Interfacial reaction and mechanical properties of diffusion bonded titanium/17-4 PH stainless steel dissimilar joint using a silver interlayer

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Abstract

Diffusion bonding of titanium (Ti) to 17-4 PH high strength stainless steel is challenging owing to the formation of brittle Ti-Fe intermetallic compounds (IMCs) at joint interface. In the current study, it was demonstrated that such detrimental Ti-Fe IMCs can be effectively eradicated by using a silver (Ag) interlayer. The diffusion bonded Ti/Ag/17-4 PH stainless steel is characterized by Ti-Ag solid solution, TiAg, remnant Ag interlayer and Ag-(Fe, Cr, Ni) interdiffusion layer. The interfacial reaction phase TiAg exhibited no detrimental effect on bonding strength. During tensile test, ductile fracture took place in the remaining Ag interlayer of resultant joint. Bonding strength up to ~420 MPa was obtained over bonding durations in the range of 15 ~ 25 min. It is thus concluded that using an Ag interlayer is highly appealing in improving bonding strength of diffusion bonded Ti/17-4 PH stainless steel dissimilar joint.

1. Introduction

Titanium (Ti) and its alloys are leading candidate materials in a wide spectrum of industry sections such as aerospace and nuclear power plant owing to their outstanding combination of high specific strength and excellent corrosion resistance [1]. However, Ti is rather expensive in comparison with commonly used metallic materials such as aluminum alloys and steels. To this end, it is frequently required to joining Ti to other metallic materials to form a hybrid component in practical applications, for the sake of synergistic cost reduction and property exploitation [2, 3].

17-4 PH is a well-established high strength maraging stainless steel designation. Owing to the addition of 17 wt.% Cr, 17-4 PH stainless steel exhibits decent corrosion resistance. Upon quenching and subsequent aging, high density of fine Cu-rich particles with mean diameter in the range of 3 ~ 5 nm would precipitate in the martensite matrix. Attributed to extraordinary strengthening effect of such high density of nano-sized precipitation particles, ultra-high strength exceeding 1400 MPa can be obtained in 17-4 PH stainless steel grade [4]. Currently, 17-4 PH stainless steel is extensively employed in a wide spectrum of industrial sections including pressurized water reactors and oil/chemical industries. In comparison with commonly used austenite stainless steels, e.g. 304 and 316 grades, the primary advantage of 17-4 PH stainless steel is the outstanding strength, which is almost twice that of austenite counterparts [5]. Previously, considerable efforts have been devoted to join Ti to austenite stainless steels for the sake of cost reduction. In this context, combining Ti together with 17-4 PH stainless steel would provide such hybrid components further enhanced mechanical performance and upgraded load bearing capacity. Essentially, several attempts toward dissimilar joining of Ti alloy and 17-4 PH stainless steel have already been documented specific to applications ranging from aero-space components to sport equipment such as golf club manufacturing [6–8].
Previous investigations concerning dissimilar welding/joining of Ti and steel have already demonstrated that it is challenging to achieve robust bonding of Ti and steel. This is primarily because of poor metallurgical compatibility of Ti-Fe system and notable mismatch in physical properties of both halves [9]. The mutual solubility of Ti-Fe system is rather limited. When conventional fusion welding techniques were employed in Ti/steel welding, large population of Ti-Fe IMCs would be generated at the joint interface. Since such IMCs are generally characterized by extreme brittleness, they would significantly deteriorate the joint strength [10]. Consequently, considerable efforts have been devoted to overcome the detrimental effect of brittle interfacial reaction products on bonding strength of Ti/steel dissimilar joint. For instance, alternative solid-state bonding techniques including diffusion bonding, brazing and friction welding was developed to alleviate excessive growth of brittle Ti-Fe IMCs [11–14].

