CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The literature related to DB of various combinations of metals are identified and referred in this section. The literature with respect to the DB processes is given in the section 2.2. The solid state joining processes of stainless steel to low-carbon steel is discussed under the section 2.3. Further, the discussion of the literature connected to duplex stainless steel with medium-carbon steel is briefed in the section 2.4. The literature review related to diffusion bonding of titanium and its alloys with austenitic stainless steel is presented in the section 2.5. The literature corresponding to the microstructure and phase identification of different dissimilar material combinations by various authors are discussed under the section 2.6. The published papers related to diffusion coefficients, the modeling and its mechanisms related to DB are given in section 2.7 and 2.8, respectively. In section 2.9, the limitations of the existing literature and the research gap are presented.

2.2 DIFFUSION BONDING PROCESSES


2.3 DIFFUSION BONDING OF LOW-CARBON STEEL GRADE AISI 1018 WITH STAINLESS STEEL

Masahashi et al (2005) reported that the laminates of iron aluminide-intermetallic alloy and CrMo steel prepared by solid-state bonding improved the oxidation resistance of the steel. The joint region was free from defects, in addition, columnar grains were observed at the steel side. The formation of columnar grains was explained by the nucleation of ‘α’ at the interface caused by ‘Al’ diffusion to stabilize ‘α’, followed by grain growth in the steel. Oxidation resistance of CrMo steel was improved by aluminium diffusion from iron aluminide.

The effect of pressure during DB of composite Fe-Al alloy with CrMo steel was studied by Masahashi et al (2006). The average length of the columnar grains was shorter than the grains obtained without pressure. Fe₃C precipitation in this zone was noticed that increases the hardness at the zone. Increase in hardness in the CrMo side beyond the columnar grain was due to
the fine microstructure. Further, application of pressure during DB retards the diffusion of ‘Al’ from Fe-Al alloy to CrMo alloy.

Superalloys find wider applications in the manufacture of gas turbine blades and parts exposed to high temperature and corrosive media. Conventional welding techniques cannot be used to join these alloys, since these alloys form hard intermetallic compounds at the interface. Han et al (2007) developed superplastic diffusion bonding technique to join nickel-based superalloy. A 25 µm thick nickel foil was used to obtain improved microstructure and mechanical properties at the joint. Wang Deqing et al (2007) have reported the solid state bonding of 304L stainless steel and carbon steel with an aluminium alloy as an interlayer material. It is learnt from the above study that the thickness of the diffused region increased with the rise in bonding temperature and time. The interfacial cohesion of the base metals is related to the thickness of the diffusion layers.

2.4 DIFFUSION BONDING OF DUPLEX STAINLESS STEEL WITH MEDIUM-CARBON STEEL

Jauhari et al (2003) estimated that the strength of the joint of superplastic duplex stainless steel and medium-carbon steel was equal to the base metal medium-carbon steel which was approximately 650 MPa. Further, it was reported that the bond strength had direct relationship with the DB process parameters such as temperature, pressure and time. The microhardness values were higher at the region close to the interface in the base metal duplex stainless steel region than the values observed at the base metal medium-carbon steel region.

Torun et al (2005) performed diffusion bonding on iron aluminide using pure iron interlayer. The Fe-Al alloy was produced by induction melting
in an argon gas environment. Polished specimens were given electrolytic coating of pure ‘Fe’ and bonded at 1100 °C for different bonding time durations and at a pressure of 3.2 MPa. The maximum bond shear strength of 396 MPa was obtained which was 86% of the parent metal shear strength.

Bulent Kurt (2007) investigated the joints made between duplex stainless steel and AISI 4140 medium-carbon steel. They reported a maximum shear strength of 767 MPa. At the interface, cracks and microvoids were not observed. In addition, the microstructure at the interface consisted of chromium carbide. The micrographs revealed the presence of dense carbide network formed around the austenite phase in the region adjacent to the interface in duplex stainless steel side. In austenitic steel, carbide was formed in the grain boundaries. Spheroidization of cementite took place, as ‘Cr’ diffused into medium carbon steel side adjacent to the interface region. A ductile mode of fracture was noticed in general for all the samples.

