

Effect of the formation process of transient liquid phase (TLP) on the interface structure of TiAl joints

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Abstract: TiAl has been joined employing the transient liquid phase (TLP) bonding with Ti combined with Cu, Ni or Fe foils. Experimental results showed that though the interface structures of the joints are quite different, all the joined zones are composed of five sublayers, *i.e.* two diffusion zones, two interfacial zones and an interlayer. It has been convinced that the formation process of the transient liquid phase controls the diffusion behavior of melting point depressant (MPD) Cu, Ni, and Fe atoms, which leads to form different interface structures of the joints.

Key words: TiAl; transient liquid phase (TLP); bonding; interface

1 Introduction

TiAl has great potential to be used in aerospace, automotive and power generation industries. However, the intrinsic poor workability limits its application in some cases. Therefore, it is necessary to develop a suitable joining process to join TiAl. Conventional joining techniques, such as brazing, diffusion bonding [1-2] and fusion bonding [3] had been investigated to join TiAl-base alloys. But a lot of difficulties, such as high quality of the mating surface for diffusion bonding, low service temperature of the brazing joint, heat-sensitive cracking for fusion bonding, had been met during bonding.

In recent years, a novel bonding technique which is termed normally as transient liquid phase (TLP) bonding or diffusion brazing (DB), had been getting more and more attentions to join modern advanced materials [4-5]. The principle of this method had been introduced elsewhere [6-8]. TLP bonding combines the advantages of diffusion bonding and brazing. The most important difference between TLP bonding and brazing is the solidification behavior of the liquid phase. The liquid phase of TLP bonding isothermally solidifies at the bonding temperature while the liquid phase during brazing solidifies gradually with the decreasing of temperature.

TLP bonding had been employed to join intermetallics. Most of the present researches focused on NiAl intermetallics [9-12]. Gale [10-11] elaborately investigated the preparation process and interface structure

of the joints in which two kinds of insert metals, *i.e.* conventional Ni-Si-B filler and copper foils, had been successfully used. Strum [12] succeeded in producing a bondline-free NiAl joint using TLP bonding. Butts [13] investigated the TLP bonding of TiAl alloys using a mixture composed of Cu powders and atomized TiAl powders as the insert metal. After post bond heat treatment (PBHT), bondline-free joints with strength comparable to that of the parent material had been fabricated. The oxidation resistance of the similar joints had been estimated by Fergus [14]. However, all of the present experiments focused mostly on the bonding process, properties and microstructure of the joints. Furthermore, all literatures dealt with the phenomena or process after the transient liquid phase had been formed. The effect of the formation process of transient liquid phase during TLP bonding on the interface structure of the joint had not been studied.

In this paper, TLP bonding has been employed to join TiAl-base alloys. Ti foil combined with Cu, Ni, and Fe foils has been chosen as the insert metals. During bonding, Cu, Ni, and Fe elements acted as the melting point depressant (MPD) of Ti element. The structure of the joined zones has been investigated and the effect of the formation process of transient liquid phase on the interface structure has been discussed in details.

2 Experimental

The parent material was Ti-42Al-2Cr (in wt% and the designation of this alloy is denoted as TiAl in this

paper) which was machined using a water cutting tool to the size of 14 mmx14 mmx4 mm and the mating surface finishes were ground with a 1200 grit SiC abrasive paper. Ti-M (M=Cu, Ni, Fe) foil combinations were used as insert metals to join TiAl. The thickness of Ti, Fe, Cu, and Ni foils were 50, 25, 20 and 10 μm respectively. The foils had been tailored to the size of 14 mmx14 mm. With reference to the eutectic temperature T_{eu} shown in Ti-Cu, Ti-Ni and Ti-Fe binary phase diagrams [15], the bonding temperatures T_b had been chosen which are listed in **table 1**,

Table 1 Temperatures and composition concerning the present work

Foil combination	$T_{eu}/^{\circ}\text{C}$	$T_b/^{\circ}\text{C}$	$C_{bl}/\text{wt}\%$
Ti-Cu	955	1000	Ti-17Cu/Cu-2Ti
Ti-Ni	942	1050	Ti-10Ni/Ni-46Ti
Ti-Fe	1085	1150	Ti-17Fe/Fe-36Ti

Interface structures were investigated by scanning electron microscopy (SEM), which was operated under a voltage of 15 kV. Composition analyses were carried out using the energy dispersion X-ray spectrum (EDX).

3 Results and discussion

3.1 Structure of the joined zone

The bond zones in all the joints are composed of five characteristic sublayers, *i.e.* two diffusion zones (sublayer 1 and 4), two interfacial zones (sublayer 2 and 3) and an interlayer. Sublayers 1 and 2 refer to the area formed near the interface between the parent material TiAl and Ti foil, while sublayers 3 and 4 refer to the region formed at the interface between TiAl and M (M=Cu, Ni or Fe) foil. The interlayer is the resultant of the liquid phase formed by the insert metals after bonding. Sublayers 1 and 4 are formed mainly by the diffusion of M (M=Cu, Ni or Fe) atoms from the liquid phase into TiAl parent materials, while sublayers 2 and 3 are formed mainly by the diffusion of Al atoms from TiAl into the liquid phase at the interface. When M (M=Cu, Ni or Fe) atoms diffuse into TiAl, the melting point of liquid phase would be increased, which leads to isothermal solidification of the liquid phase at the bonding temperature and formation

where C_{bl} represents the composition at which liquid phase appears at the bonding temperature. The bonding pressure and holding time were kept at 2 MPa and 60 min for all experiments. All of the raw materials were cleaned ultrasonically in an acetone bath for 10 min prior to bonding. All bonding experiments were performed in a vacuum hot press. The background vacuum was 4×10^{-2} Pa and the heating and cooling rates were kept at a constant rate of $20^{\circ}\text{C}/\text{min}$ for all experiments.

of the mentioned interlayer in the joint.