Among these techniques mentioned above, diffusion bonding has been demonstrated to be a viable approach to circumvent problems encountered in fusion welding. It was reported that bonding strength of 326 MPa can be achieved in diffusion bonded Ti/17-4 PH stainless steel joint. However, despite that problems encountered in fusion welding can be partially alleviated because of the notably reduced heat input in diffusion bonding, the bonding strength remains to be deteriorated by the interfacial Ti-Fe IMCs [15]. To further improve the joint strength, interlayer strategy was attempted to avoid generation of Ti-Fe IMCs. For instance, foils of Cu, Ni and Nb have already been used as intermediate materials in the case of diffusion bonding Ti to steel [13–21]. Indeed, applying interlayer can effectively suppress interaction of Ti and steel substrate and completely avoid formation of Ti-Fe IMCs. However, despite that improved bonding strength was reported in joint with these interlayers, the success is limited. This is because although using such interlayers can eradicate the formation of Ti-Fe IMCs, new IMCs which are intrinsically brittle would form. For instance, using Ni as interlayer would result in a Ti-steel joint composed of Ti2Ni, TiNi, TiNi3, remnant Ni interlayer and Fe-Ni solid solution [21]. In fact, reviewing the Ti and Fe related binary alloy phase diagrams; one can find that it is impossible to find out a metal which is concurrently compatible with both Ti and steel [21]. This indicates that by applying a single interlayer is difficult to completely eradicate the formation of IMC in Ti/steel dissimilar joint.

In a previous investigation, Ag was designed as diffusion barrier in the case of brazing Ti to Cu [22]. It was found that the interfacial reaction product between Ti and Ag, TiAg, exhibited notable fracture toughness despite its nature as IMC. Owing to the presence of Ag interlayer, excellent bonding strength comparable with parent metal properties was achieved. Referring to the Fe–Ag binary alloy phase diagram, no IMC would form in Fe–Ag system [23]. It is thus expected that using Ag as intermediate materials in Ti/steel diffusion bonding might effectively eliminate the formation of detrimental interfacial reaction products, and in turn enhance bonding strength.

To this end, the current study was carried out to validate the feasibility of diffusion bonding Ti to 17-4 PH stainless steel using an Ag interlayer. Interfacial microstructure characterization and mechanical assessment of resultant joints were conducted. It was found that using an Ag interlayer can successfully suppress the formation of brittle interfacial reaction products of Ti/17-4 PH stainless steel dissimilar joint, and bonding strength up to ~420 MPa was obtained. The underlaying metallurgical principles determining the relationship between interfacial microstructure and mechanical properties were discussed according to the experimental results.

### 2. Materials and methods

The square bars of commercially pure Ti (Gr. 2) and 17-4 PH stainless steel with the dimension of $20 \times 20 \times 35$ mm$^3$ were used as parent materials, the nominal composition can be found in table 1. Pure Ag foil with a thickness of $\sim 50 \mu m$ was used as interlayer. The mating surfaces of substrates and interlayer were manually gritted using SiC abrasive paper up to 2000 grit. Prior to bonding, the faying surfaces were cleaned in acetone to eradicate any residual contamination. The diffusion bonding process was performed in Gleeble-1500D thermal simulator at 850 $^\circ$C under a compressive load of 5 MPa for bonding time varied from 15 to 25 min under vacuum condition of $1 \times 10^{-2}$ Pa. The heating rate was fixed at $20 ^\circ$C s$^{-1}$ and the bonds were furnace cooled to ambient temperature after bonding. Schematic illustration of the bonding assembly and tensile test specimen can be found in figure 1.

| Chemical composition of CP Ti and 17-4 PH stainless steel (wt.%) |
|---|---|---|---|---|---|---|---|
| Ti | O | N | C | Fe | Cr | Ni | Nb | Cu |
| CP Ti | Bal. | 0.14 | 0.05 | 0.05 | 0.20 | — | — | — | — |
| 17-4 PH | — | — | — | 0.05 | Bal. | 16.5 | 4.2 | 0.23 | 4.0 |
Subsequent to the bonding trials, selected specimens were longitudinally sectioned by wire electrical discharge machining and prepared by metallographic techniques. The samples were manually ground using SiC abrasive paper to 5000 grit and subsequently polished using 1.5 μm Al₂O₃ polishing paste. And detailed microstructural observations were conducted in scanning electron microscope (SEM, TESCAN VEGA II) using back-scattered mode (SEM-BSE) to reveal microstructures of the reaction layers near the interfaces. Chemical composition profile across the joints was determined using energy dispersive spectroscopy (EDS).

