CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter deals with the present status related to the solid state joining of titanium alloys in general and that of dissimilar combinations of titanium alloys with stainless steels and nickel alloys in particular. Since the formation of hard intermetallic compounds is the main problem during solid state joining, the process parameters that control the formation of intermetallics are discussed. Characteristics of base metals Ti-6Al-4V, Inconel 718 and Stainless Steel (SS) 304L and methods used to characterise the joints are also discussed.

2.2 JOINING OF TITANIUM ALLOYS

2.2.1 Joining of Titanium Alloys by Diffusion Bonding

The primary parameters associated with diffusion bonding are temperature, stress, time, surface preparation and the environment employed for diffusion bonding. Studies for diffusion bonding of Ti-6Al-4V by Peck (1949) have indicated that high quality bonding could be achieved at 730°C using a bonding stress as low as 0.2 MPa, whereas Hamilton (1973) has indicated a stress requirement of 14.22 to 34.8 MPa and a temperature range of 925 to 950°C.
Guo et al (1987) diffusion bonded Ti-6Al-4V at 875 °C with three different stresses of 0.7, 1.4 and 2.1 MPa for a material with 5 µm grain size. Pilling (1988) diffusion bonded Ti-6Al-4V at a temperature range of 910 to 940 °C and a stress range of 0.35 to 3.5 MPa. Rao et al (1998) claimed that poreless joints could be made at a temperature of 930 °C, at a stress level of 10 MPa with a time period of 2 hours. A large difference in the stress requirement for diffusion bonding reported by the different investigators was due to the differences in the material surface quality and environmental conditions.

The combination of diffusion bonding process with superplastic forming has revolutionised the fabrication of Ti-6Al-4V sheets for aerospace applications. Retaining the superplastic property after diffusion bonding is essential for this alloy to enable the fabrication of industrial components on a commercial scale. Lee et al (2007) carried out diffusion bonding of super plastic ELI grade Ti-6Al-4V. The experiments were conducted at temperatures ranging from 800 to 950 °C, with a stress of 3 MPa for 1 hour in inert gas environment. Good bonding was observed at relatively low temperature and stress. The microstructure of Ti alloy diffusion bonded at 900 °C exhibited oxygen enriched alpha phase at bonded interface.

The superplastic forming and diffusion bonding (SPF/DB) of hydrogenated TC21 alloy (Ti-6Al-2Zr-2Sn-3Mo-1Cr-1Nb) was carried out by Wang et al (2010) in the temperature range of 800 - 925 °C under 1.5 MPa gas pressure. The bonding ratio of SPF/DB increased with increasing hydrogen contents up to 0.5% wt and then decreased. For the same hydrogen content, bonding ratio increased with increasing temperature.
Ravisankar et al (2002) successfully diffusion bonded Ti-6Al-4V at temperatures 900°C and 925°C with a stress of 25 MPa and time of 45 minutes. Good bonding was achieved with acceptably small grain growth which would still retain the superplastic characteristics of the Ti-6Al-4V.

2.2.2 Dissimilar Joining of Titanium Alloys by Diffusion Bonding

Ghosh et al (2003) carried out diffusion bonding of Ti-5.5Al-2.4V with stainless steel 304 grade under bonding temperatures 850°C, 900°C and 950°C, bonding stress of 3 MPa and bonding time of about 1 hour. The results show that with the increase in the bonding temperature, the width of total diffusion zone and the formation of intermetallic phases increase. The diffusion of chemical species becomes pronounced at higher processing temperatures. A number of intermetallics like FeTi, Fe$_2$Ti and Fe$_2$Ti$_4$O are formed at the reaction zone of the diffusion bonded samples and these brittle inter-metallic compounds are responsible for lowering the strength of the diffusion bonded joints. FeTi plays a dominant role in altering the bond strength.

Diffusion bonding of titanium alloys to stainless steel and low alloy steel was attempted by Aleman et al (1993). The process conditions used were temperature 900°C, stress 15 MPa and time 15 minutes in argon atmosphere. Kirkendall effect was observed with diffusion of titanium in iron being more than the diffusion of iron in titanium.

