Diffusion bonding of commercially pure titanium to 304 stainless steel using copper interlayer

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Abstract

Diffusion bonding was carried out between commercially pure titanium (cpTi) and 304 stainless steel (304ss) using copper as interlayer in the temperature range of 850–950 °C for 1.5 h under 3 MPa load in vacuum. The microstructures of the transition joints were revealed in optical and scanning electron microscopy (SEM). The study exhibits the presence of different reaction layers in the diffusion zone and their chemical compositions were determined by energy dispersive spectroscopy. The occurrence of different intermetallic compounds such as CuTi\textsubscript{2}, CuTi, Cu\textsubscript{3}Ti\textsubscript{2}, Cu\textsubscript{4}Ti\textsubscript{3}, FeTi, Fe\textsubscript{2}Ti, Cr\textsubscript{2}Ti, T\textsubscript{2} (Ti\textsubscript{40}Cu\textsubscript{60}−xFe\textsubscript{x}; 5 < x < 17), T\textsubscript{3} (Ti\textsubscript{43}Cu\textsubscript{57}−xFe\textsubscript{x}; 21 < x < 24) and T\textsubscript{5} (Ti\textsubscript{45}Cu\textsubscript{55}−xFe\textsubscript{x}; 4 < x < 5) has been predicted from the ternary phase diagrams of Fe–Cu–Ti and Fe–Cr–Ti. These reaction products were confirmed by X-ray diffraction technique. The maximum bond strength of \(\sim 318\) MPa (\(\sim 99.7\%\) of Ti) was obtained for the couple bonded at 900 °C due to better coalescence of mating surfaces. With the rise in joining temperature to 950 °C, decrease in bond strength occurs due to formation of brittle Fe–Ti bases intermetallics. At a lower joining temperature of 850 °C, bond strength is also lower due to incomplete coalescence of the mating surfaces.

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1. Introduction

In recent years, the diffusion bonded components consisting of commercially pure titanium (cpTi) and 304 stainless steel (304ss) have several applications in chemical and nuclear industries [1–3]. Diffusion couple consisting of these two dissimilar materials suffers from poor mechanical properties due to the formation of brittle intermetallics in the diffusion zone and residual stress generation caused by mismatch in linear expansion coefficient [4].

Solid solubility of iron in titanium and vice-versa is limited at room temperature; the previous investigations by the present author depicts that, direct bonding between cpTi and 304ss promotes the formation of \(\sigma\), \(\chi\), \(\alpha\), Fe\textsubscript{2}Ti, \(\beta\)-Ti and Fe\textsubscript{2}Ti\textsubscript{2}O phases in the reaction zone as during diffusion mass transfer occurs across the bond line [5,6]. All these brittle intermetallic compounds impair the mechanical properties of the transition joints; hence, the use of soft interlayer has come into limelight to eradicate the limitation and to improve the mechanical properties. In the previous attempt, nickel has been used as an intermediate material to produce the transition joints and the results indicate an improvement in bond strength (\(\sim 256\) MPa) with respect to the direct bonding (\(\sim 217\) MPa) due to lowering in volume fraction of Fe–Ti intermetallic compounds [2,7,8]. In this respect, copper can also be considered as a potential candidate to be used as interlayer to further improve the joint quality. Copper does not form any intermetallics with iron. Moreover, the melting point of the copper is lower with respect to Ti, Fe and Ni; so, increase in the flow ability of the same at higher temperature (\(>0.5T\textsubscript{m} \ T\textsubscript{m}\) melting point in K) will encourage a good contact between the faying surfaces. Though binary phase diagram of Cu–Ti indicates the occurrence of Cu\textsubscript{2}Ti,
CuTi,Ti, CuTi and CuTi Ti; with increasing Cu content, how-
er ever, improved contact area may have some beneficial effect on the bond strength of the diffusion welded joints [9].

The present study reports diffusion bonding of commer-
cially pure titanium and 304 stainless steel using copper as an interlayer in the temperature range of 850–950 °C under uni-
axial load. The investigation projects the influence of bonding temperature on the interface microstructure and tensile prop-
erties of the bonded assemblies.

2. Experimental

The cylindrical samples of cpTi and 304ss with the dimen-
sions of 15 mm diameter and 30 mm length were used for diffusion couple preparation. The chemical compositions and room temperature tensile properties of the parent materials are given in Tables 1 and 2, respectively.

The mating surface of the cylinders were prepared by conven-
tional grinding and polishing techniques by final pol-
ishing on 1 μm diamond paste. The copper foil (300 μm thick, 99.95% purity) was used as intermediate material and both the surfaces of the interlayer were polished in the same fashion. The faying surfaces were cleaned in acetone and dried in air. The cpTi–Cu–304ss assembly was kept in contact in a fixture and was inserted in a vacuum chamber. The diffusion bonding was carried out at 850, 900 and 950 °C for 1.5 h in vacuum. Uniaxial load of 3 MPa was applied along the longitudinal direction of the sample. Heating was done at a constant rate of 14 °C min−1 at the time of processing and after the operation the samples were allowed to cool in vacuum.

