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Trans. Nonferrous Met. Soc. China 25(2015) 2932−2938
Transactions of Nonferrous Metals Society of China
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Development of processing windows for diffusion bonding of Ti−6Al−4V titanium alloy and 304 stainless steel with silver as intermediate layer

M. BALASUBRAMANIAN

Department of Mechanical Engineering, R.M.K. College of Engineering and Technology, Puduvoyal, Tiruvallur 601206, India

Received 14 November 2014; accepted 29 March 2015

Abstract: As titanium alloy is chemically reactive, it is very difficult to join by conventional welding techniques. Titanium alloys can easily pick up nitrogen and oxygen from the atmosphere. In the fusion welding method, brittle intermetallic compounds are formed when joining titanium alloy and stainless steel, which decrease the mechanical behavior of the couples. Hence, for joining of titanium alloy, diffusion bonding is recommended. This work dealt with the measurement of feasible process parameters for diffusion bonding of Ti−6Al−4V and AISI 304 stainless steel with silver as an intermediate layer. The quality of the bonds was confirmed by the lap shear test and microstructural analysis. With the experimental results obtained, diffusion bonding windows were constructed and this will act as reference maps to identify the process parameters for obtaining defect free bond. Bonding was successful in the temperature range of 750−800 °C. Maximum lap shear strength was achieved under a bonding pressure of 5 MPa and holding time of 90 min.

Key words: Ti−6Al−4V alloy; silver; AISI 304 stainless steel; interlayer; diffusion bonding

1 Introduction

The properties of titanium alloy Ti−6Al−4V include high strength, high toughness, high erosion resistance, low thermal conductivity and low density [1−5]. Titanium alloy finds wide applications in spacecraft and aircraft industries [6,7]. Titanium alloy and stainless steel joints are used in space and nuclear industries due to their excellent mechanical behavior and good corrosion resistance [8]. As titanium alloy is chemically reactive, it is very difficult to be welded. Titanium alloys can easily pick up nitrogen and oxygen from the atmosphere [9,10]. In the fusion welding method, brittle intermetallic compounds are formed when joining titanium alloy and stainless steel, which decreases the mechanical behavior of the couples. Hence, diffusion bonding is recommended. Diffusion bonding is a solid state welding process that produces the coalescence of the faying surfaces, by the application of pressure at elevated temperature. The process does not involve the macroscopic deformation or relative motion of the work pieces. In diffusion bonding, high quality joints can be achieved without post weld machining [11]. When fusion welding is carried out to join Ti and stainless steel, a number of intermetallics are frequently formed in the weld pool, which results in embrittlement of joints. Existing literature reports that a number of brittle intermetallics are formed due to the limited solubility of Fe and Ti in the solid state and these intermetallics deteriorate the bond strength. Better bonding quality in diffusion bonding can be obtained by inserting an interlayer between the materials to be joined [12]. Both similar and dissimilar materials are joined by diffusion bonding [13,14]. Diffusion bonding is dependent on three major parameters like bonding temperature, holding time and bonding pressure [15]. By diffusion bonding, high strength joint can be obtained without cracking and distortion. Diffusion bonding has been used to join various metals and alloys and their strength and characterization have been already reported in the literatures [16−21].

Diffusion bonded joints of commercially pure titanium (CP Ti) to 304 austenitic stainless steel over the temperature range of 850–950 °C for 1 h under 3 MPa uniaxial pressure were studied. Reaction products formed due to diffusion were identified. Diffusional behavior of Ti, Cr, Ni and Fe has been studied. Room temperature

Corresponding author: M. BALASUBRAMANIAN; Tel: +91-9841714830; E-mail: manianmb@gmail.com
DOI: 10.1016/S1003-6326(15)63919-X

tensile strength of the transition joints was evaluated [22]. Dissimilar titanium/steel metals were successfully joined by diffusion bonding process using copper as interlayer. Joints were successfully established at 850 °C and joints were not successful below bonding temperature of 800 °C [23]. No literature was found on the construction of diffusion bonding window (DBW) for joining of Ti−6Al−4V and AISI 304 stainless steel materials with silver as an interlayer. Electrolytic copper rods were bonded to Ti−6Al−4V rods at 875 °C and 890 °C. It was observed that bonding was not successful at bonding temperature of 900 °C [22]. In this work, construction of diffusion bonding windows for Ti−6Al−4V and AISI 304 stainless steel with silver as an interlayer was carried out and the details were presented.