Sieurin et al (2007) studied the formation of sigma phase by varying the cooling rate. The precipitation of ‘σ’ started at 915 °C and the amount of ‘σ’ formed increased until the growth of the particles stopped at 650 °C. The embrittlement of duplex stainless steel was noticed due to ‘σ’ phase formation and that reduced the toughness. Further, the literature disclosed that the ‘σ’ could be controlled with proper control of cooling rate. The nucleation and growth of ‘σ’ particles were modeled during isothermal cooling and continuous cooling. The predicted ‘σ’ values were compared with experimental results. This model gave optimum cooling rate and aging time to maintain ‘σ’ phase within the desired limits.

Bulent Kurt et al (2009) reported the width of interface in ferritic stainless steel and Inconel 738 increased as the processing temperature was raised. Because of carbide precipitation at the interface, values of
microhardness were increased at all DB temperatures. DB samples processed at 1050 °C and 1100 °C were free from cracks and microvoids.

2.5 DIFFUSION BONDING OF TITANIUM/TITANIUM ALLOYS WITH AUSTENITIC STAINLESS STEEL

Diffusion bonding of Ti-6Al-4V to AISI 304L was reported by Ferrante et al (2002). The shear test yielded a maximum shear strength of 382 MPa for the samples processed at 950 °C for 3 h. The intermetallic compounds like ‘σ’, α-Ti, β-Ti, FeTi and Fe2Ti were observed at the interface. They found that the critical thickness of the β-phase and porosity at lower temperatures were two important parameters that governed the strength of the joints.

He et al (2003) developed a new technology for diffusion bonding intermetallic TiAl to steel with composite barrier layers. The composite barrier layers consisted of titanium, vanadium and copper. The strength of the joint was 420 MPa, which was very close to the strength of base metal. The interface was free from formation of hard and brittle intermetallic compounds.

Kundu et al (2004) reported the reactive diffusion bonding between pure titanium and stainless steel using nickel interlayer. They produced diffusion-bonded joints between pure titanium and 304 stainless steel using nickel interlayer in the temperature range of 800-900 °C for 1.5 h under 3 MPa pressure in vacuum.

Kundu et al (2005) reported that the solid-state diffusion bonding was carried out between pure titanium with 304 grade stainless steel using copper interlayer. Diffusion bonding was carried out in the temperature range of 850-950 °C for 1.5 h under 3 MPa pressure in vacuum. The formation of different intermetallic compounds was noted at the interface. They reported
that the samples bonded at 900 °C exhibited a maximum tensile strength of 318 MPa.

Sheng et al (2005) investigated the phase transformation in superplastic diffusion bonding of titanium alloy to stainless steel. They obtained a maximum tensile strength of 307 MPa. The diffusion bonding was performed in ten heating and cooling cycles for a maximum temperature of 890 °C and a minimum temperature of 800 °C at a pressure of 5 MPa. Intermetallic compound FeTi and β-Ti solid solution was found in the fracture region.

Kundu et al (2006) reported the formation of phases like ‘σ’, α-Fe, α-Ti, β-Ti and intermetallic compounds such as Fe₂Ti, FeTi and Cr₂Ti for the diffusion-bonded samples made between pure titanium and a precipitation hardening stainless steel. They obtained a maximum tensile strength of 326 MPa.

Duarte et al (2006) carried out solid-state diffusion bonding of gamma-TiAl alloys using titanium and aluminium thin films as interlayers. In the literature, the effect of processing conditions and the thickness of nanometric layers on microstructure and chemical composition variation across the interface was analyzed. At lower bonding temperature range of 600-800 °C, the bonding was not good for thin interlayer and a thick interlayer was needed to obtain a sound joint. However, at higher temperature of 900 °C, at the joint region porosity was noted. The authors reported that the samples processed at 1000 °C exhibited a defect free joint and the nano-crystalline interlayers were useful to obtain a sound joint.

Qin et al (2006) studied the diffusivity of elements such as ‘Ti’, ‘Fe’, ‘Cr’ and ‘Ni’ on either side of the joint. The authors reported that the
phase transformation in DB between a titanium alloy and an austenitic stainless steel was carried out in vacuum. Cyclic heating between 890 °C and 800 °C, with number of cycles 10 and bonding pressure of 5 MPa was applied to get a maximum tensile strength of 307 MPa. The X-ray diffraction performed on the samples revealed the presence of compounds such as ‘\(\sigma\)’, \(\text{Fe}_2\text{Ti}\), \(\text{FeTi}\) and \(\beta\)-\(\text{Ti}\) at the interface.

