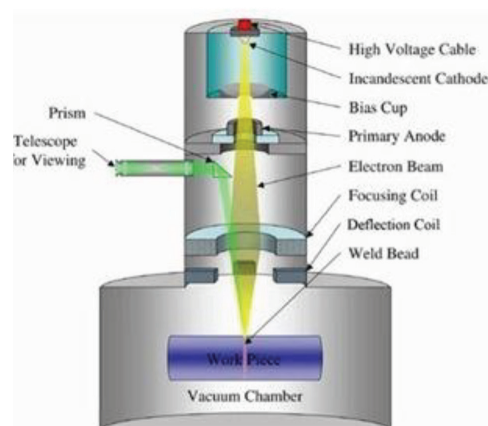


Fig. 8. The schematic of the electron beam welding process [8].

11.1.4.1. Principles of Electron Beam Welding

In electron beam welding, an electron beam is generated by an electron gun and accelerated towards the workpiece. Upon collision with the surface of the material, the kinetic energy of electrons is converted into heat, causing the material to melt in the targeted area. This process enables deep and high-quality welding due to the highly focused energy in the welding zone [31, 56].

The process is generally carried out in a vacuum chamber, which prevents contamination such as oxidation and ensures high-quality welds. As a result, welds produced by this method are typically characterized by high strength, high precision, and excellent quality [8, 31].

11.2. Solid-State Weldings

Solid-state welding refers to a group of welding methods where two workpieces are joined without the materials melting. In these processes, the joining is achieved through the application of pressure, heat, or a combination of both, at temperatures below the melting point of the materials. Unlike conventional welding methods, where the materials are melted, the materials bond together through mechanical or metallurgical approaches under the influence of temperature and pressure, forming a solid weld [8, 62].

11.2.1. Principles of Solid-State Welding

In solid-state welding, the two pieces are mechanically joined with no melting. This process is carried out in one or more stages, which may involve the application of pressure, heat, and in some cases, relative motion between the two pieces. Depending on the process specifications, additional materials or coatings may be used to

facilitate the joining. Solid-state welding processes typically occur at temperatures below the melting point of metals, ensuring no disturbance to the crystal structure and mechanical properties of the materials [62].

11.2.2. Diffusion Bonding

Diffusion bonding is considered a solid-state welding process to prohibit melting as schematically illustrated in Fig. 9. [31-36]. The bonding procedure including heating, pressing, and cooling is carried out under vacuum. IMCs volume fraction can be sufficiently decreased if the joints stay at high temperatures only for a short time [37]. Some disadvantages of this technique for the welding SS to Ti include:

- Careful surface preparation with high cleanliness standards of the joint interfaces [1, 9, 11, 15]. Using large sheets of SS and Ti in this method is impossible due to the applying huge stresses on the surface of both materials and also high volume manufacturing capacity.
- The materials should be entirely heated to a high temperature, which might not be desirable on some cases.
- A time-consuming process [31].

11.2.2.1. Principles of Diffusion Bonding

In diffusion bonding, heat is applied to promote atomic diffusion across the interface of the two closely-connected surfaces. The heat typically ranges from 60% to 90% of the melting point of the material. The pressure applied during the process helps to close any microscopic gaps between the materials, facilitating the atomic diffusion and formation of a strong bond. This bonding process can take from several minutes to hours, depending on the materials and temperature used [37, 42].

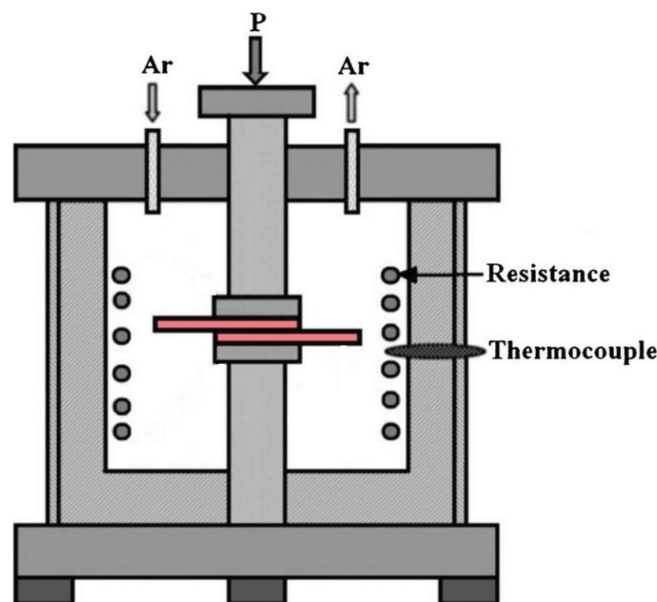


Fig. 9. A diagram of the diffusion bonding process [31].