Generally, the levels of the temperature selected for diffusion bonding are in the range of 0.6−0.8 T_m, where T_m is the melting temperature [22]. From the previous literature and experiments conducted in our laboratory, important process parameters were chosen to bond the specimens [24]. The bonding characteristic and shear strength of Ti-17 titanium alloy at different bonding time were investigated. The shear strength of bond increased with increasing bonding time and the highest shear strength of 887.4 MPa was achieved at a holding time of 60 min. The contribution of plastic deformation on the void closure and the increase of shear strength was significant even though the time of plastic deformation was short [25]. The microstructures and mechanical properties of Ti−6Al−4V/Cu−10Sn bronze diffusion bonded joint were studied via scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS). Diffusion bonding of Ti−6Al−4V to Cu−10Sn bronze was investigated at various holding time. It was identified that the bonding had high shear strength up to 102 MPa for the joints bonded at bonding temperature of 830 °C, bonding pressure of 10 MPa and bonding time of 15 min. Shear test results show that the fracture took place between the reaction layer and the Cu−10Sn bronze substrate, and the shear strength was strongly related to the formation of Cu−Ti−Sn intermetallic compounds [26].

2 Experimental

Titanium alloy, silver and AISI 304 stainless steel of dimensions of 50 mm × 50 mm × 5 mm were considered for the experimental study. The chemical compositions of the materials chosen are presented in Table 1 and Table 2. The specimens considered for investigation were polished, chemically treated and stacked in a die made up of 316L stainless steel. This setup was kept in the diffusion bonding furnace. The specimens were heated using an induction furnace and simultaneously pressure was applied. Vacuum pressure of −3.87 kPa was maintained inside the induction furnace. Once the bonding was accomplished, the specimens were cooled in the furnace. Different combinations of temperature, pressure and holding time were chosen and 37 joints were fabricated and displayed in Table 3. Metallographic specimens were prepared using conventional techniques. Titanium alloy and stainless steel were etched with Kroll and glyceregia solutions, respectively. The microstructural analysis was carried out for all the samples, to find out the formation of a diffusion layer in the interface regions. Lap shear tensile specimen was prepared using wire cut electrical discharge machine. The lap shear test was carried out in a 5 t capacity universal testing machine and the results are tabulated in Table 3.

Table 1 Chemical composition of Ti−6Al−4V titanium alloy (mass fraction, %)

Al	V	C	Fe	O_2	N_2	H_2	Ti
6.3	4	0.006	0.17	0.166	0.006	0.002	Bal.

Table 2 Chemical composition of AISI 304 stainless steel (mass fraction, %)

C	Si	Mn	Cr	Ni	S	P	Fe
0.05	0.52	0.82	18.7	8.765	0.014	0.011	Bal.

3 Results and discussion

3.1 Development of diffusion bonding windows

The joining characteristics of Ti−6Al−4V with AISI 304 stainless steel by inserting a copper interlayer was investigated in a vacuum free diffusion bonding process. The diffusion bonding was carried out at temperatures of 820, 850 and 870 °C for 50, 70 and 90 min, respectively under 1 MPa load in argon atmosphere. The influence of insert alloy layer on the strength and quality of bonded joints was also evaluated [16].

Commercially pure titanium was bonded to low carbon steel with copper interlayer at a uniaxial load of 3 MPa, bonding temperature of 800 to 850 °C and holding time of 30 to 180 min. When the diffusion temperature was above 800 °C, the joints got separated during the preparation of specimen for the metallographic observation. It may be due to the poor contact surface and insufficient thermal excitation. Hence, titanium was not bonded to steel even at 800 °C and 180 min holding time. Ti−6Al−4V rod was bonded to copper at various temperatures and time. Specimen bonded at 900 °C with 15 min holding time did not result in complete bonding. Good bonding was achieved and 890 °C at 60 min holding time [27].