Glatz et al (1997) carried out diffusion bonding of Ti-47Al-2Cr-0.2Si similar sheet materials and Ti-47Al-2Cr-0.2Si with Ti-6Al-4V. Ti-47Al-2Cr-0.2Si sheets were joined under bonding temperature of 1000°C, applied stress 40 MPa and bonding time 1 to 3 hours. For dissimilar joining
with Ti-6Al-4V, bonding parameters were the same except the bonding temperature was 700°C. The result of the investigation indicates that diffusion bonding is a promising joining technique for metallic Ti-Al based material. The variation of bonding parameters within the range of 20 - 40 MPa for stress and 1 - 3 hours for time had no significant influence on the bonding strength at room temperature and 700°C.

Ghosh et al (2003) reported that diffusion bonding of titanium to stainless steel 304 grade obtained at a bonding temperature of 850°C gave a bond strength of 242 MPa. The enhanced strength was attributed to the formation of finer size intermetallic components. The bond strength decreases with increase in the bonding temperature and this is mainly due to the increase in the width of the brittle intermetallic compounds. Ghosh et al (2005) carried out solid state diffusion bonding between commercially pure titanium and type 304 austenitic stainless steel in the temperature range of 850 to 950°C, under a uniaxial stress of 3 MPa for 1 h. In this combination, titanium traverses a minimum distance into the stainless steel side, whereas Fe, Cr, and Ni travel comparatively larger distances into the titanium side. Kurt et al (2007) carried out diffusion bonding between Ti-6Al-4V and ferritic stainless steel at temperature 980°C for 170 minutes and obtained shear strength of 187 MPa.

High bond strength was achieved by He et al (2011) during diffusion bonding of two biomaterials Ti-2.5Al-2.5Mo-2.5Zr alloy and Co-Cr-Mo alloy processed at 850°C for 1 h. Bonding at higher temperature results in the formation of CoTi₂, Co₂Ti and Cr₂Ti in the diffusion zone, which significantly deteriorate the plasticity and lead to lower bonding strength.
2.2.3 Joining of Titanium Alloys by Friction Welding

Avinash et al (2007) carried out friction welding for joining of Ti-6Al-4V. They concluded that the process parameters of rotational speed 1500 rpm, upset force 0.3 ton, friction force 0.15 ton and burn-off-length of 4 mm were found to be optimum for obtaining a good weld.

Linear friction welding of Ti-6Al-4V was carried out by Karadge et al (2007) in as-welded and post weld heat treated conditions. At the weld interface, a region of very fine martensitically formed microstructure was observed. Texture development was also studied.

Lower rotational speed and lower friction pressure were found to be advantageous in increasing the joint tensile strength in the case of friction welded TiC particulate reinforced Ti-6Al-4V joints (Silva et al 2004).

The dissimilar joints of titanium with stainless steel 304L prepared by Dey et al (2009) by friction welding with varying process parameters resulted in stronger weld. However, the joints have almost zero bend ductility due to the formation of intermetallics near the joint. They suggested a post weld heat treatment cycle for marginally increasing the bend ductility.

2.3 JOINING OF NICKEL ALLOYS

2.3.1 Joining of Nickel Alloys by Diffusion Bonding

Joining techniques for nickel based superalloys include fusion welding, brazing, diffusion bonding, as well as mechanical methods such as bolting and riveting. Problems are encountered in fusion welding of nickel based superalloys. The major problems are micro fissuring during welding
and strain age cracking during post weld heat treatment (Owczarski et al (1976), Jackman (1991)). Micro fissuring is apparently related to partial liquidation at the grain boundaries, caused by the presence of low melting phases. Strain age cracking, also known as reheat cracking, is a more severe type of cracking; it involves inter-granular fracturing, whenever components with residual stress are heated through precipitation temperature ranges. Susceptibility to this cracking is related to the rate of precipitation. The precipitation reaction in Inconel 718 is sluggish. Consequently, residual stresses are relieved before significant precipitation occurs. Other mechanisms that have been proposed to account for strain age cracking include intergranular carbide precipitation, structural changes due to partial melting, oxygen contamination and impurity elements segregating at grain boundaries. Also, mechanical properties, corrosion resistance and oxidation resistance are sometimes reduced in the weld and/or heat affected zone because of structural changes. Because of these difficulties in welding of superalloys, diffusion bonding has become an attractive alternative. It becomes even more attractive in aerospace industries as there is no increase in weight due to filler metal.

