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EFFECT OF HOLDING TIME ON BONDING STRENGTH AND JOINT INTERFACE MICROSTRUCTURE OF VACUUM DIFFUSION BONDED DISSIMILAR AUSTENITIC STAINLESS STEEL - TITANIUM ALLOY JOINTS

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ABSTRACT

In this investigation, the effect of holding time on the microstructure of joint interface and bonding strength of vacuum diffusion bonded dissimilar austenitic stainless (ASS) – titanium (Ti) alloy joints were investigated. The dissimilar joints of ASS - Ti alloy were developed using the holding time of 30, 45, 60, 75 and 90 minutes in a vacuum chamber at a temperature of 900°C and pressure of 14 MPa. The bonding strength of ASS – Ti alloy joints was evaluated using the ram tensile test. The microhardness survey was done perpendicular to the joint interface. The microstructure of the joint interface was analyzed using optical microscopy (OM). The evolution of intermetallic compounds at the joint interface was analyzed using X-ray diffraction (XRD). The microstructure of the joint interface was correlated to the bonding strength of joints.

Keywords: *Vacuum diffusion bonding, holding time, AISI 304 steel, Ti-6Al-4V alloy, microstructure and bonding strength*

1. Introduction

The joining of dissimilar materials, especially austenitic stainless steel (ASS) and titanium (Ti) alloy, carries significant importance in aerospace industries for the fabrication of mechanical components to meet the requirement of reduced weight and cost while maintaining the strength requirements [1]. However, joining dissimilar materials such as Titanium alloys to stainless steel is challenging due to the different crystal structures, melting point and mechanical properties [2]. Fusion welding of ASS – Ti alloy leads to the problems of solidification cracking, lower joint efficiency and premature failure due to the evolution of hard and brittle intermetallics in the fusion zone and alloying segregation at the joint interface [3]. Diffusion bonding is a solid state welding process typically employed for joining dissimilar materials. It involves joining two surfaces in closed contact at high temperature and pressure for a specific bonding time [4]. The materials to be joined undergo microscopic deformation and diffusion of atoms at the joining surface, resulting in forming a bond line. The diffusion bonding takes place in 3 stages. The 1st stage involves the yielding and creeping of materials. It causes the deformation of asperities at the faying surfaces so that the surfaces to be joined come in contact with each other. The 2nd stage involves the diffusion of atoms in the contact region via the boundaries of grains. This results in the rearrangement of boundaries of grains which eliminates the formation of pores in the bonding region. The 3rd stage involves the volume diffusion and the formation of diffusion bond of joining material surfaces [5].

AISI 304 is austenitic stainless steel (ASS) containing 18% chromium and 8% nickel. It offers high-temperature strength, low-temperature toughness and corrosion resistance. It exhibits good weldability and does not need pre and post-weld heat treatment. Hence is widely used in high temperature and corrosion resistance applications of the aerospace sector [6]. Ti_6Al_4V titanium (Ti) alloy is the α+β titanium alloy widely used in aerospace due to its superior mechanical properties and lower density. It accounts for 70% of Titanium alloys used in the aerospace sector. The addition of aluminium stabilizes the α phase, and the β phase is stabilized by adding vanadium. It exhibits a high strength-to-weight ratio, good mechanical strength and corrosion resistance at high temperatures up to 300°C [7].

Velmurugan et al. [8] investigated the low-temperature diffusion bonding of Ti6Al4V alloy and

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duplex stainless steel (DSS) and found that the tensile shear strength decreases with an increase in bonding temperature. Eroglu et al. [9] investigated the diffusion bonding of Ti6Al4V alloy and Micro-DSS using Cu as an interlayer. They concluded that with a decrease in the rate of heating and an increase in bonding time, the volume fraction of Ti-Fe intermetallics increases resulting in the reduction of shear strength. Balasubramanian [10] developed the process window for diffusion bonding of Ti6Al4V alloy and AISI 304 steel using silver (Ag) as an interlayer and observed that the joints could be made in 750-800ºC temperature range. The joints made using 5 MPa bonding pressure and 90 min bonding time showed higher lap shear strength. Ozdemir and Bilgin [11] investigated the properties of joining interface in diffusion bonding of Ti6Al4V alloy and AISI 304 steel using Copper (Cu) as an interlayer. Zakipour et al. [12] studied diffusion bonding of Ti6Al4V alloy and AISI 316 steel. They reported that the higher shear strength of 284 MPa was achieved for the joint developed using an interlayer thickness of 50 µm. Gopinath et al. [13] investigated the diffusion bonding of Ti6Al4V alloy and AISI 304 steel using a 200 µm thick niobium (Nb) interlayer. They observed that the joints developed using the bonding temperature of 875ºC exhibited a maximum tensile strength of 372 MPa, shear strength of 241 MPa and ductility of 4.5%. Kumar et al. [14] investigated the diffusion bonding of Ti-5Al-2.5Sn alloy and SS321 steel and observed higher shear strength of 348 MPa at 850ºC bonding temperature.