11.2.2.2. Key Characteristics of Diffusion Bonding

Some key characteristics of the diffusion bonding processes can be listed as below [31,36,73]:

1. No melting of materials: Unlike fusion welding methods, diffusion bonding does not involve the melting of the workpieces, hence, preserving the properties of materials, such as strength, hardness, and corrosion resistance, particularly in sensitive materials.
2. Controlled temperature and pressure: The process typically requires precise control of both temperature and pressure. The temperature must be high enough to promote atomic diffusion but sufficiently low to avoid melting. The pressure ensures intimate contact between the surfaces, reducing any voids or gaps which might impair the bond.
3. Time-dependent process: Diffusion bonding is generally a time-dependent process. The bonding strength increases over time as atoms diffuse more thoroughly across the interface. Therefore, the bonding time can vary depending on the materials and conditions.
4. Surface preparation: An effective diffusion bonding requires highly clean and smooth surfaces. Contaminants or oxides on the surfaces can impede the diffusion process, leading to weak or poor-quality bonds. Many cases also require surface treatments like polishing or cleaning.

11.2.2.3. Advantages of Diffusion Bonding

Some advantages of diffusion bonding process include [63, 73]:

1. High-quality bonds: Diffusion bonding typically produces strong, reliable, and uniform joints at minimal distortion. It is especially suitable for joining dissimilar materials or materials that are difficult to weld by other methods.
2. Preservation of material properties: Since diffusion bonding does not involve melting, the base materials maintain their original mechanical properties, such as strength, ductility, and hardness, which could be compromised in fusion welding methods.
3. No filler material required: Diffusion bonding does not need any filler material, making the process suitable for applications in which filler metals are undesirable or when joining materials with different compositions.
4. Ability to join dissimilar materials: One of the key advantages of diffusion bonding is its ability to join dissimilar materials, such as metals to ceramics or metals with varying alloys. This is especially useful in applications like aerospace, nuclear industries, and electronics.

11.2.2.4. Disadvantages of Diffusion Bonding

Some disadvantages of diffusion bonding process includes [54, 81, 96]:

1. Slow process: Diffusion bonding is typically a slow

process, requiring extended times for the materials to diffuse and form a strong bond. This can make the method unsuitable for large-volume productions.

2. Need for high-temperature control: Achieving the necessary temperatures for diffusion bonding requires precise temperature control. Inconsistent heating can lead to poor bonding quality or material degradation.
3. Surface preparation is critical: A successful diffusion bonding requires precise surface preparation as diffusion process may not occur effectively on the surfaces with poor cleanliness preparation, leading to weak joints.
4. Limitations for thin materials: Diffusion bonding is often more effective for joining thin materials, as it relies on atomic diffusion, which may take too long or be less efficient for thicker sections.

11.2.2.5. Applications of Diffusion Bonding

Some applications of diffusion bonding process are [31, 58, 85, 93]:

1. Aerospace: Diffusion bonding is used in the aerospace industry for assembling turbine blades, engine components, and heat exchangers. The ability to join dissimilar materials (like metals to ceramics) makes it ideal for lightweight, high-performance components.
2. Electronics: Diffusion bonding is used to manufacture hermetically sealed packages for electronic devices, such as sensors and integrated circuits. It ensures a high-quality seal without affecting the sensitive internal components.
3. Nuclear industry: Diffusion bonding is particularly beneficial in the nuclear industry for joining materials requiring high strength and resistance to radiation damage. It is used in manufacturing reactor components and fuel rods.
4. Medical devices: The process is also used in the medical industry for creating implants or surgical tools with high strength and biocompatibility. Absence of melting preserve the original properties, a crucial feature for medical applications.
5. Automotive industry: Diffusion bonding can be used to join complex components in the automotive industry, where high precision and strong bonds are necessary, especially in applications like engine parts, transmission components, and exhaust systems.

11.3. Friction Stir Welding

Friction stir welding (FSW) is a type of solid state welding process, mainly applied for welding dissimilar alloys. As depicted in Fig. 10, heat is created by the relative motion of two alloy surfaces to be welded, thus, no interfacial melting occurs under normal conditions [31]. FSW enjoys higher operational efficiency compared to the other solid state welding techniques. FSW was invented for welding light alloys. Today, FSW enables welding materials with high-melting temperature like

different types of steels and Ti and Ni-base alloys with the help of high performance tools [31]. This process requires only a short heating time comparing with the diffusion bonding; thus, the IMCs layer growth could be decreased [38]. FSW poses a great challenge for the stirring pin when the joining is accomplished on elevated melting point alloys like Ti and Fe base alloys, particularly during long-term utilization of the pin [11, 14].

11.4. Explosive Welding

As a type of solid-state welding process, explosive welding (EW) offers a fantastic alternative for welding dissimilar alloys with different physical/metallurgical properties. The schematic of this technique is depicted in Fig. 11. [31]. Furthermore, this process has been used to weld SS and Ti; the tensile shear strength of the joint is bigger than the strength of the base material.