Based on the experimental results tabulated in Table 3, the following inferences were obtained: 1) When the bonding temperature was lower than 700 °C, no bonding occurred between the titanium alloy and stainless steel and this was due to insufficient temperature to cause diffusion of atoms (Fig. 1(a)); 2). When the bonding

Table 3 Experimental conditions and results of lap shear strength

Joint No.	Bonding temperature/ °C	Bonding pressure/ MPa	Holding time/ min	Bonding (Yes or No)	Lap shear strength/ MPa	Joint No.	Bonding temperature/ °C	Bonding pressure /MPa	Holding time/ min	Bonding (Yes or No)	Lap shear strength/ MPa
1	650	2	30	No		20	750	5	30	Yes	102
2	675	3	30	No		21	750	5	60	Yes	123
3	700	2	60	Yes	43	22	750	5	70	Yes	125
4	700	2	90	Yes	48	23	750	5	90	Yes	136
5	700	2	120	Yes		24	750	5	120	No	
6	700	3	30	Yes	46	25	750	5	150	No	
7	700	3	60	Yes	53	26	800	2	30	Yes	102
8	700	3	90	Yes	58	27	800	3	30	Yes	124
9	700	3	120	Yes		28	800	3	60	Yes	128
10	700	5	30	Yes	68	29	800	3	90	Yes	132
11	700	5	60	Yes	62	30	800	3	120	No	
12	700	5	90	Yes	58	31	800	5	30	Yes	158
13	700	5	120	No		32	800	5	60	Yes	128
14	725	2	90	Yes	58	33	800	5	70	Yes	138
15	750	2	30	Yes	62	34	800	5	90	Yes	158
16	750	2	60	Yes	68	35	800	5	120	No	
17	750	3	30	Yes	62	36	825	2	30	No	
18	750	3	60	Yes	83	37	825	3	30	No	
19	750	3	90	Yes	96						

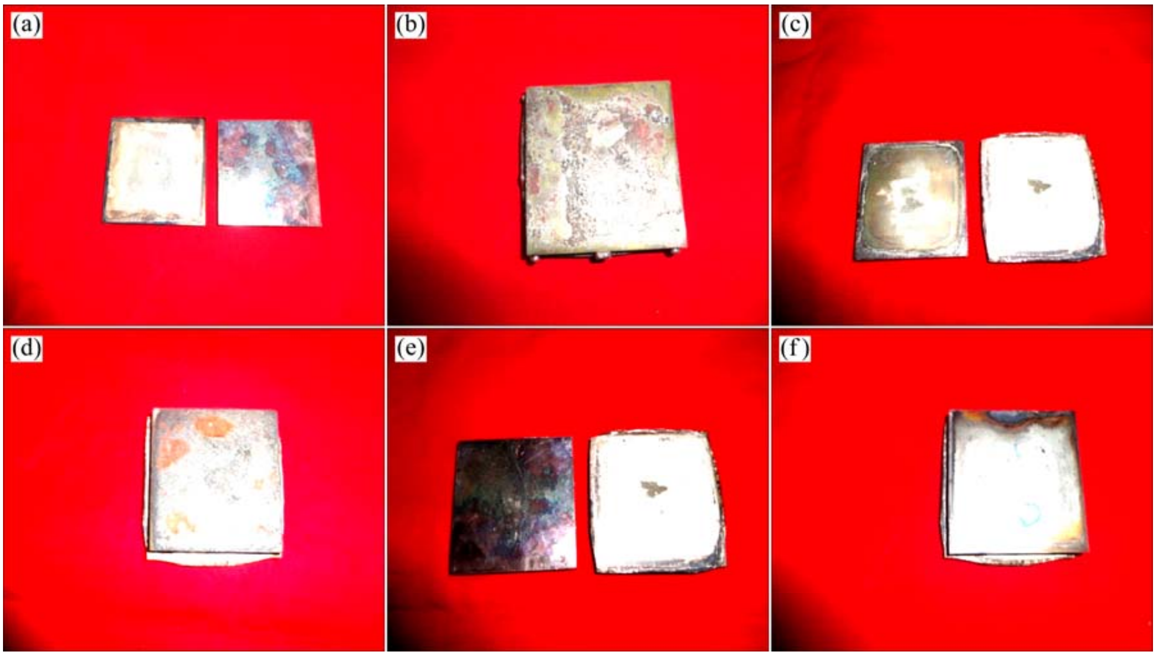

Fig. 1 Fabricated diffusion bonded coupons: (a) Bonding temperature lower than 700 °C; (b) Bonding temperature higher than 825 °C; (c) Bonding pressure lower than 2 MPa; (d) Bonding pressure higher than 5 MPa; (e) Bonding time less than 15 min; (f) Bonding time longer than 120 min