The research on diffusion bonding of Ti alloys and SS is mainly reported on dissimilar combinations of pure Ti and AISI 304 steel using Cu, Ni as interlayer, Ti6Al4V alloy and DSS, Ti6Al4V alloy and M-DSS, Ti6Al4V alloy and FSS. Some research is reported on diffusion bonding of Ti6Al4V alloy and AISI 304 steel with different interlayers such as Cu, Al, Nb and Ag. The research is mainly reported on the effect of bonding temperature and pressure on the shear strength of joints. However, there is a lack of investigation on the effect of holding time in diffusion bonding of AISI 304 steel and Ti6Al4V alloy without interlayer. So, the main objective of this investigation is to study the effect of holding time on the microstructure of joint interface and the shear strength of joints.

2. Experimental methodology

In this investigation, 5 mm thick AISI 304 steel and Ti-6Al-4V alloy plates were used as the parent metal. Tables 1 and 2 present the chemical composition of AISI 304 steel and Ti-6Al-4V alloy, respectively. The mechanical properties of Ti alloy and ASS are given in Table 3. The plates were cut to 50 x 50 x 5 mm to make the dissimilar joint. The surface of the specimens to be joined were polished using emery papers, chemically cleaned and then fitted in a die. The lap joint setup of AISI 304 steel and Ti6Al4V alloy was then kept in the furnace of the diffusion bonding machine. The dissimilar joints were developed using the diffusion bonding machine (Model No. VBCC/DBE/1600°C-01) as shown in Fig. 1. The specimens were heated in the vacuum induction furnace along with the simultaneous application of pressure. The 10^{-5} torr vacuum was maintained inside the induction furnace. Once the diffusion bonding of dissimilar joints was over, the specimens were allowed to cool inside the furnace. The dissimilar joints of ASS – Ti alloy were developed for the holding time of 30, 45, 60, 75 and 90 minutes at the diffusion bonding pressure of 14 MPa and bonding temperature of 900ºC. Table 4 shows the process parameters used to develop the dissimilar joints.

Table 1 Chemical composition of AISI 304 steel

C	Cr	Mn	Ni	P	S	Si	Fe
0.05	18.7	0.82	8.76	0.014	0.011	0.52	Bal

Table 2 Chemical composition of Ti–6Al–4V alloy

Al	V	Fe	C	Si	Ti
6.0	4.0	0.25	0.029	0.025	Bal

Table 3 Mechanical properties of base metal

Base metal	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Microhardness ($HV_{0.5}$)
ASS	305	505	30	200
Ti alloy	880	950	14	350

The ram tensile test specimens were cut from the specimens using wire-cut electric discharge machining (W-EDM). The testing was carried out using a universal tensile testing machine having a capacity of 5 tons. The non-standard shear strength and ram test were performed to measure the shear strength and bonding strength of the developed joints because the developed joints are not large in size for regular ram tensile testing. Fig. 2 shows the dimensions of the lap shear test specimen. The photograph of typical ram tensile test specimen is shown in Fig. 3.