Nevertheless, the flexibility of this technique is very low comparing with the liquid-state welding techniques [22, 36, 38]. The issue of connecting interface plastic deformation is serious. Meanwhile, it is prone to produce crevices and discontinuities in the interface regions [37].

EW of the steel with Ti alloy forms an IMCs layer on the joint interface. Nevertheless, the IMCs thickness is less than that of the other welding processes. Moreover, the wave formation process on the joint boundary disturbs the coherence and continuity of the layer, enhancing the joint strength [6]. Some of the advantages of EW in welding the steel to titanium alloy are:

- The possibility of welding both small and large sheets,
- Outstanding mechanical properties of the joints,
- Low cost.

The disadvantages of the EW of steel with titanium alloy are the place could be performed the joining process and also the correct choice of the welding parameters [6].

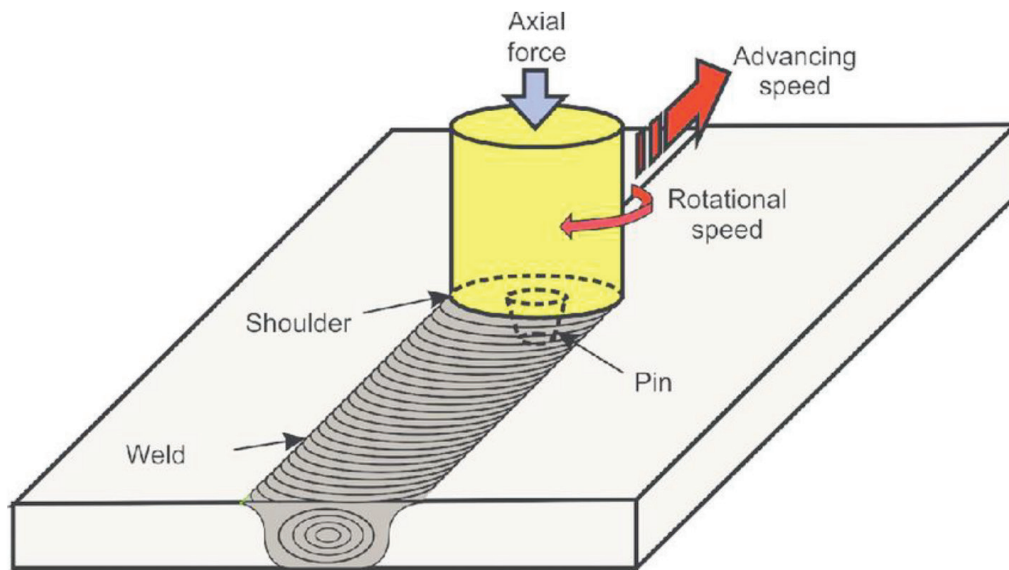


Fig. 10. A diagram of the friction stir welding technique [31].

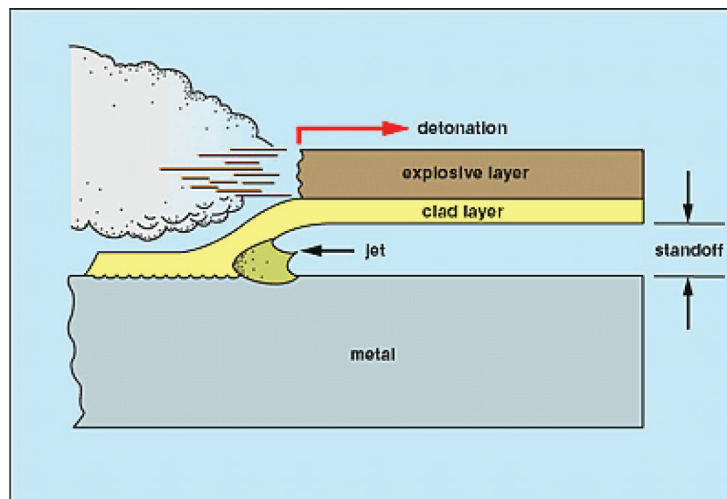


Fig. 11. The schematic of the explosive welding process [31].

11.5. Brazing

Brazing process is not a good choice for high-temperature applications. The schematic of this process is shown in Fig. 12. [9, 40]. Vacuum brazing has following advantages compared to the diffusion bonding:

- Low residual stress in the brazed joint because the filler metal serves as a buffer for the stress, and
- Low pressure is needed within the bonding area during the joining [8].

11.5.1. Principles of Brazing

In brazing, the base metals (the pieces to be joined) are placed in close contact with each other, and a filler metal is used as an intermediary. The melting point of the filler metal is typically lower than the base metals. Upon heating, the filler metal melts and flows into the joint, metallurgically bonding to the base materials [61,65,94].

- Heat: Heat is applied to melt the filler metal, typically between 430 to 1200°C, depending on the materials being joined.
- Pressure: In many cases, light pressure is applied to assist the flow of the filler metal to improve the quality of bonding by removing any imperfections or air pockets.
- Filler metal: The common filler metals include bronze, brass, silver, gold, or specific alloys such as aluminum and copper [44].

