

Diffusion bonding of a titanium alloy to a stainless steel with an aluminium alloy interlayer

K Chandrappa^{*1}, Amit Kumar^{*2} and Kumar Shubham³

¹ Associate Professor, Department of Mechanical Engineering, Siddaganga Institute of Technology, Tumkur – 572 103, Karnataka, India

^{2,3} Under Graduate Student, Department of Mechanical Engineering, Siddaganga Institute of Technology, Tumkur – 572 103, Karnataka, India

*Corresponding author: kchandrappa@sit.ac.in, amit.1s14me019@gmail.com

Abstract. Diffusion bonding is the process of joining similar or dissimilar materials at the interface rather than edge joining using welding process or other metal joining processes. It is a solid state welding process carried out under the conditions of soaking temperature, bonding time and load on the surfaces to be joined. Generally this is carried out under vacuum or inert atmosphere to avoid interface reactions to actuate the corrosion. Diffusion bonding process done at different conditions of temperature, bonding time and load. These parameters are optimised for better bond strength, the bonded specimens are analysed for microstructural changes and bond strength since diffusion bonding is an atomic transfer between the surfaces. The micro hardness test is conducted to evaluate the bond strength at the interface. The strength of the bond can be improved by inserting another material at the interface as an interlayer. The base metal titanium with stainless steel is bonded with aluminium as an interlayer.

1. Introduction

The titanium alloy has high tensile strength, high corrosion resistance, can withstand moderately high temperature without creeping and therefore titanium alloy are used in aircraft. The use of titanium alloy has been increased in aircraft industries, so its proper utilization is required [1-3]. The joining of titanium alloy to the stainless steel has also found some of its implementation in satellite cooling system. The highly précised joints of titanium alloy/stainless steel having good bonding properties can be obtained by diffusion bonding process at different temperature, time and load.

Ti-Fe inter-metallic compounds are formed when stainless steel are joined directly to titanium alloy and it makes the joint brittle. Due to the large difference of linear expansion between Ti alloy and stainless steel, high internal stresses are formed and it also leads to bonding crack. Hence, indirect bonding with addition of interlayer metal is in use[4]. Aluminium alloys possess few erosion resistance properties and also have good plasticity, therefore the practicability of diffusion bonding of titanium alloy to stainless steel with an aluminium as an interlayer improves the bonding strength and is demonstrated in this paper [5-8]. The microstructural analysis at the interface shows rearrangement of the atoms with the diffusion process thereby increasing holding strength of the atoms at the boundary layer [9-12].



1.1. Diffusion bonding setup

The Diffusion bonding setup used for joining the two similar or dissimilar metals is shown in the figure 1. This setup mainly consisting of heating chamber with a carbon rods or plates for producing temperatures above 900°C with a vacuum generation facility provided by diffusion pump and a vacuum pump.

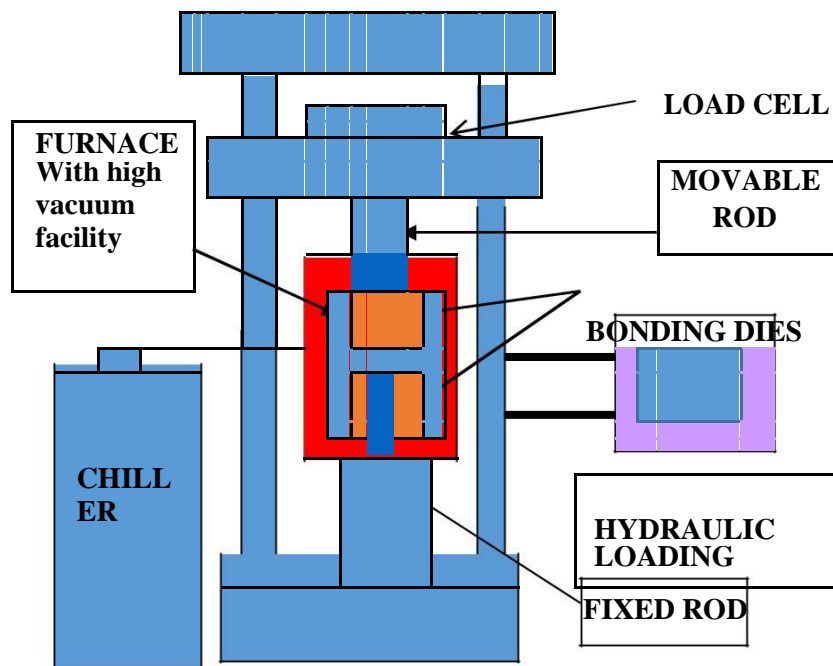


Figure 1. Schematic diagram of Diffusion bonding setup.