Micro-hardness profile of the joint interface was evaluated using a load of 10 g for duration of 5 s. Room temperature tensile tests using sub-sized specimen as schematically illustrated in figure 1 were performed in a tensile testing machine (Instron 1342) at a crosshead speed of 0.5 mm/min, according to the guideline of standard ASTM: E8. The tensile specimens were machined from the as-fabricated joint via wire electrical discharge machining. Prior to tensile test, the specimens were ground using SiC abrasive papers to 1000 grit to ensure the flatness of the sample surface. Considering the dimension tolerance generated in the machining and grinding processes, the actual dimensions of each individual specimen were measured for strength calculation. Six specimens were tested and the average value of joint strength was adopted in order to ensure the reliability of results. Fracture morphology observations were conducted to identify the fracture location and characteristic of the joints.

3. Results and discussion

Figure 1 shows the SEM-BSE overview images of the Ti/Ag/17-4 PH joints diffusion bonded at 850 °C for 15 min, 20 min and 25 min. It can be found that the Ag interlayer remained integral and successfully suppressed the inter-diffusion and reaction between Ti and 17-4 PH substrates under all bonding conditions. Most of the interlayer was retained after the bonding process. No voids of discontinuity can be detected at the joint interfaces, indicating the formation of intimate interfacial bonding. In general, bonding duration of up to 1 ~ 2 h is required to achieve intimate interfacial bonding between Ti and stainless steel at bonding temperature of 800 °C ~ 900 °C in conventional diffusion bonding practice. In the present case, a considerably reduced duration was required to achieve this goal. This can be attributed to the soft and ductile nature of Ag interlayer, which is highly favorable in promoting asperity collapse and shrinkage of voids upon compressive loading. Bonds formed at different durations are quite similar with obvious diffusion reaction layer formed at the Ti/Ag interface, whilst no detectable reaction products can be found at the Ag/17-4 PH stainless steel interface.

Moreover, the reaction layer was thickened with increased bonding time and additional diffusion layer can be found at prolonged bonding durations at the Ti/Ag interface, as shown in figures 2(b) and 2(c).

To reveal the interfacial reaction products of the resultant joint in further detail, SEM-BSE pictures at relatively higher magnification along with EDS scanning spectrum of the joints were given in figure 3 and figure 4. Corresponding EDS analysis results are collected in table 2. Shown in figure 3 is the interfacial microstructure of joint bonded for 15 min. It can be seen from figure 3(a) that a reaction layer with thickness of ~10 μm was generated at the Ti/Ag interface. EDS line scanning spectrum (figure 3(c)) across this interface shows a plateau, indicating that this reaction layer is an IMC phase with stoichiometric composition. To identify the phase constituent of this layer, EDS point analysis was conducted at location 1. It revealed a composition of Ti-51.3 at.% and Ag-48.7 at.%. According to the Ti-Ag binary alloy phase diagram, it can be concluded that this interfacial reaction layer is Ti₅Ag phase. Figure 3(b) gives the microstructure of the Ag/17-4 PH stainless steel interface. In contrast to the Ti/Ag interface, no obvious interfacial reaction products can be detected. Corresponding EDS line scanning spectrum (figure 3(d)) indicated that an inter-diffusion layer of

![Figure 1. Schematic illustration of diffusion bonding assembly and specimen for tensile test.](image-url)
approximately 1 μm was formed at this interface. This is in well agreement with prediction considering the Fe-Ag alloy phase diagram. The Fe-Ag binary alloy system exhibits very limited mutual solubility. This system could be considered as immiscible as no solid solution nor IMC can be read in Fe-Ag phase diagram. Despite the immiscible nature of Fe-Ag system, previous investigation has already proved that strong metallurgical bonding can be achieved between Ag and steel upon thermal activated diffusion bonding [24].

In view of the great similarity, the interfacial microstructure of joint bonded for 20 min is not given here. Instead, joint bonded for 25 min was characterized in detail considering the formation of additional reaction layer between Ti substrate and Ag interlayer. The results are given in figure 4. Analogous to the joint bonded for 15 min, TiAg phase with stoichiometric composition of approximately Ti-50/Ag-50 presented at the Ti/Ag

Figure 2. SEM-BSE images of Ti/Ag/17-4 PH joint for (a) 15 min, (b) 20 min and (c) 25 min.