11.5.2. Advantages of Brazing

Some advantages of brazing are [37, 72]:

1. Joining dissimilar materials: Owing to its lower temperature and lack of melting, brazing is especially useful for joining metals to non-metals such as ceramics, glass, graphite, and even plastics.
2. Lower temperature requirement compared to

welding: The brazing process requires lower temperatures compared to traditional welding methods, lowering the thermal damages to the base materials.

3. High-strength joints: When done correctly, brazing produces strong and reliable joints with good resistance to corrosion and wear.
4. Energy and time efficiency: Brazing is faster and more economical, especially for large-volume productions.
5. Suitable for thin parts: Brazing is well-suited for joining thin parts that cannot withstand the high pressures or temperatures used in other welding processes.

11.5.3. Disadvantages of Brazing

Some disadvantages of brazing process are [22, 37, 49]:

1. Limited to thin parts: Brazing is more effective for joining thin or medium-thickness materials. Joining thick parts may be challenging as the filler metal may not flow evenly into the joint.
2. Importance of filler metal selection: the proper choice of filler metal with good compatibility to the base materials is crucial. Inappropriate filler metal result in weak or unstable joints.
3. Potential for contamination: If the surfaces are not properly cleaned, contaminants may hinder the bonding process, resulting in weak joints.
4. Process precision required: Brazing requires precise control over heat and filler metal flow as incorrect application can lead to poor joints or incomplete bonding.

11.5.4. Types of Brazing Methods

There brazing process can be divided into four types [93, 97, 104]:

1. Gas brazing: This method uses a gas flame (typically a mixture of oxygen and acetylene) to generate the heat needed to melt the filler metal. It is suitable for joining

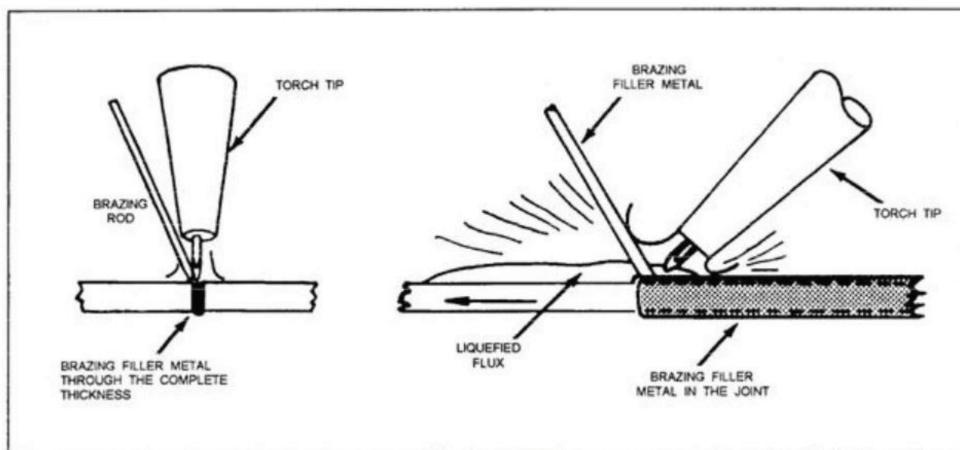


Fig. 12. The schematic of the brazing process [9].

lightweight and thin materials.

2. Furnace brazing: In furnace brazing, the parts are heated in a furnace to melt the filler metal and form the joint. This method is typically used in high-volume production and for larger parts.

3. Induction brazing: Induction brazing uses electric current to generate heat through induction coils. This is a fast and efficient method, particularly for small, precise joints.

4. Resistance brazing: In this method, an electric current is passed through the joint to create heat through electrical resistance, melting the filler metal and forming the bond.

11.5.5. Applications of Brazing

Some applications of this process are [64, 99, 106]:

1. Automotive industry: Brazing is used in the automotive industry for joining parts such as HVAC systems, heat exchangers, and other components requiring lightweight, strong connections.

2. Electronics industry: In electronics, brazing is used for joining delicate components or for creating hermetically

sealed packages for sensors and integrated circuits.

3. Aerospace industry: Brazing is widely used in the aerospace industry for joining high-performance components that require resistance to heat and corrosion, such as turbine blades and heat exchangers.

4. Medical devices: Brazing is used in the production of medical tools and implants where high strength and biocompatibility are essential. The preservation of material properties is critical for these applications.

11.6. Roll Welding

Laser roll welding (LRW) is a new welding technique. This process is not classified as a liquid or solid state weldings, and brazing/soldering. In this process, one of the base metals is heated up to the bonding temperature, followed by being pressed to the adjacent base metal without application of any intermediate layer, resulting in quick cooling by cold base metal as demonstrated in Fig. 13(a). [1, 12, 37]. For comparison, the weld appearance of the fusion, solid-state, LRW, as well as brazing, are displayed in Fig. 13(b).