The required vacuum to avoid the reactions between the bonding surfaces can be produced at the order of 10^{-6} supplying liquid nitrogen to the diffusion pump. Since the heating chamber should not over heated hence constant cooling using water cooling system. Overcooling may result in the production of vapors which indirectly affects the diffusion bonding process hence moderate cooling is required and done with a electronic controller. Precise loading of the bonding surfaces possible with a use of hydraulic loading [8].

The diffusion bonding process is a means of transferring atoms from one surface to another and breaking of aspirates on the surfaces of bonding or diffusing of clusters of atoms of the similar and dissimilar metals. Vacancy is referred to an unoccupied site in a lattice structure. Diffusion of atoms is a thermodynamic process where temperature and infusibility of the material are considerable parameters. The atomic transfer during the diffusion bonding process is a result of activation energy of the atoms achieved by heating the surface maintaining the temperature at less than or equal to 0.6 times the melting temperature of the base metal. The plastic flow of the material helps in the determination of the flow stress to be applied on the surface to avoid the buckling of the material or creep at elevated temperatures.

2. EXPERIMENTAL

Diffusion bonding experiment comprising of titanium alloy, stainless steel and aluminium alloy as an interlayer was conducted. The specimen of 1mm thickness with 10×10mm size is diffusion bonded under the various condition of bonding temperature, time and load. The master alloys to which the bonding is to be done were machined and so was the aluminium alloy to join them. The surface of the material used for bonding are very well polished with different emery paper of different grades starting with 200 to 3000 so that irregularities at the surface can be made smooth for better bonding. Suitable chemical agents (ethanol to remove grease or any dust) are applied for cleaning the surface to avoid reactions at the interface so that better strength can be achieved at the interface.

A vacuum pressure of 3×10^{-3} Pa was applied during the experiment. A high-frequency induction equipment was used in the experiment and the heating rate of 2000°C/min was applied throughout the experiment. For tensile testing, small blocks were taken out and the testing was performed at nominal strain rate of 3×10^{-4} s⁻¹. The microstructure at the interface of three materials can be seen by the use of SEM images.



Figure 2. Vacuum hot press diffusion bonding equipment.

Table 1. Chemical composition in % of the material OT4-1 (Ti-Al-Mn) alloy

Fe	C	Si	Mn	N	Ti	Al	Zr	O	H	Impurity
Max 0.3	Max 0.1	Max 0.15	0.7-2	Max 0.05	94.138- 98.3	1-2.5	Max 0.3	Max 0.15	Max 0.012	Other 0.3

The percentage of titanium is given approximately

Table 2. Mechanical properties under T=20°C of the material OT4-1

Assortment	Dimension	Direct	S _E	S _T	D ₅	Y	KCU	Heat treatment
-	mm	-	Mpa	Mpa	%	%	KJ/m ²	-
Sheet	1-2	-	600-750	570-30	-	-	-	-
Bar	-	-	600-750	500-600	20	30	500	-

Table 3. Chemical compositions of master alloy weight %.

CONTENT	MATERIAL		
	TC4	1Cr18Ni9Ti	LF6
C	0.1	0.02	-
Si	0.2	1.0	0.5
Mn	-	2.0	0.5-0.8
Cr	-	18	-
Ni	-	9	-
Ti	Bal	1.0	0.5
Fe	0.3	Bal	-
V	4.5	-	-
Al	5.5	-	-
N	0.05	-	Bal
H	0.02	-	-
O	0.2	-	-
Mg	-	-	5.8-6.8
Cu	-	-	0.1

3. RESULTS AND DISCUSSIONS

3.1. Result of bonding temperature T on strength of diffusion bonding

The experiments are conducted under the various conditions of bonding parameters. The samples are made with a size of 10×10mm. These samples are kept under the furnace free from atmospheric inclusions by creating sufficient vacuum with a use of diffusion pump, vacuum pump with a water cooling system to prevent excessive heating and production of vapours which activates reaction at the interface of the bonding area. The experimental results are tabulated for different conditions of temperature, bonding time and pressure applied on the surfaces to be bonded.