The diffusion bonding joints thus formed were cut longitudi-
nally and prepared by usual techniques for metallographic observation. The titanium side was etched in an aqueous solution of 14 ml H2O (4 ml HF and 8 ml HNO3). The stainless steel side was etched by a mixture of HNO3 (10 ml), HCl (2 ml) and ethanol (96 ml) was used for etch-
ing pure copper. The structural change owing to diffusion was observed in a light microscope (Correct SDME TR5). Polished samples were also examined in scanning electron microscope (JEOL JXA 840A) using back-scattered mode (SEM-BSE) to reveal the reaction layers near the diffusion-welded interface. The composition of the reaction layers was determined near the two bond lines.

The SEM-BSE images of the transition joints are given in Fig. 2. Both stainless steel–copper (ss–Cu) and copper–titanium (Cu–Ti) interfaces are resolved at higher magnification. The composition of the chemical species was determined near the two bond lines.

For the ss–Cu interface at 850 °C joining temperature (Fig. 2(a)), a deeply shaded reaction layer has been observed near the stainless steel side, which is enriched with Fe (≈65.8 at%) and Cr (≈28.8 at%) with a small quantity of Ti (≈2.7 at%), Ni (≈2.2 at%) and Cu (bal.); hence, the composi-
tion indicates the phase mixture of 3FeNi + Cu [10–12]. Close to the
Fig. 1. Optical microstructure of the diffusion bonded assemblies joined at: (a) 850 °C, ss–Cu interface, (b) 850 °C, Cu–Ti interface, (c) 900 °C, ss–Cu interface, (d) 900 °C, Cu–Ti interface, (e) 950 °C, ss–Cu interface and (f) 950 °C, Cu–Ti interface.

λ + γ region, the thin bright region consists of Fe (∼57.6 at%) and Ti (∼20.1 at%) in association with Cr (∼19.1 at%), Ni (∼2.4 at%) and Cu (bal.); hence, the composition perhaps is the phase mixture of λ + Fe₂Ti [13]. The shaded matrix with irregular shaped bright islands (arrows in Fig. 2(a)) has been observed in Cu interlayer. The composition of the shaded matrix is Ti (∼47.5 at%), Fe (∼22.5 at%), Cu (∼25.33 at%), Ni (∼3.45 at%) and Cr (bal.). The bright islands contain Ti (∼43.72 at%) and Cu (∼46.03 at%) with a small amount of Fe (∼8.32 at%), Ni (∼1.93 at%) and Cr (bal.). Hence, bright islands and shaded matrix are T₅ (T₅ is Ti₄₋ₓFeₓ; 4 < x < 5) and FeTi + T₅ + Cu, respectively [14]. In Cu–Ti diffusion zone, two distinct reaction layers have been observed (Fig. 2(b)). The light shaded band is enriched with Ti (∼61.36 at%) and Cu (bal.); hence, the Ti–Cu binary phase diagram indicates the formation of CuTi₂ + CuTi phase mix-
Fig. 2. SEM-BSE images of the transition joints processed at: (a) 850 °C, as-Cu interface, (b) 850 °C, Cu–Ti interface, (c) 900 °C, as-Cu interface, (d) 900 °C, Cu–Ti interface, (e) 950 °C, as-Cu interface and (f) 950 °C, Cu–Ti interface.

ture [14]. Close to copper, the light shaded reaction layer contains Ti (∼44.7 at%), Fe (∼2.35 at%) and Cu (bal.). The isothermal section of Fe–Cu–Ti ternary phase diagram indicates the presence of phase mixture T₅ + Cu₄Ti₃ + CuTi (T₅ is Ti₄₅Cu₅₅−ₓFeₓ; 4 < x < 5) in this layer [14,15].