Figure 3. SEM-BSE images and corresponding EDS linear scanning spectrum across (a), (c) Ti/Ag and (b), (d) Ag/17-4 PH interfaces of the joint bonded for 15 min.
interface (marked as 3 in figure 4(a)). Moreover, an additional layer with grey contrast can be found between TiAg and Ti substrate. Corresponding EDS line scanning spectrum (figure 4(c)) indicated that the Ti and Ag concentration profile of this layer is smooth with continuous variation, indicating that this layer is a solid solution phase. EDS point analysis (point 2) revealed a Ti-rich composition of Ti-96.6 at.% and Ag-3.4 at.%. According to the Ti-Ag alloy phase diagram, this reaction layer can be identified as Ti-Ag solid solution (s.s).

The microstructure of Ag/17-4 PH interfaces of the joint bonded for 25 min (figure 4(b)) resembles the joint bonded for 15 min to a great extent, without obvious interfacial reaction products. However, the inter-diffusion across the interface was significantly enhanced. As shown by the EDS line scanning results (figure 4(d)), a diffusion layer up to 3 μm was generated, indicating the formation of excellent metallurgical bonding.

The mechanical assessment and fracture characteristic analysis results of joints bonded for different durations is given in figure 5. Shown in figure 5(a) are representative engineering stress-strain curves of joint bonded for various durations, along with pertinent average bonding strength inserted. Average tensile strength of 417 MPa, 421 MPa and 414 MPa were achieved for joints bonded for 15 min, 20 min and 25 min, respectively. Such bonding strength is significantly improved in comparison with the directly diffusion bonded joint or joint with Cu, Ni and Nb interlayers. Representative fracture morphology of fractured joint bonded for 25 min (Ti side) is given in figure 5(b) as well. It can be found that the fracture surface is dominated by dimples, indicating

![Figure 4. SEM-BSE images and corresponding EDS linear scanning spectrum across (a), (c) Ti/Ag and (b), (d) Ag/17-4 PH interfaces of the joint bonded for 25 min.](image)

Table 2. Chemical composition of the marked regions in figure 1 (at.%).

| Regions | 1   | 2   | 3   |
|---------|-----|-----|-----|
| Ag      | 48.7| 3.4 | 49.2|
| Ti      | 51.3| 96.6| 50.8|
| Phase   | TiAg| Ti-Ag s.s | TiAg |

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that ductile fracture took place upon tensile loading. EDS analysis of fracture surface was conducted to identify the fracture location of this joint. As shown by the EDS spectrum in the bottom of figure 5(b), only Ag was detected on fracture surface. This indicates that fracture took place with the remnant Ag interlayer during tensile test. The above results are in well agreement with previous investigation on brazing Ti to Cu using an Ag diffusion barrier. In that case, joints consisting of TiAg, pure Ag interlayer and Ag-Cu solid solution were obtained. During tensile test, the TiAg remained stable and exhibited no deleterious effect on bonding strength [22]. In brief, by applying Ag interlayer in the case of Ti/17-4 PH stainless steel diffusion bonding, the brittleness can be effectively eradicated attributed to decent fracture toughness of the interfacial TiAg phase.

Previously, considerable amount of investigations concerning the diffusion bonding of Ti and steel (stainless steel) have been documented. Reviewing the literature, it can be summarized that the primary obstacle to achieve high strength diffusion bonding of Ti to stainless steel is the inevitable formation of brittle IMCs at the joint interface. For instance, direct diffusion bonding of commercially pure Ti and 17-4 PH stainless steel was conducted at 850 °C ∼ 950 °C [15]. Maximum tensile strength of 326 MPa was obtained when bonded at 900 °C for 2 h. During tensile test, fracture took place along the brittle Ti-Fe IMC phases of the joint. Although the detrimental effect of Ti-Fe IMC could be alleviated by using interlayers such as Cu, Ni and Nb to some extent, the success was limited since brittle IMCs including TiCu, TiNi or FeNb remained within the joint [16–21]. Consequently, the bonding strength was far less than the base metal properties.