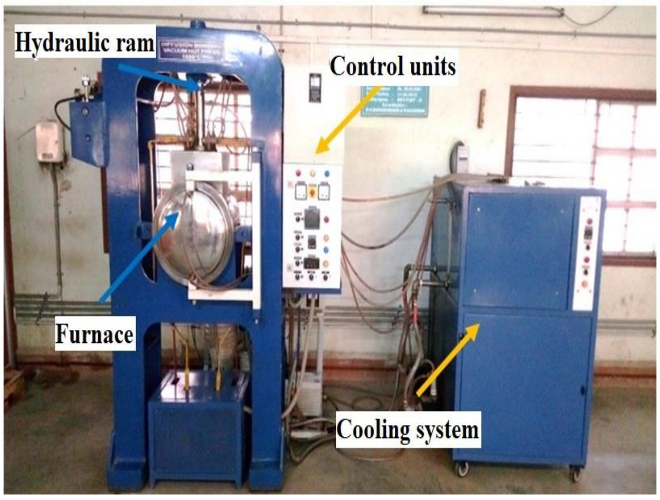

Fig. 1 Vacuum diffusion bonding machine

Table 3 Process parameters used in this investigation

Sr. No.	Holding time (min)	Bonding pressure (MPa)	Bonding temperature (°C)
1.	30	14	900
2.	45	14	900
3.	60	14	900
4.	75	14	900
5.	90	14	900

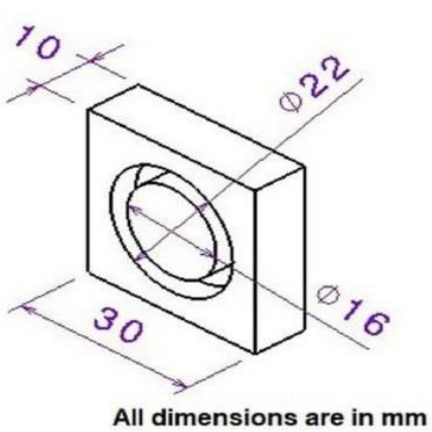

Fig. 2 Dimensions of ram tensile test specimen

Fig. 3 Typical ram tensile test specimen of diffusion bonded ASS-Ti alloy joint

The cross-sectional surface of the diffusion bonded dissimilar joints was a mirror. Ti alloy and ASS steel mirror polished areas were etched using Keller's reagent and glyceregia solution, respectively. The microstructural features of the dissimilar joint interface were analyzed using optical microscopy (OM). The intermetallic phases formed at the dissimilar joint interface were analyzed using the X-ray diffraction (XRD) technique.

3. Results and Discussion

3.1 Effect of holding time on bonding strength

The effect of holding time on the bonding strength of joints is shown in Fig. 4. An increase in holding time from 30 minutes to 75 minutes results in increased bonding strength of dissimilar joints of ASS - Ti alloy. Further increase in holding time results in a reduction in the bonding strength of joints. It is correlated to the increase in the width of the diffusion bonding region. Increased width of the diffusion bonding region leads to the evolution of brittle intermetallics at the dissimilar joint interface and deteriorates the strength of joints. The dissimilar joints of ASS - Ti alloy bonded using the holding time of 75 minutes exhibited a higher bonding strength of 244 MPa. It is attributed to the better coalescence of the joining surfaces. It is mainly due to the optimum diffusion of Fe and Ti atoms at the joint interface, resulting in the complete collapse of surface asperities. It thereby achieves an intimate contact at the dissimilar joint surface. It is also attributed to the evolution of the optimum width of interface layers having minimum embrittlement effects**.** The dissimilar joints bonded using the holding time of 30 minutes exhibited lower bonding strength of 231 MPa. It is mainly due to the insufficient coalescence of the joining surfaces. At this level, the time available for the diffusion of Ti and Fe atoms is less, resulting in a lower diffusion rate of Ti and Fe atoms at the joining surfaces. This promotes the formation of a thinner diffusion bonding region and incomplete coalescence of the joining surface at the contact, thereby lowering the joint strength.

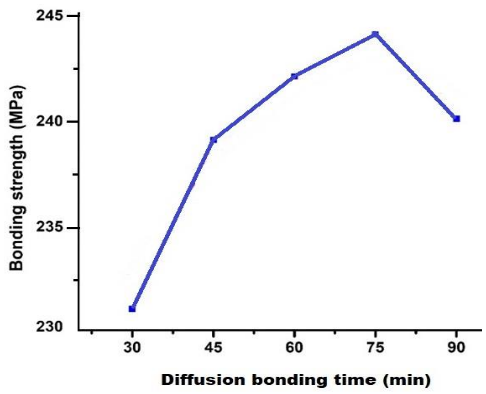

Fig. 4 Effect of holding on the bonding strength of joints

3.2 Effect of holding time on microhardness

Fig. 5 shows the microhardness survey of the dissimilar joint interface at different levels of holding time. The dissimilar joints showed increased hardness at increased diffusion bonding time levels. It is mainly attributed to the increase in the width of the bonding line at the joint interface. This increases the evolution of brittle and hard Fe-Ti intermetallics in the bonding region at the joint interface. This reduces the plastic deformation behaviour of the joint interface when subjected to tensile loading. This is the main reason that the strength of joints decreases above 75 minutes. Thus, the results showed that diffusion bonding time significantly influences the evolution of microstructure, bonding strength and hardness of joints. Hence, selecting the optimum level of diffusion bonding time is important to attain the superior performance of dissimilar joints of titanium alloy and stainless steel.