temperature was increased to 825 °C, the interlayer silver started to melt as the melting point of silver was nearing and the pressure decreased automatically as seen in Fig. 1(b); 3) When the bonding pressure was lower than 2 MPa, no bonding took place due to the minimum contact points between the material as visualized in Fig. 1(c); 4) When the bonding pressure was higher than 5 MPa, plastic deformation took place, resulting in bulging at the outer edges as seen in Fig. 1(d); 5) When the holding time was less than 15 min, bonding was not achieved and this is due to the lack of sufficient time for the diffusion reaction to take place, as seen in Fig. 1(e); 6) When the holding time was longer than 120 min, bonding was not successful, followed by plastic deformation, as visualized in Fig. 1(f). Failure occurred during specimen preparation for tensile testing.

Successful bonding between titanium alloy and stainless steel with silver interlayer was achieved at the bonding temperature of 700−800 °C, bonding pressure of 2−5 MPa and holding time of 30−120 min. DBW was constructed by keeping the bonding temperature in the *Y* axis and holding time in the *X* axis. Processing limits were found out by maintaining the pressure constant at 2, 3 and 5 MPa and varying the bonding temperature and holding time. With these observations, the diffusion bonding windows were constructed and displayed in the Figs. 2 and 3. The selection of diffusion bonding process parameters inside the region of diffusion bonding window Figs. 2(a)–(c) always yields successful bonding between the base materials and this was validated by conducting more experiments.

3.2 Influence of diffusion bonding parameters on tensile strength

From the results obtained, it is observed that the lap shear strength of the bonds depends on bonding temperature, bonding pressure and holding time. It is well known that, adequate heat, diffusion time and pressure are required for atoms to diffuse between the materials. Pressure–time diagram was constructed by keeping the temperature constant and varying the pressure and holding time to find out the working limits. If the bonding temperature increases, the holding time required to obtain defect free bonds decreases, irrespective of the bonding pressure. The selection of diffusion bonding process parameters inside the region of the pressure–time diagram in Figs. 3(a)–(c) always yields successful bonding between the materials.

Commercially pure titanium and low carbon steel plates were joined through diffusion bonding using a silver alloy as 51Ag−36Cu−11Zn interlayer at various bonding temperatures and holding time. In order to determine the strength of the resulting joints, tensile−shear tests and hardness tests were applied. The results showed that the highest interface strength was obtained for the specimens joined at a bonding temperature of 850 °C and holding time of 90 min. Earlier studies were made with commercially pure titanium and low carbon steel using silver as interlayer at the temperatures of 700, 750, 800, and 850 °C and different bonding durations (30, 60, 90 and 120 min). Bonding performed at 700 °C and 30 and 60 min of diffusion time resulted in de-bonding of the samples. The

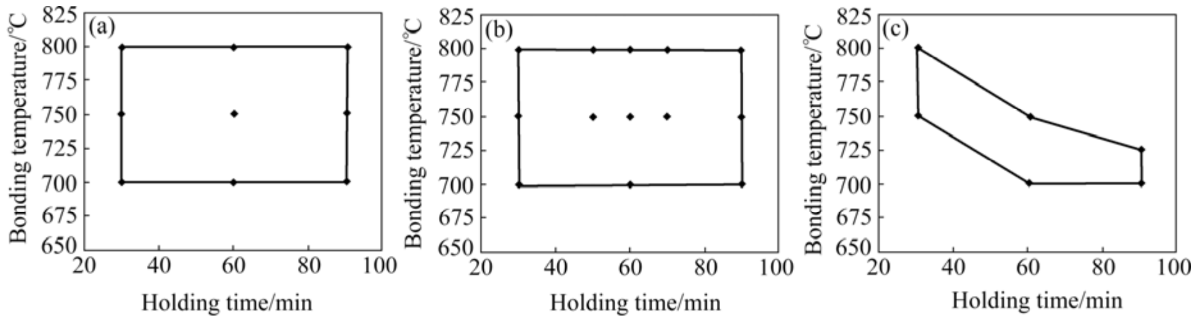

Fig. 2 DBW of titanium alloy stainless steel under different pressures: (a) 3 MPa; (b) 5 MPa; (c) 2 MPa