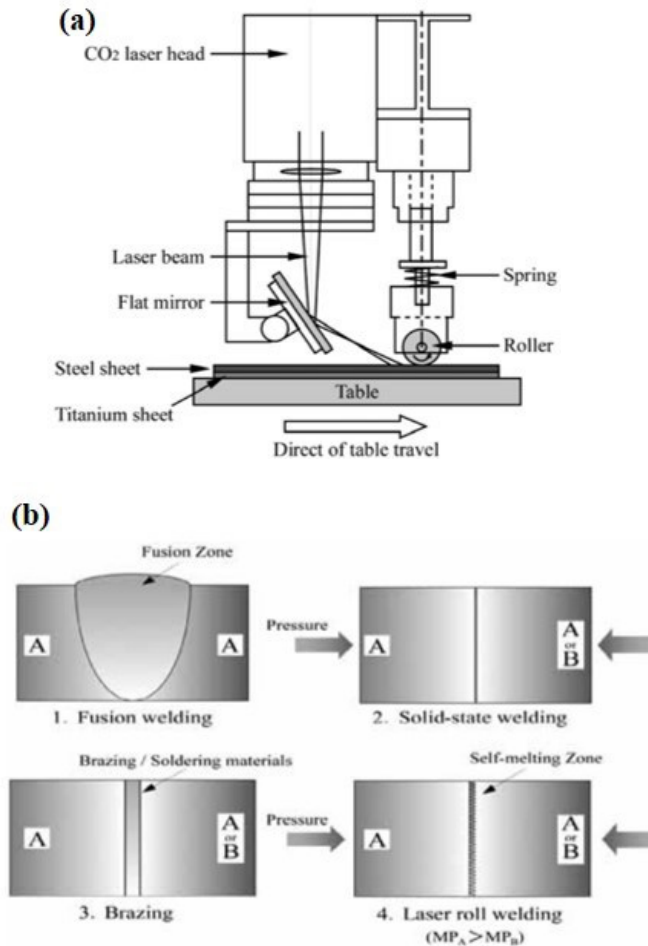


Fig. 13. A schematic diagram of (a) the laser roll welding and (b) comparing the weld appearance of some joining processes [12].

12. Recent in Vestigations on Ti-SS Joints

The researchers have attempted to accomplish many fusion welding techniques on the Ti-SS pairs in the last 24 years as illustrated in Table 3. Meanwhile, the results of the last investigations performed with solid-state welding processes for the welding of SS to Ti are listed in Table 4. Regarding the extensive applications of Ti6Al4V and 304 SS, it is necessary to consider the results performed on the same mentioned dissimilar materials.

Tables 5 and 6. list the results of the recent investigations on the laser and the solid-state weldings, respectively. The maximum joint strength of fusion welded Ti6Al4V-304 SS with the thickness of 2 mm was reported by Elmi Hosseini et al. [14,121]. The strength of ~350 MPa was observed using the combination of 1 mm Cu and 0.5 mm V as the interlayer between the pairing materials. However, the highest tensile strength of the Ti6Al4V-304 SS joint is roughly 417.5 MPa when the diffusion bonding process and Nb interlayer are used for the investigation [32].

Table 3. Results on dissimilar fusion welding of Ti alloy-SS over last two decades.