By contrast, in the present case, notably improved bonding strength up to 420 MPa was achieved. This can be ascribed to the eradication of brittle interfacial reaction products. As shown in figures 2–4, the diffusion bonded Ti/17-4 PH dissimilar joints are primarily composed of Ti-Ag s.s, TiAg and remnant Ag interlayer. It is generally accepted that both Ti-Ag s.s phase and pure Ag interlayer would be highly ductile in character. Although the TiAg formed at joint interface, previous experiences have already demonstrated that it possesses decent fracture toughness despite its nature as a stoichiometric IMC phase. In this regard, it is reasonable to deduce that the brittleness of Ti/stainless steel diffusion bonded joint was successfully overcome by using an Ag interlayer. The eradication of brittleness of the Ti/Ag/17-4 PH diffusion bonded joint was further verified by the fracture morphology observations. As shown in figure 5(b), the joint fractured along the remnant Ag interlayer in a ductile manner, indicating that the soft Ag interlayer was the weakest location of the joint. TiAg phase exhibited no detrimental effect on the joint strength. It is worthwhile to mention that the joint strength is much higher than strength of pure Ag foil, which is no more than 200 MPa.

To elucidate the mechanical behavior of joint during tensile test, micro-hardness test was conducted using joint bonded for 25 min and the results are collected in table 3. The hardness of the Ti-Ag solid solution was not evaluated because of its small size. It can be found that the TiAg phase exhibited a moderate hardness which is only marginally higher than the Ti substrate. The remnant Ag exhibited the lowest hardness, suggesting that it is the weakest part of the joint. In this regard, the joint consisting of Ti substrate/Ti-Ag solid solution/TiAg/Ag/ 17-4 PH can be considered as an assembly with a soft and ductile Ag foil enwrapped by two hard substrates. Since yield strength of the Ag interlayer is less than that of the base materials, the interlayer will begin to deform plastically upon tensile loading while the base materials are still elastic. However, under uniaxial tensile loading any axial plastic extension of the interlayer is accompanied by a transverse contraction. This contraction of the

Figure 5. (a) Representative stress-strain curves of joints bonded under various bonding durations and (b) fracture morphology of the joint bonded for 25 min.
thin Ag interlayer would be restricted by the stronger base materials (which have not yet yielded) and transverse stresses would be built up, leading to a triaxial tensile stresses state\(^{[25]}\). The presence of triaxial tensile stresses would minimize the effective shear stress within the interlayer, thus reducing the tendency of the interlayer to plastically deform. As a result of such mechanical constraint provided by the stronger base materials, high tensile strength can be obtained in the Ti/Ag/17-4 PH joint despite the relatively low strength of soft Ag interlayer.

Another importance feature of the diffusion bonded Ti/17-4 PH stainless steel with Ag interlayer is the desirable joint microstructure and high bonding strength can be obtained over a wide range of bonding parameters. In the cases where brittle IMCs were generated in Ti-stainless steel diffusion bonded joint, the bonding strength is highly sensitive to the bonding strength. In brief, bonding strength would initially increase with elevated bonding temperature or prolonged bonding duration to a maximum value, and then decrease with further increment in bonding temperature of duration\(^{[14–17]}\). This can be attributed to the competitive effect of positive effect from coalescence of mating surfaces and negative effect from the excessive growth of brittle IMCs. At the initial stage, mating surfaces coalescence plays a predominate role in enhancing the bonding strength. However, prolonged bonding duration of elevated bonding temperature would promote excessive growth of brittle IMCs which is catastrophically detrimental to the bonding strength. As a consequence, optimized joint strength can be only obtained within a narrow processing parameter window. By contrast, in the present case, since the TiAg has no detrimental effect on joint strength, the brittleness of Ti-stainless steel was completely eradicated. Accordingly, desirable joint microstructure free from brittle interfacial reaction products can be obtained as long as the Ag interlayer can effectively block mass transfer and interaction between the substrate. Since solid state diffusion is sluggish, it is reasonable to speculate that consistent joint microstructure composed of Ti-Ag solid solution, TiAg and remnant Ag interlayer can be obtained over a wide range of bonding temperature and duration. Thus in turn, highly reliable bonding strength can be expected.