The bonding temperature T influences the yield strength which results in atomic diffusion of the base metals, this can be analysed with an empirical relations as explained in the introduction. With an experimental results it was found that the bonding strength will increases based on the type of the material to be joined, the conditions of the surface like aspirates, regularity in the surface cleanliness of the surface. Effect of bonding temperature T on the tensile strength σ_b of the joints (as shown in figure 3). At the temperature of 623K, there is a regular variation of bonding temperature with the tensile strength of the bonded joints. At this temperature, the joints shows tensile strength of only $122 \times 10^6 \text{N/m}^2$.

The stainless steel shows a high yield strength and therefore the contact is very poor between the bonded surface. Simultaneously there is a decrease in atomic diffusivity due to low thermal excitation. The fracture of specimen takes place mostly on stainless steel/LF6 interface. As the bonding temperature increases from 623K to 723K, decrease in yield stress of master alloy and increase in atomic diffusivity can be seen. Hence, it results in high interfacial deformation and chemical bonding becomes easier. Due to this, there is a increase in tensile strength of the joints. As the bonding temperature approaches 723K, the tensile strength of the bonded joints reaches a maximum value of

$183 \times 10^6 \text{N/m}^2$ and at the stainless steel/LF6 interface specimen fracture takes place. It occurs mostly on interlayer metal LF6, and the fracture was ductile fracture. As the bonding temperature is increased to 873K, there is a drastic decrease in tensile strength of joints and it approaches a minimum value of $34 \times 10^6 \text{N/m}^2$. The fracture that occur at stainless steel/LF6 interface was entirely brittle (as in figure). As T starts exceeding from 723K, the bond strength starts decreasing with increase in bonding temperature. As per result it was observed that there is an optimization of the bonding parameters with the values of bonding temperature of 623K, 60min bonding time and 1200kg as a load. The microstructural analysis and variation of strength are plotted using the bar graph shown in figure 3.

3.2. Dispersion of elements

The dispersion of the elements and rearrangement of the atoms at the interface of three materials shows that there is a drastic change in the roughness value due to the presence of gap between the surfaces. Hence it is needed to have smooth surface free from any foreign particle during the diffusion bonding in the vacuum atmosphere.

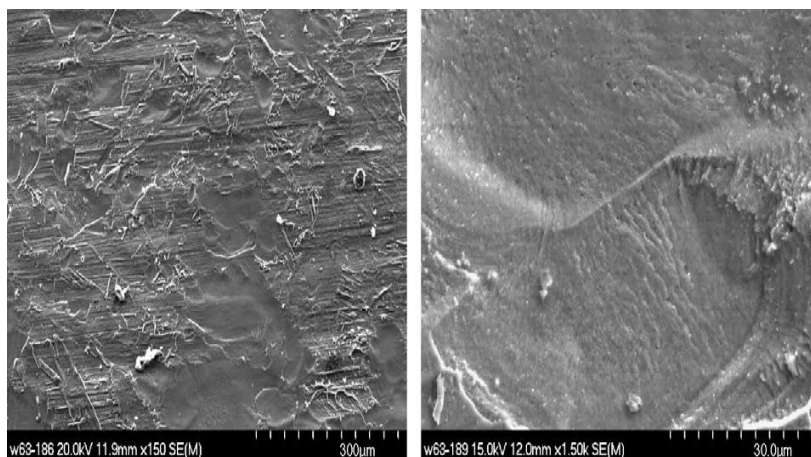


Figure 3. SEM image of bonded joint interface.

3.3. Result of average pressing speed on strength

The rate of deformation of the three materials aluminium, titanium and stainless steel was affected due to the average speed and its affects on strength can be seen in figure 3b. The highest value of strength ($183 \times 10^6 \text{N/m}^2$) was obtained at the pressing speed of 70mm/min. It is observed that the bonding stress is low for low value of pressing speed V. As the oxide film is not removed well, lower value of friction force at the interface is obtained. It can be observed that the specific bonding stress has a very important role in formation of practical contact and atomic bonding process.