Ref. No.	Welding process	SS type	Ti type (phase type)	Sheet thickness/mm	Filler material	Filler thickness/mm	Weld. speed/ $\frac{m}{min}$	Laser power/kW	Offset (Ti-, SS+)/mm	Maximum strength/MPa	Joint Efficiency/%
[7]	Laser	304	CPTi	0.5	-	-	0.15, 0.6	-	Lap	-	-
[9]	Laser	316L	TC4 ($\alpha+\beta$)	2	V	1	2	3	Pass1: 0.1 far from V/Ti, pass2: 0.1 far from V/SS	367	58
[17]	Electron Beam				Cu	0.5	1, 1.8, 2.5, 3	-	-0.25 to +0.7	350	-
[41]	Laser & Electron Beam			Cu	0.32		1.5	Cu/SS interface	337 (EBW), 359 (Laser)	-	
[4]	Electron Beam	304	TA 15	2.5	V,Ni,Cu	0.5	-	-	Filler center	234 (Cu)	45
[42]			TA 15		V,Ni,Cu,Ag	0.5			310 (Ag)	5	
[25]			TA 15		Cu	0.5			0.2 far from SS/Cu	300	55
[27]			TA 15(α) (Ti6Al2Mo2V2 Zr)		Cu	1			-	310	60
[40]			Ti-15V-3Al (β)		Cu	1			-	234	42
[19]			Ti6Al2Zr2Mo2V(α)		V/33Cu-67 V	0.7			Pass1: 0.2 far from SS, pass2: V center	395	52% SS
[5]			Ti-15V-3Al (β)		Cu	-			-	66	21
[10]	Laser	304	CP Ti	3	V,Ta	0.7	3	3.5	0.15	40	7
[43]	Laser	301L	Ti6Al4V	0.8	Nb	1	0.1	1.05	-0.2 far from Ti/Nb	370	-
[44]	Laser	304	CPTi	0.25	-	-	-	-	-	200	-
[11]	Laser	304L	Ti6Al4V	2	AZ31B Mg alloy Filler	1	2	1.6-3.5	$\delta = 0.4$	221	-
[15]	Laser+Arc	316			Cu-Si wire		1.5, 3, 5	1.5, 2, 3	Tip of SS	212	-
[1]	Laser	316	Ti Grand2 (α)	0.8	-	-	0.02	0.3, 0.525, 0.75	0, -0.15, -3	81	-
[18]	Laser	201	Ti6Al4V	1	-	-	2	2	-0.6 to +0.6	150	-
[30]	Laser	304	CPTi	3	Ta+Cu	Ta:0.1, Cu:1	0.9-1.2	1.5-2.4	-	417	-
[45]					TiN, Y ₂ O ₃ , Cr nanopowder	-	1	2.35	-3	375	77
[20]	Laser	316L	Ti6Al4V	Ti1.8, SS 1	-	-	0.05-0.3	-	-0.2	-	-
[22]	MIG	316L	Ti6Al4V	Ti1.7, SS 2	CuSb	1	-	-	0.5, 0.85, 1.2	200	-
[29]	Laser	¹² Cr ¹⁸ Ni ¹⁰ Ti	VT1-0	2	Cu	1	1	3	-	-	-
[28]	Resistance spot welding	304	Ti6Al4V	1	Nb	0.1	-	-	-	5.61 kN	-

[3]	Laser	301L	Ti6Al4V	0.8	Cu	0.4	0.25	1.04	Cu center	350	-
[94]	Laser	304	Ti6Al4V	1	Monel400	0.25	0.6	1.2	+1	216	-
[95]	Laser	301L	Ti6Al4V	1	Ni	0.5	0.65	0.456	+0.5 far from SS/Ni	178	-
[96]	Laser	304	Ti6Al4V	1	38Zn-61Cu	0.2	0.6	0.624	+1.5 far from SS/38Zn-61Cu	210	-
[97]	Laser	304	Ti6Al4V	1	Ag73-Cu16-Zn11	0.2	0.612	0.500	+1.5	129	-
[98]	Laser	301L	Ti6Al4V	0.8	V	1	0.250	1.05	Pass1: 0.25 far from Ti/V Pass2: 0.25 far from V/SS	587	-
[99]	Laser	301L	Ti6Al4V	0.8	Cu	0.4	0.150	1.05	+0.20 far from Cu/SS	320	-
[100]	Laser	301L	Ti6Al4V	0.8	-	-	0.150	1.05	-0.45	336	13
[101]	Laser	301L	Ti6Al4V	0.8	Ta+V+Fe	V=1, Ta=0.2, Fe=0.2	0.250	0.184, 0.127	Pass1: Ta center Pass2: Fe center	627	-
[102]	Laser	304	Ti6Al4V	1	TA2+Q235	2	0.700	0.456	Pass1: Ti/YA interface Pass2: Q235/SS interface	548	-
[103]	Laser	304	Ti6Al4V	1	Ag45-30Cu-Zn25	0.2	0.600	0.612	+1.6	284	-
[104]	Laser	304	Ti6Al4V	1	V+Cu	V=0.2, Cu=0.16	0.280	0.450, 0.420	-1.3	181	-
[105]	Laser	304	Ti6Al4V	1	38Zn-61Cu	0.2	0.650	0.480	-1.5	128	-
[106]	Laser	304	TiNi	1	38Zn-61Cu	0.2	0.650	0.576	+1.2	153	-
[107]	Laser	301L	Ti6Al4V	0.8	V	1	0.250	1.05	pass 1: 0.2 far from Ti/V pass 2: +0.2 far from V/SS	Method 3: 599	-
[108]	Laser	304	Ti6Al4V	1	TA2+304	1-10	-	-	TA2/304 SS Interface	545	-
[109]	Laser	301L	Ti6Al4V	0.8	-	-	0.200	1.05	-0.35	182	-
[110]	Laser	304	Ti6Al4V	1	Monel400/Nb	Monel400=0.25, Nb=0.5	-	0.405	+0.9, -0.7	258	-
[111]	Laser	301L	Ti6Al4V	0.8	Ni+Nb	Nb=0.8, Ni=0.8	0.200	0.148	Pass1: Ti/Ni interface Pass2: Ni/Nb interface Pass3: Nb/SS interface	269	-
[112]	Laser	304	Ti6Al4V	1	TA2+T2	1	0.720	0.370	TC4/TA2 interface, T2/SS interface	428	-
[113]	Laser	4HP-17	Ti6Al4V	40	V	15	0.210	0.180	SS/V Interface, V/Ti Interface	700	-
[114]	Laser	304	Ti6Al4V	3	TC4+304 explosion welded composite	3	0.600	1.20	SS/SS interface, Ti/Ti interface	830	-