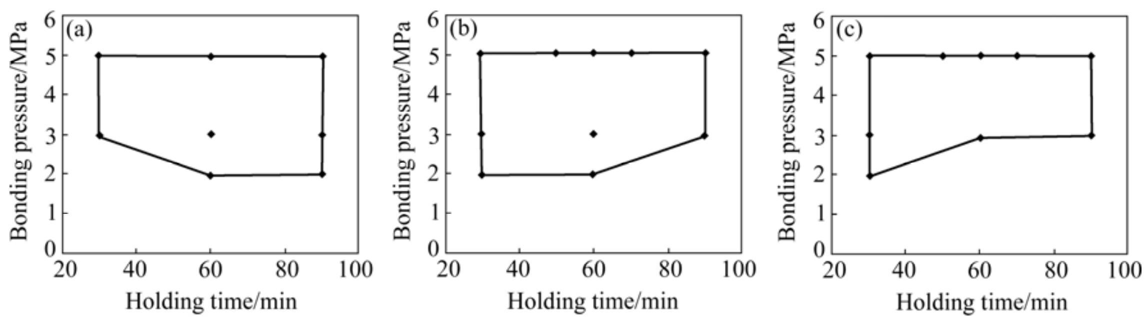

Fig. 3 Pressure–time diagrams of DBW at different temperatures: (a) 700 °C; (b) 750 °C; (c) 800 °C

failure of bonding at 700 °C for 30 and 60 min of diffusion time can be attributed to both the low temperature and the insufficient diffusion time given to the samples. When diffusion time was increased to 90 min or bonding temperature was increased to 850 °C without any increment in diffusion time, bonding could be accomplished. It is well known that adequate heat, diffusion time, and pressure are required for atoms to diffuse in this bonding method. Diffusion time is a dependent operation parameter and is interrelated with temperature, pressure, and the type of bonding [17].

Diffusion time is dependent on operating parameter and it is interrelated with temperature, pressure and the type of bonding [17,18]. If the pressure increases, the time required to get effective bond decreases. Both maximum and minimum bonding temperatures to get effective bonds remain unaltered, irrespective of bonding pressure. From the results, it is observed that the shear strengths of the bond depend on the temperature, bonding pressure and holding time. The shear strength of the aircraft structures is in the order of 10−20 MPa [19]. From the lap shear values, it is observed that all the bonds satisfy the requirements and fall under good bonding category. Formation of diffusion layer at the interface influences the shear strength of the joint. Hence, optical micrographs were taken to analyze the formation of diffusion layer. From Figs. 4(a)−(f), it is understood that a wide diffusion layer will lead to low shear strength. Hence, diffusion layer must be optimized to obtain a higher shear strength.