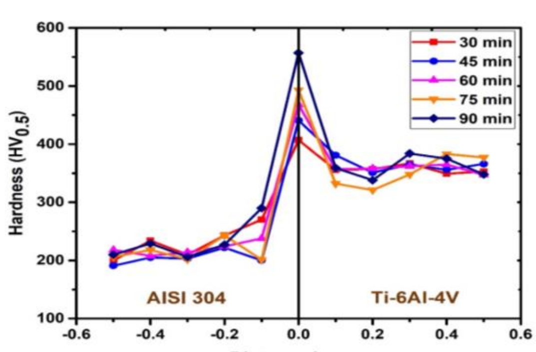

Fig. 5 Effect of holding time on microhardness of dissimilar joints of ASS – Ti alloy

3.3 Effect of holding time on the microstructure of joint interface

Fig. 6a and b show the optical microstructure of Ti6Al4V alloy and AISI 304 steel. The optical micrograph of Ti6Al4V alloy showed columnar grains along the rolling direction. It showed the presence of the equiaxed α phase, which is light in colour and the intergranular β phase, which is darker in colour. The optical micrograph of AISI 304 steel showed equiaxed austenitic grains with annealing twins.

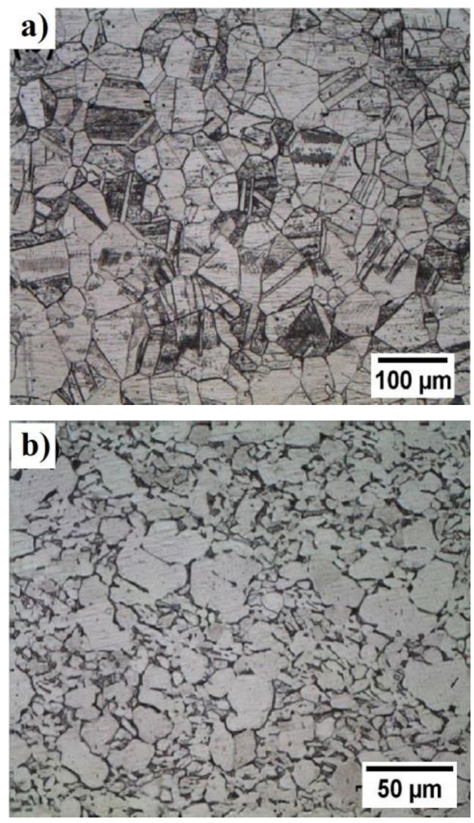

Fig. 6 Optical microstructure of base metal: a) AISI 304 steel; b) Ti6Al4V alloy

Fig. 7 shows the optical micrograph of the dissimilar joint interface at different diffusion bonding time levels. The dissimilar joint interface showed the development of a good joint with no defects such as cracking at the joint interface, porosity etc., The dissimilar joint interface revealed the formation of a diffusion line (DL) at the joint interface. An increase in diffusion bonding time increases the width of the diffusion bonding line. It is mainly attributed to enough time allowed for the metallurgical reaction to occur during diffusion bonding. This results in more diffusion of titanium (Ti) and ferrous (Fe) atoms at the joint interface.