Ravisankar et al (2009) carried out diffusion bonding of SU 263 alloy of composition 20.5% Cr, 21.6% Co, 3.2% Mo, 1.12% Ti, 0.7% Al and balance Ni. A sound bond was achieved in SU 263 alloy, at 1050°C, at a stress of 0.9 times the yield strength and for a period of 24 hours. A second phase of composition 1.26% Al, 2.11% Ti, 21.96% Cr, 20.17% Co, 3.96% Mo and 50.53% Ni was observed to form during bonding.
2.3.2 Dissimilar joining of nickel alloys by diffusion bonding

Nimonic AP-1 superalloy powder of 150 µm size was successfully diffusion bonded with stainless steel AISI 304 wrought product, by hot isostatic pressing (HIP) by Somani et al (1998). Bonding temperatures 1200°C and 1270°C offered the best bond. The optical microscopy showed thin interface zone of 30 to 40 µm. No microporosity or cracks were observed in either base metal or at the bonded region, indicating excellent defect free welding. The strength ratio (ratio between the strength of the joint to the strength of parent metal) for the diffusion bonded joints made at 1200°C varied from 0.71 to 0.93. At 1270°C, a strength ratio of 0.89 was obtained.

Incoloy 825 was diffusion bonded to AISI 4130 low alloy steel by an industrial hot extrusion process. The low alloy steel had resulted in a pearlite - bainite structure after bonding and also showed a thin decarburised layer. However, equiaxed, unaltered microstructure was reported in the Incoloy 825 (Gutierrez et al 1991). Hochanadel et al (2006) carried out diffusion bonding of a high chromium nickel alloy, Alloy 690. Diffusion bonding was carried out on Gleeble thermo mechanical simulator with bonding temperature 800 to 1025°C, bonding stress 50 MPa and bonding time 30 to 120 minutes. Increase in hardness was observed at bonded surface in case of joints diffusion bonded at lower temperatures.

Aleman et al (1995) reported a complicated combination microstructure after diffusion bonding of Inconel 625 alloy to Ti 6242 alloy at 900°C, at a stress of 40 MPa for 30 minutes. Figure 2.1 shows the schematic representation of the intermetallics present at the interface of Ti 6242 and Inconel 625.
Figure 2.1  Schematic representation of intermetallics close to the interface of the diffusion bonded Inconel 625-Ti 6242 couple

Inconel 718 was diffusion bonded with SiC by Moseley et al (1991) at 1160°C. The ceramic - metal couple showed interfacial yield shear strengths of 120 to 141 MPa. Another superalloy Inconel 909 was diffusion bonded with SiC at 1160°C, at a stress of 103 MPa for 3 hours (McDermid et al 1983). IN 600 was bonded with alumina at temperatures ranging from 1100 to 1300°C under a stress of 100 MPa for 30 to 120 minutes (Colin et al 1991).

A continuous intermetallic film formed at the interface of Inconel 718 - 17-4 PH stainless steel joints diffusion bonded at the temperature of 1000°C for 60 minutes with stress ranging from 16 MPa to 48 MPa (Guoge et al 2001). The formation of such phases was caused by the agglomeration of niobium and titanium. In all joints, failure occurred at the interface without any plastic deformation. The maximum tensile strength obtained was 774 MPa.
2.3.3 Joining of Nickel Alloys by Friction Welding

Study on similar joints of different nickel alloys was carried out by Preuss et al (2006) through inertia friction welding method. The materials taken up for the study were Inconel 718, Alloy 720 (Ni-16Cr-15Co-3Mo-5Ti -2.5 Al-1.25 W alloy) and RR1000 (Ni-15Cr-16Co-5Mo-3.75Ti -3 Al-1.5Ta alloy). It was concluded that Inconel 718 joints had a precipitation free region leading to significantly reduced strength near the weld line in contrast to that of the other two alloys. As a result, the residual stress in Inconel 718 joints is lesser than that in the other two alloys. The post weld heat treatment on friction welded Inconel 718 joints showed reduction in residual stress by 400 MPa.

The effects of pre-weld and post-weld heat treatments on friction welded Inconel 718 - EN24 steel joints were studied by Lalama et al (2008). Inconel 718 was in either annealed or solutionised condition before welding; EN24 steel was in either annealed or quenched & tempered condition. After friction welding, the joints were tempered at 220°C for 3 hours.