Kundu et al (2007) in their work disclosed the interfacial microstructure and mechanical properties of diffusion-bonded titanium-stainless steel joints using a nickel interlayer. They produced diffusion-bonded joints between pure titanium and 304 stainless steel using nickel interlayer in the temperature range of 800-950 °C for 1 h under 3 MPa pressure in vacuum. At 950 °C, Ni-Ti interface exhibited a phase mixture of \(\lambda + \gamma + \alpha\)-\(\text{Fe}\), \(\lambda + \alpha\)-\(\text{Fe}\), \(\lambda + \text{FeTi} + \beta\)-\(\text{Ti}\) and \(\text{FeTi} + \beta\)-\(\text{Ti}\) at the stainless steel nickel interface. The authors reported that nickel could retard diffusion of ‘\(\text{Ti}\)’ into stainless steel up to 900 °C; above that temperature ‘\(\text{Ti}\)’ diffuses into stainless steel.

Lang Ze-bao et al (2007) in a published literature reported the solid-state diffusion bonding of Ti-6Al-4V powder compacts with an austenitic stainless steel electroplated to various thicknesses with nickel. Diffusion bonding was carried out in the temperature range of 800-900 °C for 2 h under 100 MPa pressure in vacuum. The authors reported that the samples bonded at the temperature range of 800-820 °C exhibited a maximum tensile strength of 388 MPa with an interlayer thickness of 40 μm.

Kundu et al (2008) produced diffusion-bonded joints made between pure titanium and micro-duplex stainless steel. They proposed the optimum parameters for bonding the material combination as temperature 850 °C, pressure 3 MPa and a holding time of 1.5 h. Diffusion bonding was carried
out between pure titanium and 304 stainless steel using nickel interlayer in the temperature range of 800-950 °C for 1.5 h under 3 MPa pressure in vacuum. At 900 °C and above, a phase mixture of $\gamma+\alpha$-Fe, $\gamma +$FeTi and FeTi +$\beta$-Ti occurred at the stainless steel titanium interface. Basu (2008) performed DB of Ti-6Al-4V superalloy and observed that the mode of fracture was ductile.

Evren Atasoy et al (2008) reported diffusion bonding of pure titanium to low-carbon steel using silver interlayer. Bonding was carried out at a temperature of 850 °C, pressure 3 MPa and a holding time of 90 min. The shear test specimens were subjected to maximum shear force of 3222.8 N. The shear strength was increasing with respect to rise in bonding temperature; further increase in temperature decreased the shear strength. The depth of silver diffusion increased with rise in bonding temperature. The microstructure of the bonded samples revealed the grain growth in both base metals.

He et al (2008) reported the method of hot pressing diffusion bonding of titanium alloy to a stainless steel with an aluminium alloy interlayer. The maximum tensile strength of the joints processed at 450 °C, a pressing speed of 70 mm/min and a surface roughness value of 3.2 μm was 183 MPa. It was reported by the authors that the mode of fracture was ductile in nature. Large number of intermetallic compounds such as FeAl$_6$, Fe$_3$Al and FeAl$_2$ that were brittle appeared along the interface. The fracture took place along the stainless steel-aluminium interface for all the samples processed at lower or higher temperatures. Effect of temperature on the joint strength was more pronounced as the temperature was raised at the interface.

Yan et al (2009) performed vacuum hot roll bonding of Ti-alloy and stainless steel using nickel interlayer and obtained a tensile strength of 440.1 MPa. The thickness of the intermetallic layer formed between Ti-alloy
and nickel interface increased with the rise in temperature. However, the tensile strength was decreasing with respect to rise in bonding temperature.