Table 3. Micro hardness (HV) of the phases in joint bonded for 25 min.

| Phase       | Ti  | TiAg | Ag  | 17-4 PH |
|-------------|-----|------|-----|---------|
| Hardness    | 133 ± 3 | 151 ± 6 | 46 ± 5 | 337 ± 7 |

In light of above experimental results and analysis, it can be concluded that the problems of forming brittle interfacial reaction products in diffusion bonding of Ti to 17-4 PH stainless steel can be readily circumvented by using an Ag interlayer. This is primarily because of the suppressed reaction between substrates and decent fracture toughness of TiAg phase. However, although detrimental effect of brittle interfacial reaction products can be eliminated and bonding strength can be improved, the joint strength remains to be lower than the base metal properties. According to the principles of joint with soft interlayer enwrapped with hard substrates, the strength of joint is closely related to the properties of the interlayer. The thinner and stronger the interlayer is, the higher the joint strength would be. In term of feasibility, it is impractical to further reduce the thickness of the Ag interlayer. Accordingly, strengthening the Ag interlayer via alloying with strong solid solution strengthening element such as Pd without altering the interfacial reaction characteristic might be a viable route to further enhance the mechanical properties of diffusion bonded Ti/17-4 PH joint. And this would be the topic of future investigation.

4. Conclusions

In summary, strong and reliable solid-state diffusion bonding of Ti to 17-4 PH stainless steel was achieved at 850 °C for durations ranging from 15 min to 25 min, with the aid of an Ag interlayer. The following conclusions can be drawn:

1. Ag interlayer can effectively suppress the inter-diffusion and reaction between Ti and 17-4 PH stainless steel, avoiding the formation of Ti-Fe IMC phases.

2. Joint consisting of TiAg, remnant Ag interlayer and Ag-Fe inter-diffusion layer can be obtained when bonded for relatively short duration. Prolonged bonding duration resulted in the formation of additional Ti-Ag solid solution between Ti substrate and TiAg.
(3) TiAg exhibited no detrimental effect on bonding strength of diffusion bonded Ti/17-4 PH stainless steel joint. Upon tensile loading, fracture took place with remaining Ag interlayer in a ductile manner and bonding strength up to ~420 MPa was obtained over bonding durations in the range of 15 ~ 25 min.

(4) Ag interlayer is highly appealing in achieving strong and reliable diffusion bonding of Ti and 17-4 PH stainless steel via avoiding the formation of brittle interfacial reaction products.

Author contributions

Bo Feng and Yongqiang Deng conceived this project and drafted the manuscript; Xiaowei Feng conducted the bonding experiments, SEM characterization and tensile test; Bo Feng, Juan Wang and Kaihong Zheng drummed up the funding projects. All authors analyzed the data and reviewed the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

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References

[1] Leyens C and Peters M 2003 Titanium and Titanium Alloys: Fundamentals and Applications. (Weinheim: WILEY-VCH Verlag GmbH & Co. KGaA)

[2] Li B, Chen Z, He W J, Wang P, Lin J S, Wang Y, Peng L, Li J and Liu Q 2019 Effect of interlayer material and rolling temperature on microstructure and mechanical properties of titanium/steel clad plates Mater. Sci. Eng. A 749 241–8

[3] Onuike B and Bandyopadhyay A 2020 Functional bimetallic joints of Ti-6Al-4V to SS410 Additive Manufacturing 31 100931

[4] Wang Z M, Li H, Shen Q, Liu W Q and Wang Z Y 2018 Nano-precipitates evolution and their effects on mechanical properties of 17-4 precipitation-hardening stainless steel Acta Mater. 156 158–71

[5] Yeli G M, Auger M A, Willford K, Smith G D W, Bagot P A J and Moody M P 2017 Sequential nucleation of phases in a 17-4PH steel: microstructural characterization and mechanical properties Acta Mater. 125 38–49

[6] Shiu R K, Wu S K and Shiu J Y 2008 Infrared brazing of Ti-6Al-4V and 17-4 PH stainless steel with (Ni)/Cr barrier layer(s) Mater. Sci. Eng. A 488 186–94

[7] Adomako N K, Kim J O, Lee S H, Noh K H and Kim J H 2018 Dissimilar welding between Ti-6Al-4V and 17-4 PH stainless steel using a vanadium interlayer Mater. Sci. Eng. A 732 378–97