The friction welded joints of MA956, a mechanically alloyed oxide dispersion strengthened iron based super alloy prepared by Ates et al (2007) had coarse and elongated grains at the weld zone. The HAZ width and tensile strength increased up to a certain value with increasing friction pressure. The best mechanical properties were obtained on the joints welded at the friction pressure higher than 50 MPa.
2.4 JOINING OF STAINLESS STEELS

2.4.1 Joining of Stainless Steels by Diffusion Bonding

Diffusion bonding for dissimilar joining of different grades of stainless steels with titanium alloys has been studied by various researchers. Study on diffusion bonding of duplex stainless steel - mild steel joint and austenitic stainless steel - mild steel joint by Kurt et al (2007) revealed that the network of chromium carbide in a ferrite phase was observed in a duplex stainless steel - mild steel joint. The maximum shear strength of this joint was determined as 767 MPa. The grain boundary carbide was formed in an austenitic stainless steel - mild steel joint. The maximum shear strength was found to be 475 MPa.

2.4.2 Joining of Stainless Steels by Friction Welding

Sahin et al (2009, 2007) carried out joining of austenitic stainless steel of 304 type by friction welding. A maximum tensile strength of 795 MPa was obtained for optimum parameters of friction time 9 seconds, friction stress 60 MPa, upset time 20 seconds, upset stress 110 MPa and rotational speed 1440 rpm. The study showed that there was no hardness variation from the interface to the unaffected parent metal. Grain refinement was observed at the welded region due to the combined effect of thermal and mechanical stresses.

2.4.3 Dissimilar Joining of Stainless Steels by Friction Welding

Friction welding of AISI 304 austenitic stainless steel was carried out by Sathiya et al (2005) and the effect of welding parameters on the joint integrity and quality was analysed. As the friction time increased, the width of
the fully plastically deformed zone near the interface increased and the width of the partially deformed zone decreased. The joint strength decreased with increase in friction time.

Ananthapadmanaban et al (2009) conducted a study of mechanical properties of friction welded mild steel to stainless steel joints. The parameters were friction stress 80 and 160 MPa, upset stress 160 and 280 MPa and burn-off-length 1 to 2 mm. They found that the hardness values in the weld zone were not too high indicating absence of carbide formation in the weld zone. SEM micrographs of the fractured surface showed ductile fracture.

Satyanarayana et al (2005) made a dissimilar metal friction welding of austenitic stainless steel to ferritic stainless steel. The parameters were frictional force 4 and 6 kN, forge force 8 and 12 kN, burn-off-length 3 and 5 mm. The toughness and strength properties of dissimilar metal welds were better than that of ferritic stainless steel parent metal.

An amorphous layer formed by mechanical alloying and by solid state reactions was found at the interface of friction welded of 5052 aluminium alloy with 304 stainless steel joint. It was an intermetallic phase until formation of the intermetallic compound formation (Fukumoto et al 2000).

Sathiya et al (2008) carried out friction welding of AISI 430 ferritic stainless steel with varying process parameters. The friction welded joints were tested through tension test, impact test, hardness test and microstructural characterisation. The joints exhibited 95.52% of base metals strength.
2.5 JOINING OF OTHER MATERIALS BY DIFFUSION BONDING

The gray cast iron - mild steel diffusion bonded joints prepared by Kurt et al (2007) exhibited good bonding. Graphite lamellas in the interface of the bonded joints started to dissolve once the bonding temperature increased above 850°C. The highest shear strength of 142 MPa was obtained for bonding temperature of 1000°C.


The diffusion zone of the magnesium – aluminum joint bonded at the temperature of 480°C, stress of 0.08 MPa and time of 60 minutes consisted of intermetallic compounds MgAl, Mg₃Al₂ and MgAl₃ (Peng et al 2005). The concentration of Mg₃Al₂ was higher near magnesium than that near aluminium. Titanium - aluminium joints diffusion bonded by Jiangwei et al (2002) with the process parameters of temperature 640°C, stress 24 MPa and time of 90 minutes had an interface zone with intermetallics TiAl and TiAl₃.