At 900 °C joining temperature, the deeply shaded area has been noticed (arrow in Fig. 2(c)) near stainless steel, containing Ti (∼45.76 at%), Fe (∼20.2 at%) and Cu (∼27.24 at%) with a small amount of Cr (∼1.8 at%) and Ni (bal.). This region is presumably the phase mixture of FeTi + Cu + T₅.
T3 is Ti4Cu57−xFe3x; 21 < x < 24 having structure closely related to Ti3Cu7 [14]. Adjacent to FeTi + Cu + T3, the river like bright reaction band consists of Ti (∼79.3 at%), Fe (∼18.4 at%) and Cu (∼36.9 at%) with a small amount of Cr (∼1.6 at%) and Ni (bal.), which perhaps is a phase mixture of FeTi + Cu. van Beek et al. reported that nearly 38 at% Cu could be dissolved in FeTi [15]. A lightly shaded region is found in between FeTi + Cu and ss–Cu interface, consisting of Ti (∼44.4 at%) and Cu (∼36.4 at%) in association with Fe (∼16.2 at%), Cr (∼19.4 at%) and Ni (bal.). This reaction layer is a phase mixture of FeTi + Cu. The bright islands in this area [10–12] is enriched with Ti (∼43.8 at%), Fe (∼78.6 at%) and Cu (∼37.3 at%) and Ni (bal.); hence, the phase mixture of FeTi + CuTi 2 + Cu may be present. The shaded area is enriched with Ti (∼43.8 at%), Fe (∼78.6 at%) and Cu (∼37.3 at%) and Ni (bal.); hence, the composition indicates the FeTi + T2 phase mixture.

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At 950 °C processing temperature at ss–Cu interface (Fig. 2(e)), the bright area contains Fe (∼64 at%), Ti (∼3.4 at%), Cr (∼27.93 at%), Ni (∼3.13 at%) and Cu (bal.). The composition of the bright region is Fe (∼60.2 at%), Ti (∼6.99 at%), Cr (∼24.9 at%), Ni (∼3.5 at%) and Cu (bal.). Hence, the bright and shaded region indicates the FeTi + T2 phase mixture. The dark area in Fig. 2(e) is enriched with Ti (∼75.7–75.5 at%) and Fe (∼103–109 at%) with a small amount of Cu (8.7–10.5 at%), Cr (∼3.3–3.1 at%) and Ni (∼bal.); hence, the composition indicates the stabilized FeTi + β–Ti intermetallics [16].

At 950 °C processing temperature at ss–Cu interface (Fig. 2(e)), a combination of bright and shaded region appeared adjacent to ss side. The shaded area contains Fe (∼64 at%), Ti (∼3.4 at%), Cr (∼27.93 at%), Ni (∼3.13 at%) and Cu (bal.). The composition of the bright region is Fe (∼60.2 at%), Ti (∼6.99 at%), Cr (∼24.9 at%), Ni (∼3.5 at%) and Cu (bal.). Hence, the bright and shaded region indicates the FeTi + T2 phase mixture. The shaded area contains Fe (∼64 at%), Ti (∼3.4 at%), Cr (∼27.93 at%), Ni (∼3.13 at%) and Cu (bal.). The composition of the bright region is Fe (∼60.2 at%), Ti (∼6.99 at%), Cr (∼24.9 at%), Ni (∼3.5 at%) and Cu (bal.). Hence, the bright and shaded region indicates the FeTi + T2 phase mixture. The dark area in Fig. 2(e) is enriched with Ti (∼75.7–75.5 at%) and Fe (∼103–109 at%) with a small amount of Cu (8.7–10.5 at%), Cr (∼3.3–3.1 at%) and Ni (∼bal.); hence, the composition indicates the stabilized FeTi + β–Ti intermetallics [16].

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improve substantially in comparison to direct bonding of the same dissimilar materials; hence, it can be inferred that embrittlement effect of Cu–Ti intermetallics is lower than the Fe–Ti intermetallics. Moreover, formation of intermetallics in the diffusion zone of Cu–Ti also deteriorates the bond strength as failure takes place from the above interface during tensile loading. Despite the presence of the brittle reaction products in the diffusion zone, the use of copper as intermediate materials improves the joint quality by eradicating voids formation near interface, which were observed for the direct bonding of titanium–stainless steel due to differential mass transfer across the bond line [11,12].

4. Conclusions

The solid-state diffusion bonding was carried out between commercially pure titanium and 304 stainless steel using 300 μm copper interlayer. Bonding was carried in the temperature range of 850–950 °C for 1.5 h under 3 MPa uniaxial load in vacuum. The characterization of the transition joints reveals the following:

SEM-BSE images exhibit that the Fe–Cu–Ti ternary products (T₂, T₃ and T₅) are formed in both the diffusion interfaces at the joining temperature of 850 and 900 °C. Whereas, at 950 °C bonding temperature, Fe–Cu–Ti and Cu–Ti bases intermetallics are not formed in the diffusion interfaces. However, it is evident from the study that copper interlayer cannot block the diffusion of Fe, Cr and Ni to Ti side and Ti to 304ss side. Maximum bond strength of ~318 MPa and ductility of ~8.5% has been obtained for the diffusion joint processed at 900 °C due to better coalescence of mating surface. With the rise in joining temperature to 950 °C, bond strength drops due to the enhanced volume fraction of brittle intermetallics. At a lower joining temperature of 850 °C, bond strength is also poor owing to incomplete coalescence of the mating surfaces.

References