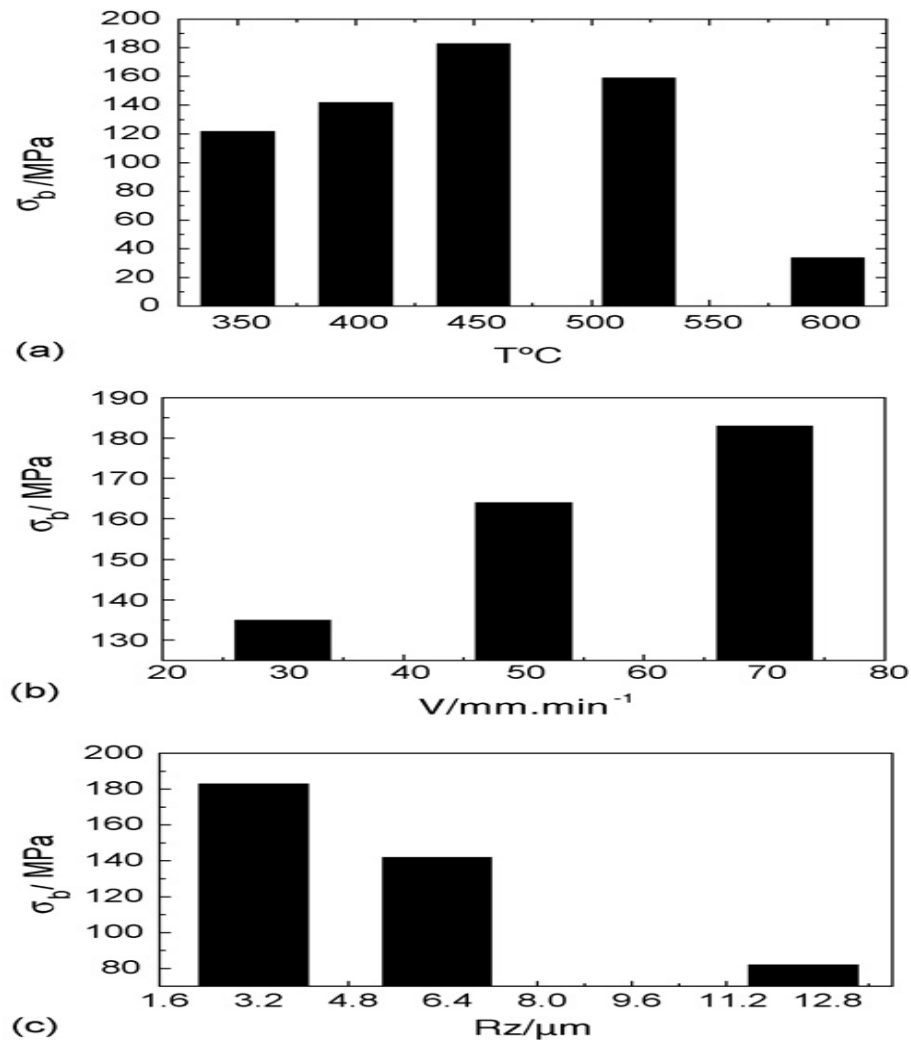


Figure 4. Result of the bonded joints. (a) Bonding temperature Vs tensile strength; (b) average pressing speed Vs tensile strength ($T=450^{\circ}\text{C}$); (c) surface roughness degree Vs tensile strength.

3.4. Microstructure analysis

The microstructure at the interface of three materials aluminium, titanium and stainless steel shows that the atomic transfer is very effective at the interface on the application of bonding temperature so that melting temperature of these materials is very high [3]. Therefore application of high temperature results in handling of bonding process. Therefore an effective cooling system should be provided for the furnace to avoid formation of reactions agents.