2.6 JOINING OF OTHER MATERIALS BY FRICTION WELDING

Sahin et al (2007) carried out friction welding of AISI 1040 parts and obtained fatigue strength and notch impact toughness of the joints close to those of base metal for the process parameters of friction time 5 seconds, friction stress 30 MPa, upset time 20 seconds and upset stress 110 MPa.
Sahin (2005) carried out friction welding of high speed steel and medium carbon steel with the parameters, friction stress 110 MPa, upset stress 150 MPa, upset time 20 seconds, and friction time 4 seconds. As the friction time and stress were increased, the tensile strength of the joints increased. Corresponding to a friction time of 4 seconds and a friction stress of 110 MPa, a maximum tensile strength of 600 MPa was obtained. Further increase in friction time and friction stress resulted in a drop in tensile strength to 300 MPa. The fatigue strength of the welded joints showed similar behavior like the tensile properties. The drop in hardness close to the interface indicated decarburisation.

Yilbas et al (1995) carried out an investigation on friction welding of aluminium bars. The welding parameters used were speed of rotation between 2000 to 2800 rpm, applied load 5 to 22.93 kgf and welding duration 4 to 10 seconds. In this study, reducing the speed of rotation was found to deteriorate the weld quality, but the quality was improved by increasing the burn-off-length. It was also found that high levels of welding speed and burn-off-length led to high weld-zone temperatures, giving rise to excessive flow of material from the welding zone to the sides. There was no change in the hardness values across the weld zone due to narrow heat affected zone.

Meshram et al (2007) conducted friction welding of dissimilar combinations of pure metals viz., Fe-Ti, Cu-Ti, Fe-Ni, and Cu-Ni. The parameters used were burn-off-length 3 and 5 mm, friction force 3 kN, forge force 5 kN and speed of rotation 1000 rpm. It was observed that increased interaction time led to a decrease in strength in eutectoid forming insoluble systems like Fe-Cu and increase in strength in soluble systems.
2.7 USE OF INTERLAYERS IN DIFFUSION BONDING

Use of interlayers in diffusion bonding is a method to solve alloying compatibility problems when joining dissimilar metals. An interlayer should have lower strength and contain a diffusive element. Also, it being soft, confines deformation to itself and thus minimizes distortion of work pieces when pressed to contact. Interlayers will, however, give rise to decreased strength or stability. The most commonly used interlayer materials are nickel, tantalum, niobium and silver.

Direct bonding of Ti-6Al-4V with Inconel 718 and SS 304L promotes residual stresses at the interface region caused by mismatch of thermal expansions between the bonding materials. It also leads to the formation of brittle intermetallics in the diffusion zone. Inter-diffusion between titanium and stainless steel occurs by atomic migration of chemical species across the bond interface and promotes the formation of Fe-Cr-Ti and Fe-Ti intermetallic phases in the reaction zone. These brittle intermetallics deteriorate the mechanical properties of the transition joints. The use of appropriate intermediate material can minimize the formation of the brittle intermetallics. This in turn increases the strength of the diffusion bonded joint.

Diffusion bonding of commercially pure titanium with stainless steel 304 was carried out by Kundu et al (2008) using 300 μm thick nickel interlayer at bonding temperature of 800 to 950°C, bonding stress of 3 MPa and bonding time of 3 hours. The bonding carried out at 850°C, 3 MPa, 2 hours resulted in a sound weld with absence of iron-titanium intermetallic with bond tensile strength 311 MPa, shear strength 236 MPa and elongation 9.1%. Total diffusion zone at stainless steel - nickel interface was smaller than that at nickel - titanium interface. Hardness was much higher at stainless
steel - nickel interface (1200HV) than that at nickel - titanium interface (670HV). At 900°C and above, strength dropped due to the brittle Fe-Ti intermetallic formation. Nickel interlayer completely restricted the diffusion of Fe and Cr into Ti and Ti into stainless steel 304 till 850°C. At higher joining temperature, Ni layer cannot block the diffusion of titanium to stainless steel 304.

The diffusion bonding experiments on joining of stainless steel 410 with copper using a nickel interlayer by Sabetghadam et al (2010) resulted in the formation of distinct diffusion zones at both Cu/Ni and Cu/SS interfaces. The experiments were carried out at the temperature range of 800 - 950°C with a stress 12 MPa for 1 hour. The joint processed at 900°C showed maximum shear strength of about 145 MPa.

Ghosh et al (2005) carried out diffusion bonding of SS304 and Ti-6Al-4V. They chose the bonding variables on the basis of the importance of grain boundary diffusion in α-β phase of the titanium alloys. The study showed formation of Fe-Cr-Ti intermetallics. For diffusion bonding of this combination, copper was also used as an interlayer. The study revealed the formation of various intermetallics like CuTi₂, CuTi, Cu₃Ti₂, Cu₄Ti₃, FeTi, Fe₂Ti etc as confirmed by XRD.