The effect of impulse pressure on the bonded samples between Ti-alloy to stainless steel was studied and presented by Yuan et al (2008). A maximum tensile strength of 321 MPa was reported for the bonding temperature 825 °C and the effective bonding time was only 180 s. Presence of more amounts of diffusion species such as ‘Fe’, ‘Cr’ and ‘V’ promote eutectoid transformation in the Ti-6Al-4V closer to the interface and form ‘β’ phase and intermetallic compounds, namely, Fe$_2$Ti, FeTi, Al$_2$CrNi$_{15}$, Ni$_4$Ti$_3$ and Fe$_2$V$_3$.

The solid-state diffusion bonding of pure titanium and precipitation hardening stainless steel was reported by Poddar (2009). The optimum parameters were; temperature 950 °C, time 1 h and pressure 3.5 MPa. Bonding temperature had greater influence on bond strength; increase in temperature as well as decrease in temperature had an adverse effect on the strength of the joint. Above 950 °C strength of the DB samples decreased because of the formation of hard and brittle intermetallic compounds. At lower bonding temperature decrease in strength was noticed because of lack of diffusion and porosity at the interface. The concentration profile drawn from the interface indicated that the diffusion of several elements occurred from one region of the base metal to the other. The diffusion-bonded samples processed at 950 °C exhibited a maximum tensile strength of 344.3 MPa.

Elrefaey et al (2009) in their published work, reported that the possibility of solid-state diffusion bonding of titanium to steel using a copper base alloy as interlayer. Successful diffusion bonded joints were obtained at 850 °C only but at 800 °C and at lower temperature level, successful joints were not obtained. A maximum shear strength of 105.2 MPa was obtained for
the bonded joints with holding time of 90 min because of better contact between the mating surfaces. The fractured surface revealed that the presence of intermetallic compounds such as $\text{Ti}_2\text{Cu}$ and TiCu.

Torun (2009) had conducted metallurgical characterization and assessment of mechanical properties of the diffusion-bonded joints made between nickel aluminide and titanium. The author reported a maximum shear strength of 205 MPa for the samples processed at 900 °C at 2 MPa and treated for 2 h. The XRD analysis reported the formation of intermetallics TiNi, $\text{Ti}_2\text{Ni}$, Ni$_3$Al, and ‘Ti’ phase at the interface.

2.6 MICROSTRUCTURE AND PHASE IDENTIFICATION

Sireesha et al (2000) applied a new technique to join 316 LN austenitic stainless steel with 9Cr-1Mo steel for power plant applications, using a super alloy insert having composition of 31.8%Ni +19.9%Cr +Bal. Fe. The weld fusion zone and the interfaces with the base materials were characterized in detail using optical and transmission electron microscopy. In this study, occurrence of type II grain boundary running parallel to the fusion boundary was observed. The presence of type II grain boundary was because of concentration gradient created during solidification of weld metal in the normal direction of the fusion boundary.

Jimenez et al (2001) studied the superplastic properties of dual phase duplex stainless steel and development of fine grains at the optimum strain rates. The as-received base metal microstructure consisted of $\delta$-ferrite matrix in which islands of ‘γ’ phase was noted. At higher temperatures, the $\delta$-ferrite grains transform to lamellar ferrite, austenite and sigma below 950 °C. The authors had noted the formation of ‘σ’ phase below 950 °C. Sun et al (2003) performed dual torch welding of duplex stainless steel and measured
the ferrite percentage after welding. The measured ferrite percentage was little more than the ferrite content before welding. During cooling, solidification was primarily delta ferrite. At the ferrite grain boundaries austenite transformation was initiated while the weld metal was cooled. The change in microhardness values were less because the variation in ferrite percentage was very less.

The effect of alloying elements on ferrite growth from austenite by using controlled decarburization as a method was disclosed in the literature by Phillion et al (2004). The ferrite layer growth under decarburization conditions at various temperatures were presented in this work. This method was considered appropriate for the experimental test of current theories of substitution solute drag mechanism. The supplied thermal energy enabled solute atom to attain lattice position of solvent, so that substitution diffusion in pure metals was possible. The phase diagram drawn between manganese and silicon by Okamoto (2004) revealed the formation of $\alpha$-Mn$_3$Si having 14.6 to 15.0% Si and balance ‘Mn’.