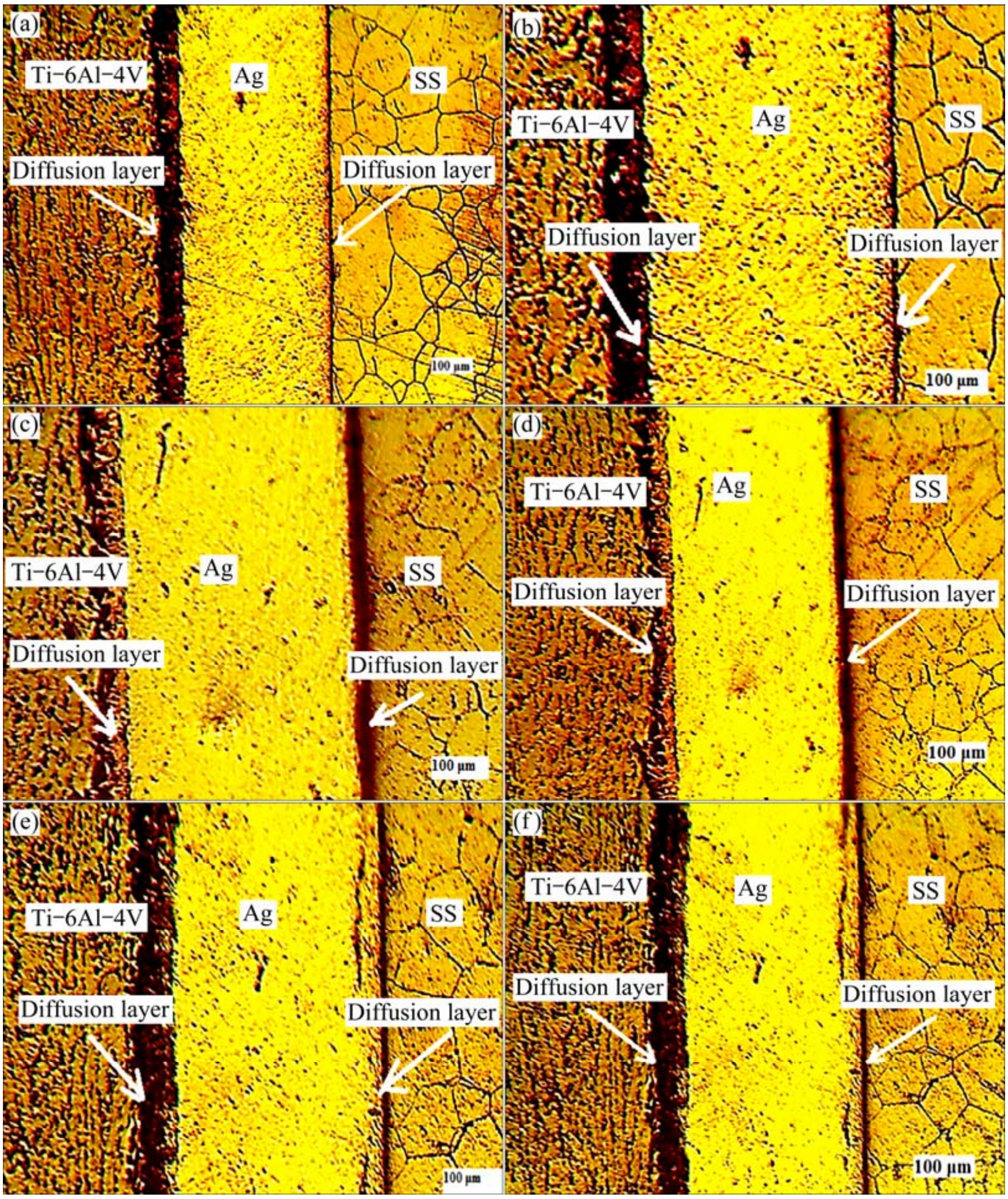

Fig. 4 Optical micrographs of joint bonded under different conditions: (a) Joint No.15; (b) Joint No. 19; (c) Joint No.18; (d) Joint No. 34; (e) Joint No. 31; (f) Joint No. 24

4 Conclusions

1) The experimental study gives an insight to fabrication of Ti−6Al−4V and AISI 304 joints with silver as interlayer. Successful joints are achieved with silver interlayer.

2) The diffusion bonding windows presented in this work will act as reference maps for selecting appropriate parameters for joining of Ti−6Al−4V and AISI 304 stainless steel with silver as an interlayer.

3) Successful bonding is achieved at 750−800 °C. Above 825 °C, bonding is not successful for this combination of dissimilar materials.

4) Maximum lap shear strength is achieved at a bonding pressure of 5 MPa and holding time of 90 min.

Acknowledgments

The author wishes to thank All India Council for Technical Education (AICTE), New Delhi, India, for the financial support rendered under the Grant No: 8023/ RID/RID/RPS-76/2010-11. The author would also like to thank Mr. G. RAMESH, research scholar, Anna University, India for his contribution during experimentation.

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以银为中间层扩散连接 Ti−6Al−4V 和 304 不锈钢的工艺窗口

M. BALASUBRAMANIAN

Department of Mechanical Engineering, R.M.K. College of Engineering and Technology, Puduvoyal, Tiruvallur 601206, India

摘　要：由于钛合金具有高的化学活性，很难采用传统焊接技术进行连接。在钛合金和不锈钢熔焊过程中，钛容易与空气中的氮和氧反应形成脆性中间化合物，降低焊接接头的力学性能。因此，宜采用扩散连接钛合金。以银为中间层，研究扩散连接 Ti−6Al−4V 和 AISI304 不锈钢的工艺参数。通过搭接剪切实验和显微组织分析对接头质量进行评价。通过实验结果得到扩散连接的工艺窗口，为获得无缺陷接头工艺参数提供参考。在 750−800 °C 时可以成功进行扩散连接。在 5 MPa 和 90 min 条件下焊接接头可获得最大搭接剪切强度。

关键词：Ti−6Al−4V 合金；银；AISI 304 不锈钢；中间层；扩散连接

(Edited by Yun-bin HE)