[8] Kundu S, Mishra B, Olson D L and Chatterjee S 2013 Interfacial reactions and strength properties of diffusion bonded joints of Ti64 alloy and 17-4 PH stainless steel using nickel alloy interlayer Mater. Des. 51 714–22

[9] Kundu S, Roy D, Chatterjee S, Olson D and Mishra B 2012 Influence of interface microstructure on the mechanical properties of titanium/17-4 PH stainless steel solid state diffusion bonded joints Mater. Des. 37 560–8

[10] Tomashchuk I, Sallamand P, Andrzejewski H and Grevey D 2011 The formation of intermetallics in dissimilar Ti6Al4V/copper/AISI 316L electron beam and Nd:YAG laser joints Intermetallics 19 1466–73

[11] Liao J S, Yamamoto N, Liu H and Nakata K 2010 Microstructure at friction stir lap joint interface of pure titanium and steel Mater. Lett. 64 2317–20

[12] Akbarimousavi S and GoharKia M 2011 Investigations on the mechanical properties and microstructure of dissimilar CP–titanium and AISI 316L austenitic stainless steel continuous friction welds Mater. Des. 32 3066–75

[13] Laik A, Shirzadi A A, Tewari R, Kumar A, Jayakumar T and Dey G K 2013 Microstructure and interfacial reactions during active metal brazing of stainless steel to titanium Metall. Mater. Trans. A 44A 2212–25

[14] Kundu S and Chatterjee S 2006 Interfacial microstructure and mechanical properties of diffusion-bonded titanium–stainless steel joints using a nickel interlayer Mater. Sci. Eng. A 425 107–13

[15] Kundu S, Ghosh M and Chatterjee S 2006 Diffusion bonding of commercially pure titanium and 17-4 precipitation hardening stainless steel Mater. Sci. Eng. A 428 18–23

[16] Thirunavukarasu G, Kundu S, Mishra B and Chatterjee S 2014 Effect of bonding time on interfacial reaction and mechanical properties of diffusion-bonded joint between Ti-6Al-4V and 304 stainless steel using nickel as an intermediate material Metal Mater Trans A. 45 2076–90
[17] Thirunavukarasu G, Kundu S, Patel V V and Alankar A 2020 Analytical investigation on the evolution and growth of $\beta$-Ti and Fe-Nb-based intermetallics in diffusion coupled joints of TiAl4V/$\text{Nb}$ | SS Diffusion Foundation. 27 3–24

[18] Xie G M, Yang D H, Luo Z A, Li M, Wang M K and Mishra R D K 2018 The determining role of Nb interlayer on interfacial microstructure and mechanical properties of Ti/steel clad plate by vacuum rolling cladding Metals 11 1983–99

[19] Kundu S and Chatterjee S 2010 Evolution of interface microstructure and mechanical properties of titanium/304 stainless steel diffusion bonded joint using nb interlayer ISIJ Int. 50 1460–5

[20] Kundu S and Chatterjee S 2007 Effect of temperature on formation of reaction products and strength properties of titanium and stainless steel joints using copper interlayer Mater. Sci. Technol. 23 368–73

[21] Kundu S, Chatterjee S, Olson D and Mishra B 2007 Effects of intermetallic phases on the bond strength of diffusion-bonded joints between titanium and 304 stainless steel using nickel interlayer Metal Mater Trans A. 38 2053–60

[22] Lee M K, Lee J G, Lee J K, Park J J, Lee G J, Uhm Y R and Rhee C K 2008 Strong bonding of titanium to copper through the elimination of the brittle interfacial intermetallics J. Mater. Res. 23 2254–63

[23] Massalski T B 1990 Binary Alloy Phase Diagrams. 2nd ed. (Materials Park (OH): ASM International)

[24] Rosen R S and Kassner M E 1990 Diffusion welding of silver interlayers coated onto base metals by planer magnetron Sputtering J. Vac. Sci. Technol. A 8 19–29

[25] Tolle M C and Kassner M E 1995 Mechanisms of ductile fracture in pure silver under high-triaxial stress states Acta Metal Mater. 43 287–97