Tuppen et al (2005) carried out diffusion bonding of Ti-6Al-4V with micro duplex stainless steel using a pure copper interlayer. From the results, it was seen that heating rate and holding time directly affect microstructural development at the joint, especially with respect to the formation of TiFe intermetallic compounds, and this in turn affects the shear strength of the bonds. A sound bond was obtained with a heating rate of 100 K/min and holding time of 5 minutes. It was concluded that a high heating
rate and a short holding time must be used in the diffusion bonding of Ti-Al-4V to a micro duplex stainless steel when pure copper interlayer is used. As the heating rate was decreased and holding time increased, the amount of TiFe intermetallic increased, and consequently shear strength decreased.

Diffusion bonding of titanium alloy to stainless steel with nickel interlayer was carried out by He et al (1999) at bonding temperatures 850°C and 880°C and bonding stress of 8 to 10 MPa and time of 10 to 20 minutes at a vacuum of 3x10⁻³ torr. Formation of intermetallic components TiFe, TiFe₂ and TiC resulted in a brittle weld interface. To avoid this brittleness, Ni was used as an interlayer. The shear strength of the bond joints was evaluated as 60 to 74 MPa. As the bonding temperature increased, shear strength increased.

Ozdemir et al (2009) studied the joining characteristics of Ti-6Al-4V with AISI 304 stainless steel by inserting a copper interlayer in diffusion bonding process. The diffusion bonds were carried out in the temperature range of 820, 850 and 870°C for 50, 70 and 90 minutes, respectively with a stress less than 1 MPa in argon atmosphere. Due to the close packed FCC structure of these materials, the SS 304 / Cu interface is free from intermetallic compounds diffusion layer and a thin diffusion layer was revealed for all the holding times and temperatures applied during experiments. Most significant structural changes occurred in the interface of Cu / Ti-6Al-4V due to the open crystallography of Ti matrix. An enhancement in holding time and temperature caused to a change in microstructure and the width of diffusion zones. The shear strength increased with increasing process temperature and holding times. The highest shear strength of 118 MPa obtained in the sample boded at 870°C and holding time of 90 minutes due to better coalescence of mating surfaces.
Elrefaey et al (2009) carried out joining of dissimilar titanium / steel metals by diffusion bonding with the use of a copper-based interlayer. The results showed that the joint could not be diffusion bonded at a temperature lower than 800°C even at a holding time of 180 minutes. However, at 850°C, successful joining was achieved at all holding times. On the other hand, atom diffusion and migration between Ti and Fe or C were effectively prevented by adding a copper-based interlayer and hence, Fe-Ti and Ti-C intermetallics were not formed in the joint. This technique provides a reliable method of bonding titanium to steel.

Ahmad et al (2003) carried out diffusion bonding of stainless steel (SS) to Zircaloy-4 in the presence of tantalum interlayer, using the process parameters, stress 4.9 MPa, temperature 900°C and time 3 hours. The formation of a Cr-rich layer on the SS side that acts as a diffusion barrier was noticed. Carbides and voids were observed in SS on the Ta foil side.

Diffusion bonding of titanium with austenitic stainless steel using multi-interlayer of Nb /Cu /Ni was conducted by Li et al (2012). The sound joint was obtained at the bonding temperature of 850°C for 30 - 45 min with bond strength of 300 MPa. Nickel atoms aggregated at the copper - niobium interface, which promoted Cu solution in Nb. This phenomenon forms the Cu-Nb solution strengthening effect.

The attempt on diffusion bonding of stainless steel using multiple interlayers of nickel, copper and silver by Gawde et al (2010) resulted in bond strength of 130 MPa. The EPMA results revealed that there were no intermetallic compounds at the interface.
Usage of interlayers for diffusion bonding of nickel alloys has also been reported. Inconel 718 was diffusion bonded by Chandler et al (1982) in the temperature range of 955 to 980°C, using nickel interlayers. However, superalloys were extensively diffusion bonded with other class of engineering materials.

2.8 USE OF INTERLAYERS IN FRICTION WELDING

The use of copper interlayer in friction welding of TiAl with AISI 4140 prevented the formation of crack and martensitic transformation. A highest tensile strength of 375 MPa was reported (Lee et al 2004).