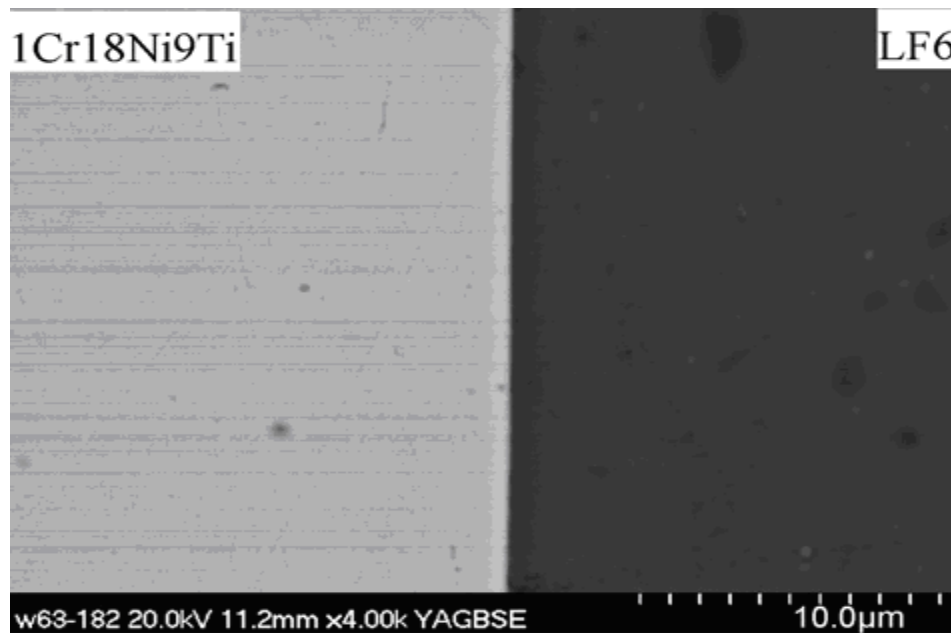


Figure 5. SEM image of bonded joint

4. CONCLUSIONS

- (1) The strength of the bonding depend on the nature of the surface to be bonded, pair of materials to be bonded and the operating process parameters. The experimental parts covering the process parameter optimization with surface indicates that the optimized bonding temperature is 823K, one hour bonding time and a force of 1200kgs on a specimen sample size of 10×10mm with 1mm thickness of sheet.
- (2) The micro hardness at the interface of the bonding shows that the hardness values varies from the contact zone to the farther zones.
- (3) The maximum hardness value purely depends on the surface in contact, activation energy of the atoms, minimum voids and maximum contact surface.
- (4) During the bonding process it is observed that the strength is better if sufficient vacuum is created during the bonding process to avoid the oxide layer formation and the bonding surface.

5. References

- [1] Mahesh D C, H V Divya, Laxmana Naik L, B.Yogesha and S.S. Bhattacharya, *Superplastic Tensile Behaviour of a Ti-Al-Mn alloy*.
- [2] A K Ghosh ,C H Hamilton 1986 Rockwell International Science Centre, Thousand Oaks, USA, *Superplastic Forming and Diffusion Bonding of Titanium Alloys*, Def Sci J.**36**, 153-177.
- [3] A Elrefaey, W 2009 Tillmann Effect of Brazing Parameters on Microstructure and Mechanical properties of Titanium Joints,*Journal of Materials Processing Technology* .**209**,4842–4849.
- [4] L I Durate, F Viana, A S Ramos, M T Vieira, C Leinenbach, U E Klotz, M F Vieira 2011 Diffusion bonding of gamma-Ti-Al using modified Ti/Al nano layers. *Journal of Alloys and Compounds* .**536**,424– S427.

- [5] Kemal Aydın, Yakup Kaya, Nizamettin Kahraman 2012 Experimental study of diffusion welding/bonding of titanium to copper., *Materials and Design*. **37**, 356–368.
- [6] Jian Cao, Jiakun Liu, Xiaoguo Song, Xingtao Lin, Jicai Feng 2013 Diffusion bonding of Ti-Al inter-metallic and Ti₃AlC₂ ceramic: Interfacial Microstructure and joining properties , *Materials and Design*. **56**,115–121.
- [7] Liu Huijie, Feng Xiuli 2009, Study of Diffusion Bonding Of Fine Grain Tc21 Titanium Alloy, *Rare Metal Materials and Engineering*.**38**,1509–1513.
- [8] K A Padmanabhan, R A Vasin, F U Enikeev 2001,Superplastic Flow: Phenomenology and Mechanics, *Springer-Verlag, Berlin*.**11**,5-27.
- [9] C E Pearson,1934 The viscous properties of extruded eutectic alloys of lead–tin and bismuth tin, *J. Inst. Metals* .**54** ,111–124.
- [10] Ravisankar B, Krishnamoorthi J, Ramakrishnan SS, Angelo PC 2009 *Diffusion bonding of SU 263*.*J Mater Process Tech* . **209(4)**, 2135–44.
- [11] G.D. Benough,1912 *A Study of the properties of alloys at high temperatures*, J. Inst. Metals 7 (**123–174**, ISSN 0020-2975.
- [12] Lee HS, Yoon JH, Park CH, Ko YG, Shin DH, Lee CS 2007, A study on diffusion bonding of superplastic Ti–6Al–4V ELI grade,*J Mater Process Tech*.**187–188**:526–9.