[115]	Laser brazing	304	Ti6Al4V	1	CuZn	1	-	0.0624	CuZn Center	210	41
[120]	Laser	304	Ti6Al4V	1	AgCuTi	0.1	0.75	0.432	+2.5	104	-
[23]	Laser	304	Ti6Al4V	2	Cu	1	2	4	Cu/SS interface	300	45
[14,121]	Laser	304	Ti6Al4V	2	Cu+V	Cu=1, V=0.5	2	3.5	Cu/V interface	350	-

CP Ti: Commercial Pure Ti.

TC4 equals Ti6Al4V.

Offset: - for the radiation towards Ti, + for the radiation towards SS.

Table 4. Results on dissimilar solid state welding of Ti alloys-SS over last three decades.

Ref. No.	Steel type	Ti type	Filler material	Filler thickness/mm	Joint configuration	Maximum strength/MPa	Joint Efficiency/%	Elongation/%
Diffusion Bonding								
[46]	MDSS	CP Ti	-	-	Cylinder	306	96	6.9
[47]	MDSS	TC4	Ni alloy (NiA)	0.15		560	84	8.3
[48]	17-4 PH	TC4	Ni alloy (NiA)	0.15		523	53	6.2
[48]	17-4 PH	TC4	-	-		477	48	4.2
[49]	MDSS	TC4				510	77	6.5
[50]	MDSS	TC4				520	78	6.8
[51]	MDSS	TC4				556	84	-
[52]	17-4 PH	CP Ti	Ni	0.3		325	102	10.6
[53]	304	CP Ti				302	94	-
[54]	304	CP Ti				Ni	0.3	270
[37]	304L	TC4	Ni	0.4	Butt	440	81	20
[32]	304		Nb	0.5	Butt	417.5	77	-
[55]	321		Ni	0.4	Lap	467	-	-
[56]	Low carbon steel	CP Ti	Ag, Cu, Zn	0.08	Lap	shear strength=3222.8 N	-	-
[57]	Pure Fe	CP Ti	-	-	Lap	-	-	-
[58,59]	Low carbon steel	CP Ti	Cu-12Mn-2Ni	0.1	Butt	Shear strength=105	-	-
[33,34]	304	TC4	Ni	0.03	Lap	Shear strength=148	-	-
[60]	321		Al alloy (LF6)	0.5	-	183	-	-
[8]	321		Ag-26.7Cu-4.6Ti	0.05	-	188	-	-
[61]	304L	CP Ti	Ag-ABA	0.05	Lap	-	-	-
[62,63]	316L	TC4	Cu	0.05, 0.1, 0.15	Lap	284	-	-
[64]	Super SS (20Cr-18Ni-6Mo)	CP Ti	(58Ti-16Zr-26Ni) amorphous alloy foil	0.1	V/Cr/Ni:30/10/20µm	480	-	-
[65]			Ag-28Cu eutectic alloy foil (BAg-8)	0.07	Ag coated on Ti by sputtering	410	-	-
[66]			Ag, Ti, Zr, and Ni alloys	-	-	280 (Ti)	-	-
[67]			72Ag-28Cu,66.2Ag-25.8Cu-8Pd	0.07	Ag coated on Ti by sputtering	423	92	-
[35]	304	TC4	Ag	-	Lap	Shear strength=149	80	-
[67,69]	304L	CP Ti	-	-	-	242	75	5
[70]						217	68	2.2
[71,72]						226	71	5.8
[73]		Ti-5.5Al-2.4V	272	47	3.5			

[74]	304	Ti-4.5Al-2.2V(Ta17)	-	-	Lap	307	56	-
[75]						321	59	-
[76]		CP Ti	Ag	0.05		421	-	-
[77]	304	CP Ti	Ag(30-50%)-Cu	0.1	Lap	50	-	-
[78]	MDSS	TC4	-	-		-	-	-
[79]	304	CP Ti	-	-		380	80	40
[36]	304L	TC4	-	-		242	41	-
[80]	321	CP Ti	Nb+Cu+Ni	0.01, 0.01, 0.01		300	68	-
[81]	304	CP Ti	-	-		-	-	-
[116]	IF	Ti6Al4V	Cu+Ni	Cu=0.015, Ni=0.0085	Butt	Shear strength=186	-	-
[117]	316L	Ti6Al4V	-	-	Butt	208	-	-
[119]	17-4	Ti6Al4V	Ni+Cu	0.3	Butt	660	-	10
Friction Welding								
[38]	304, 3 mm	CP Ti, 1 mm	-	-	Lap	-	-	-
[82,83]	Structural steel, 6 mm	CP Ti, 2 mm	FSW	-	Lap	Fracture load=14 kN	-	-
[84,85]	304L	CP Ti	-	-	Cylinder	460	98	-
[17]	304L	CP Ti	-	-	Butt	400	91	-
[86,87]	304L	CP Ti	FSW	-	Butt	Shear strength=119	73,98	-
Explosive Welding								
[88]	304	CP Ti	-	-	Lap	535	-	-
[89]			304 SS	0.3, 0.5, 1		-	-	
[90]	304L	TC4	-	-		Shear strength=726	102	-
[91,92]	304L	CP Ti	-	-		-	-	-
[93]	304L	CP Ti	-	-		457	105	20
[118]	304	TC4	304+TC4(TA2)	-		600	65	2.5