Liu et al (2004) mentioned in their literature that the weld simulation tests were conducted on low alloy steel containing 0.18%C, 0.61%Cr, 1.21%Mn, 0.29% and 0.28%Mo. They observed that the decrease in hardness, impact toughness and fracture toughness in the heat affected zone. The fractograph revealed large number of dimples and river patterns indicating the ductile mode of fracture. Very few numbers of dimples and large cleavages on the fracture surface were also seen.

Ducki (2006) examined the precipitation of intermetallic compounds at a high temperature during the heat-treatment of Fe-Ni alloy. In this work, the samples were solution conditioned at 980 °C for 2 h and quenched in water followed by aging at various temperatures and time. The
presence of transformed austenite and intermetallic compound Ni$_3$Ti was also observed. The formation of Ni$_3$Ti resulted in the formation of cellular structure as many grains of Ni$_3$Ti were clustered.

The presence of large size dimples and fibrous mode of fracture was indicated that confirmed the ductile mode of fracture in the observations made by Srinivasan et al (2006). Sieurin et al (2007) evaluated the formation of sigma phase by varying the cooling rate. The precipitation of ‘σ’ started at 915 °C and the amount of ‘σ’ formed increased until the growth of the particles stopped at 650 °C. The ‘σ’ phase embrittle duplex stainless steel and reduces toughness. Further, the literature disclosed that the adoption of proper cooling rate could control the formation of ‘σ’ phase. The nucleation and growth of ‘σ’ particles were modeled during isothermal and continuous cooling. They predicted ‘σ’ values and compared with experimental results. This model presented optimum cooling rate and aging time to maintain ‘σ’ within desired limits.

Young et al (2007) studied the influence of ‘γ’ content and its morphology on the impact and fatigue properties of 2205 duplex stainless steel. Fracture appearance of the base plate consisted of transgranular fatigue fracture and small amount of elongated ductile fracture. The short duration of post weld heat treatment maintained the ‘γ’ percentage to the original level to obtain good impact toughness of the weldment.

Cao et al (2011) had produced tungsten inert gas welded joints made with martensitic and austenitic stainless steel. The fractographs taken at the fracture site of the martensitic stainless steel consisted of fibrous zone and large number of fine dimples indicating the ductile mode of fracture.
The microstructural transformation of ferrite into transformed austenite and sigma phase during long-term exposures to high temperatures in a duplex stainless steel was studied by Lara et al (2011). In this study, new grain boundaries were formed indicating a cellular structure comprising fine ferrites. At the \(\delta/\gamma\) interface, bright regions were observed that indicated the precipitation of secondary phases. Chromium depleted ferrite regions were formed and increased diffusion of carbon resulted in the formation of chromium carbides at the \(\delta/\gamma\) interface. At higher temperatures, the ‘\(\delta\)’ ferrite transformed to secondary austenite and sigma phase.

Kundu et al (2011) conducted diffusion bonding of Ti-6Al-4V with microduplex stainless steel and reported microstructure and strength properties of the joints at the interface. Fantao Kong et al (2011) performed hot pack roll bonding of Ti-6Al-4V and TiAl laminate sheet and reported the microstructure and shear strength property of the joints.

2.7 DIFFUSION COEFFICIENTS

Lee et al (1990) had estimated the diffusion coefficient values of chromium in ‘\(\alpha\)’ iron for different temperatures. The diffusivity values of ‘Cr’ increases in ‘\(\alpha\)’ iron as the temperature increased and this indicated that the temperature dependence of diffusion coefficient values in metals. They estimated the diffusion coefficient values as \(4.67 \times 10^{-15}\text{ m}^2/\text{s}\) (at 901 °C) and \(1.39 \times 10^{-15}\text{ m}^2/\text{s}\) (at 852 °C) for ‘Cr’. The intrinsic diffusion coefficients of ‘Ti’ \((D_{Ti} =5.5 \times 10^{-14}\text{ m}^2/\text{s}\) at 900 °C and \(D_{Ti} =9 \times 10^{-14}\text{ m}^2/\text{s}\) at 800 °C) were presented by Hinotani et al (1988) and Aleman et al (1993).