2.9 ULTRASONIC TESTING

There have been many methods developed and practiced to test the bonding quality. These tests are mostly mechanical tests like tension test, shear test etc. and metallurgical characterization tests like optical microscopy, SEM-EDS etc. All these tests were destructive in nature which were carried out on the test samples, but not on the actual components. Nondestructive evaluation (NDE) is used to evaluate the bond quality on actual components. Out of various NDE methods, ultrasonic method is the more reliable and accurate for testing the bonding quality of joints made by solid state welding methods.

Ultrasonic testing is one of the most widely used nondestructive evaluation methods for materials characterisation. In the past few decades, the technology of ultrasonic test has gone to stage where it is used not only for flaw detection but also for determination of microstructural and mechanical properties of materials. The ultrasonic parameters useful for materials
characterisation studies, qualification of processing treatments during fabrication and assessment of damage during service have been reported by Nanekar et al (2004).

Ultrasound testing for characterisation of bond quality was performed by Kato et al (1996) on diffusion bonded mild steel - titanium joints to correlate the bond strength, bonding interface and ultrasonic parameters. Fourier spectra of the ultrasonic wave reflected from the bonding interface were dependent on the state of the bonding interface; when an interlayer did not melt, the spectrum showed a simple profile with one peak, and when the interlayer melted, the spectrum showed a profile with a large irregularity.

2.10 ULTRASONIC C-SCAN ANALYSIS

The most commonly used form of presentation of ultrasonic testing is known as scan-A presentation, in which a graph is plotted for the elapsed time Vs echo amplitude. Ultrasonic test results can also be presented in the form of images and two of such presentations are known as B-scan and C-scan. B-scan displays the cross sectional view of the component and flaws within it and C-scan displays the sectional view at various depths of the component and flaws within it. The ultrasonic C-scan analysis for various applications was discussed by Anishkumar et al (2007), Tsao et al (2005) and Srivastava et al (2003).

Kas et al (2005) demonstrated that the ultrasonic C-scan imaging can be used to evaluate the microvoids present in epoxy composite plates. In the C-scan analysis, a certain value of energy loss was selected and made as set level and further losses were considered as defect or microvoid. In the C-scan analysis, optimum images can be obtained using small focus
transducer focused on bonded joints and the sensitivity for C-scan should be set with the artificial defect (Liang et al 2008).

Cao et al (2005) proposed an ultrasonic nondestructive testing for evaluation of diffusion bonding in terms of interface bonding ratio, which can be used in industrial field. It was proved that bonding ratio is an indicator of the mechanical bonding strength. The schematic diagram of the ultrasonic C-scan system and the reflection of ultrasonic wave at an interface are shown in Figure 2.2. The bonding ratio was calculated after the C-scan image was segmented into bonded region and non-bonded region based on an appropriate threshold. The C-scan images of their experiments on Al - Al₂O₃ and Si - K4 glass are shown in Figure 2.3. The C-scan image of Al - Al₂O₃ joint showed poor bonding status while the C-scan image of Si - K4 glass joint showed well bonding status.

Figure 2.2  The schematic diagram of (a) ultrasonic C-scan system and (b) reflection of ultrasonic wave at an interface
2.11 NEED FOR THE PRESENT STUDY

The literature survey revealed that there were only limited works carried out in dissimilar joining of titanium alloys with Inconel 718 and other materials either by diffusion bonding or by friction welding. Similarly, studies on dissimilar joining of stainless steel by friction welding were also limited.

A good number of works has been reported on joining of stainless steels with titanium by diffusion bonding without or with interlayer had been carried out. In these works, the joint characteristics were mainly analysed based on the chemical composition was at the interface which in turn correlated with the experimental conditions. The results of mechanical testing like tension and shear test were also reported and correlated with the phases formed at the interface. No work was reported on usage of non destructive
evaluation method like ultrasonic method as a characterisation tool for evaluation of the joints of dissimilar material combinations.

The present work is aimed to fulfill the above shortcomings by carrying out dissimilar joining of Ti-6Al-4V with Inconel 718 and Ti-6Al-4V with SS 304L using diffusion bonding and friction welding processes and by examining the suitability of ultrasonic C-scan as the non-destructive testing method for the joints.