MDSS: Micro-Duplex Stainless Steel

Table 5. Results on dissimilar fusion welding of Ti6Al4V-304 SS over the last two decades.

First author	Ref. No.	Welding process	SS type	Ti type	Sheet thickness/mm	Filler material	Filler thickness/mm	Welding speed/ $\frac{m}{min}$	Laser power /kW	Offset (Ti-, SS+)/mm	Max. strength/MPa	Joint Efficiency/%
Gao	[11]	Laser	304L	Ti6Al4V	2	AZ31B Mg alloy Filler	1	2	2.5	$\delta = 0.4$	221	---
Elmi Hosseini	[23]	Laser	304	Ti6Al4V	2	Cu	1	2	4	Cu/SS interface	300	45
Elmi Hosseini	[14,121]	Laser	304	Ti6Al4V	2	Cu+V	Cu=1, V=0.5	2	3.5	Cu/V interface	350	---

Table 6. Results on dissimilar solid state welding of Ti6Al4V-304 SS over the last three decades.

First author	Ref No.	SS type	Ti type	Welding process	Filler material	Filler thickness/mm	Joint configuration	Max. strength/MPa	Joint Efficiency /%
Zhao	[32]	304	Ti6Al4V	Diffusion Bonding	Nb	0.5	Butt	417.5	77
He	[33,34]	304			Ni	0.03	Lap	Shear strength=148	---
Balasubramanian	[35]	304			Ag	---	Lap	Shear strength=149	80

13. Conclusions

This study presents an in-depth investigation into the welding of titanium alloys to stainless steel, addressing critical challenges such as the formation of brittle intermetallic compounds (e.g., Fe₂Ti and FeTi), residual stresses, and significant differences in the thermal and mechanical properties of the two materials. The key findings and insights derived from this research could be listed as follows:

- The primary issues in joining these materials include the formation of brittle intermetallic compounds due to limited solubility between titanium and iron, as well as the development of residual stresses by the disparity in thermal expansion coefficients. These factors negatively impact joint strength and durability, especially in fusion welding methods.
- Advanced fusion welding techniques, such as laser welding and electron beam welding, demonstrated the ability to produce high-quality joints at optimized process parameters. Laser welding, in particular, is effective when coupled with interlayers to suppress intermetallic formation. For example, the combination of copper and vanadium interlayers achieved a tensile strength of 350 MPa, while pure copper interlayers significantly reduced the residual stresses and improved the joint performance.
- Solid-state welding methods, such as diffusion bonding and friction stir welding, effectively decreased the formation of brittle phases by operating at lower temperatures and shorter heat exposure times. Diffusion bonding using niobium interlayer achieved the highest tensile strength of 417.5 MPa, showcasing its superiority for producing strong and reliable joints. Friction stir welding offered additional benefits, such as minimal residual stress and consistent mechanical properties, making it suitable for high-performance applications.
- The incorporation of interlayers, including copper, niobium, silver, and vanadium, effectively improved the joint quality. These interlayers not only minimized the formation of brittle intermetallic compounds but also improved the overall mechanical properties of

the welds. Niobium interlayers were particularly effective in diffusion bonding, while copper provided excellent thermal conductivity and stress relief in the fusion welding.

- The findings of this study are highly relevant to industries such as aerospace, chemical processing, automotive, and medical fields, which demand lightweight, high-strength, and corrosion-resistant joints. The use of optimized welding techniques and suitable interlayers offers a practical pathway for reducing production costs and enhancing the reliability of dissimilar joints in these critical applications.
- Despite significant progress in this field, further research is recommended to explore the optimization of interlayer compositions, the use of novel materials, and the development of hybrid welding techniques. These advancements could further enhance the mechanical and metallurgical properties of titanium-stainless steel joints, enabling broader industrial adoption.

In summary, this study highlights the critical role of advanced welding techniques and interlayers in overcoming the inherent challenges of joining titanium alloys to stainless steel. The results provide valuable guidance for the design and implementation of welding processes, ensuring high-performance and reliable joints for a wide range of industrial applications.

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