Diffusion coefficient values of chromium in ‘\(\alpha\)’titanium and its alloys were presented in the published literature by Nakajima et al (1990). At 851 °C the diffusion coefficient value of Cr was \(7.351 \times 10^{-15}\text{ m}^2/\text{s}\) in
Ti-2.65%Al-2.51%Sn and at 693 °C it was $6.087 \times 10^{-16}$ m$^2$/s. These values indicated that the temperature dependence of ‘Cr’ diffusion coefficient values in ‘α’ titanium. The important observations made in this study were ‘Cr’ diffused faster into ‘α’ titanium and the addition of aluminium retards the diffusion of chromium because ‘Al’ diffused faster than ‘Cr’ and formed compounds.

Yajiang et al (2005) calculated the amount of elements present near the interface and compared these values with the measured values. With the increase in heating temperature and holding time, the depth of diffusion of various elements was increased in both the base metals. They predicted that the calculated diffusion coefficient, the activation energy values near the interface was favourable for diffusion.

Moly Yunker and Van Orman (2007) estimated the diffusion coefficient ($D_{Ni}$) value of nickel as $1.58 \times 10^{-14}$ m$^2$/s at 1280 °C for a diffusion time of 6 h in Fe-alloy with 10 at.%Ni. A graphical plot between the diffusion coefficients and homologous temperature described the temperature dependence of high-pressure diffusion data. The authors reported that the homologous temperature relation was a reasonably accurate method for extrapolating diffusion data in iron-nickel alloys to high pressure, up to 23 GPa.

2.8 DIFFUSION BONDING MODELLING AND MECHANISM

Thomas Helander et al (1997) estimated the composition variation of carbon in the diffusion-bonded joints obtained between a stainless steel and low-alloy steel by using the DICTRA simulation software. The calculated values were compared with the experimental values for various temperatures. Maximum carbon diffusivity was observed at higher temperatures. Further,
the diffusivity of carbon decreased with respect to decrease in processing temperature. The carbon content in the stainless steel very close to the low-carbon steel was 0.15% at 1200 °C and it increased up to 3% at 600 °C. The local enrichment of carbon resulted in the formation of approximately 40% of $M_7C_3$ and 20% of $M_{23}C_6$ carbides at lower temperatures. Allen et al (1998) investigated the effect of irradiation and post-irradiation annealing of grain boundary composition in austenitic Fe-Cr-Ni alloys and created a model based on the experimental findings.

He et al (2006) in their published work entitled “Mechanism of forming interfacial intermetallic compounds at interface for solid state diffusion bonding of dissimilar metals”, proposed a flux energy principle of formation of intermetallic compounds at the interface for the multi-composition diffusion couple. Further, the phase with the largest thermodynamic driving force resulted in the formation of intermetallic compounds because of variation in pre-exponential constant ($D_0$) and activation energy ($Q$) at the interface for various elements. The formation of intermetallic compounds for different diffusion couples were disclosed in their study. At the interface in the diffusion couple between titanium alloy and nickel, intermetallic compounds like $TiNi_3$, $TiNi$ and $Ti_2Ni$ were observed. Similarly, at the interface in the diffusion couple between stainless steel and titanium alloy, compounds such as $TiFe_2$, $TiFe$, and $Ti_2Fe$ were found.

2.9 LIMITATIONS OF THE EXISTING LITERATURES

The literature survey mentioned above dealt with diffusion bonding of different grades of stainless steel to various grades of steel, duplex stainless steel to different types of steel and pure titanium, Ti-alloys to stainless steels of different grades. It is observed that the following areas require further study and investigation.
- Lack of literature for DB of AISI 304 austenitic stainless steel to low-carbon steel with AISI 304L interlayer was observed.
- During DB grain coarsening and its effect on mechanical properties needs further study.
- DB of SAE 2205 to medium-carbon steel AISI 1035 is seldom found in the published literatures.
- The effect of bonding parameters on microstructure and mechanical properties of the DB joints made between duplex stainless steel and medium carbon steel needs further investigations.
- DB of Ti-6Al-4V to AISI 304L is rarely found in the published literatures.
- The formation of intermetallic compounds and their effect on microstructure and mechanical properties are to be elaborately studied for the material combinations taken in this research work.
- The calculation of diffusion coefficients (D), pre-exponential constant (D₀) and activation energy (Q) for various elements in the above mentioned material combinations are not found in the published literatures.