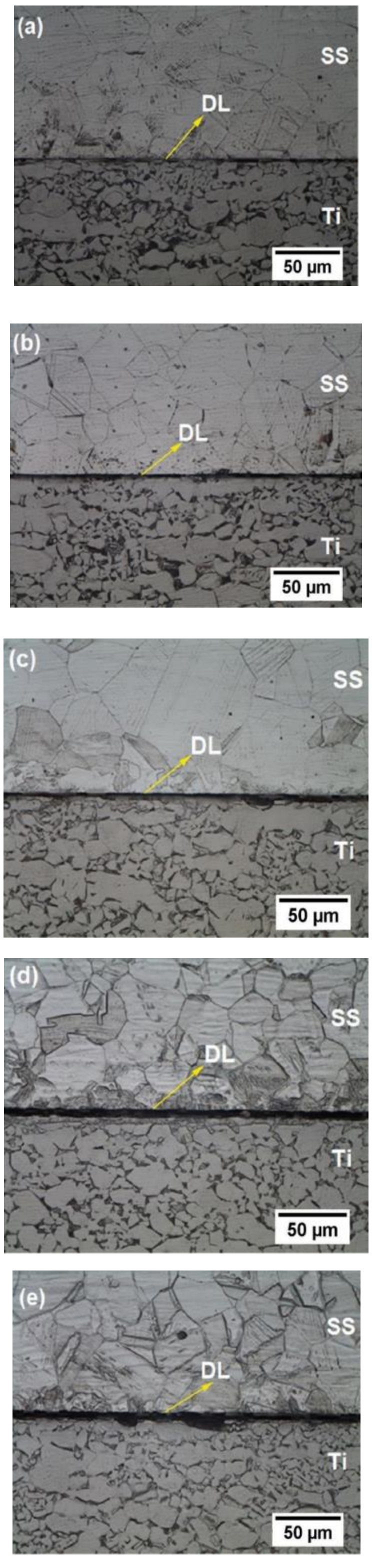

Fig. 7 Optical microstructure of joint interface at holding time of: a) 30; b) 45; c) 60; d) 75 & d) 90 min

As the holding period increases from 30 min to 45 and 75 minutes, the diffusion line (DL) gets wider. The diffusion line is more visible at the dissimilar joint interface after the bonding time of 30 minutes. As the bonding time increases, the volume fraction of Fe2Ti intermetallic at grain boundaries increases. The broader width of the diffusion bonding line is not desirable as it promotes the evolution of volume fraction of intermetallic, which deteriorates the mechanical properties of dissimilar joints

The X-ray diffraction results are shown in Fig. 8. The use of XRD and EDS has shown the presence of intermetallic phases such as $FeNi_3$, Fe_2Ti_4O, Fe_2Ti, $NiTi_2$, FeNi, Fe_3OTi_3, FeTi, and Cr_2Ti, as well as intermetallic phases such as $NiTi_2$. The amount of intermetallics evolved at the diffusion zone increases with an increase in diffusion bonding time.

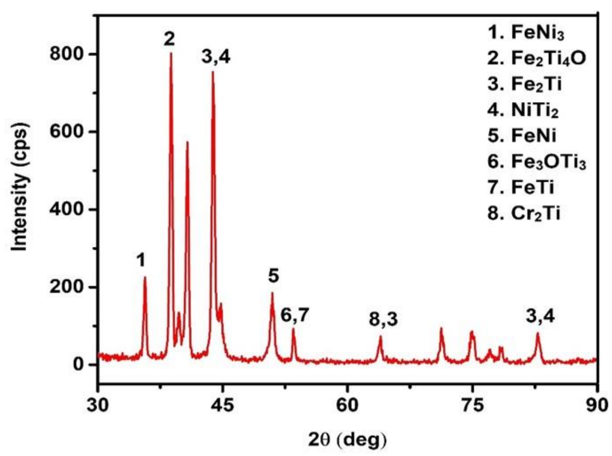

Fig. 8 X-ray diffraction pattern for joint interface bonded at 75 minutes

4. Conclusions

1. The diffusion bonding time significantly influences the microstructure evolution and bonding strength of dissimilar joints of AISI 304 steel - Ti6Al4V titanium alloy.
2. An increase in diffusion bonding time increases in bonding strength of dissimilar AISI 304 steel - Ti6Al4V alloy joints up to 75 minutes. Further increase in diffusion bonding time up to 90 minutes showed a reduction in bonding strength of joints. It is mainly attributed to the increase in bonding line thickness and intermetallic' evolution.
3. The dissimilar joints of ASS – Ti alloy developed using the holding time of 75 minutes showed higher bonding strength of 244 MPa. It is mainly attributed to the better coalescence of

the joining surfaces and the evolution of optimum width of interface layers having minimum embrittlement effects.

4. An increase in diffusion bonding time increases the width of the diffusion bonding line at the dissimilar joint interface. It is mainly correlated to the increased diffusion of Ti and Fe atoms at the joint interface resulting in the increased precipitation of intermetallics.

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