Figure 1 shows a typical interface structure of the joint TiAl/Ti-Cu/TiAl. The thickness of sublayer 4 is a little thicker than that of sublayer 1. No bonding defects, including inclusions, voids and unbonded zones have been found in the joined zone. **Table 2** shows the composition in different areas in the bond zone, which demonstrates that the bright phase has high Cu content. Sublayers 2 (point 7) and 3 (point 8) have nearly the same composition, which confirms that the diffusion flux at both the interfaces between the liquid phase and TiAl parent materials is almost equal.



Figure 1 Interface structure of the TiAl/Ti-Cu/TiAl joint (1000 $^{\circ}\text{C}$, 2 MPa, 60 min).

Table 2 Composition (in wt%) of different areas in the joined zone shown in figure 1

Sublayer	Phase* (point)	Ti	Al	Cr	Cu
Interlayer	Bright(1)	75.23	8.92	0.96	14.59
	Grey (2)	82.99	14.18	0.00	2.82
Sublayer 1,4	Bright (3,4)	70.23	21.42	2.59	5.77
	Grey (5,6)	75.05	21.69	1.07	2.19
Sublayer 2,3	Grey (7,8)	82.10	15.28	0.33	2.30

Note: # refers to the phase denoted by the number shown in figure 1.

Figure 2 illustrates the interface structure of the joint TiAl/Ti-Ni/TiAl fabricated at 1050°C under 2

MPa for 60 min. No bonding defects have been observed but an asymmetrical interface structure has

been obtained. The thickness of sublayer 1 is thicker than that of sublayer 4. Moreover the thickness of the interlayer becomes much thinner compared to that shown in figure 1. **Table 3** lists the composition of different areas in the joined zone. The white phase in the joint contains high Ni content and sublayers 2 and 3 are mainly composed of Ti and Al.

Figure 3 shows that the joint TiAl/Ti-Fe/TiAl has quite different interface structures from those shown in figure 1 and 2. An asymmetrical joined zone has been obtained, in which the thickness of sublayer 1 is much thicker than that of sublayer 4. No bonding defects have been observed in the joined zone. The morphology of the interlayer is quite similar to that of sublayers 2 and 3. **Table 4** summaries the composition of the sublayers shown in figure 3. The composition of

the bright phase or grey phase in sublayers 1 and 4 is nearly equal though the thickness of the corresponding sublayers is quite different.

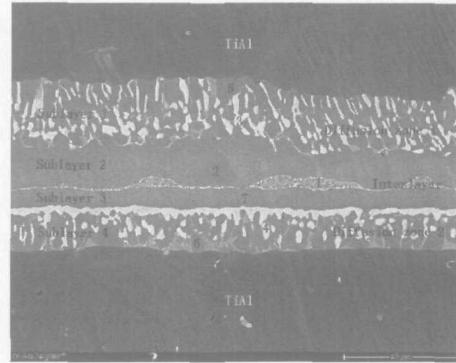


Figure 2 Interface structure of the TiAl/Ti-Ni/TiAl joint (1050°C, 2 MPa, 60 min).

Table 3 Composition (in wt%) of different areas in the joined zone shown in figure 2

Sublayer	Phase [#] (point)	Ti	Al	Cr	Ni
Interlayer	Bright(1)	71.33	21.49	5.31	1.87
Sublayer 1,4	Bright (3,4)	41.20	26.48	2.90	29.02
	Grey (5,6)	71.42	23.41	3.73	1.44
Sublayer 2,3	Grey (2,7)	77.78	21.51	0.70	0.01

Note: # refers to the phase denoted by the number shown in figure 2.

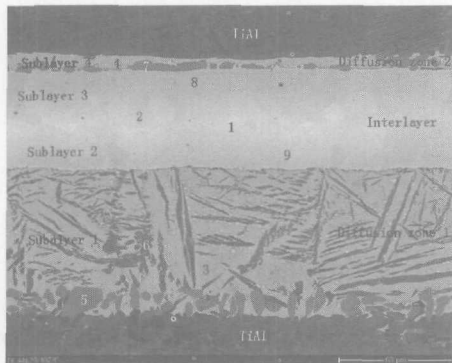


Figure 3 Interface structure of the TiAl/Ti-Fe/TiAl joint (1150°C, 2MPa, 60min).

3.2 Formation process of the joints

According to the difference in thickness between sublayers 1 and 4, the interface structures of the joined zones could be divided into two kinds. The one is that for the TiAl/Ti-Cu/TiAl joint with thick sublayer 4 and the other was for the TiAl/Ti-Ni (or Fe)/TiAl joint with thick sublayer 1. It is well known that the diffusion process of MPD during TLP bonding is a key step for joint formation. So it is convincible that the diffusion process of MPD has decisive effect on the structure development of the joint zone.

Table 4 Composition (in wt%) of different areas in the joined zone shown in figure 3

Sublayer	Phase [#] (point)	Ti	Al	Cr	Fe
Interlayer	Bright (1,2)	40.85	21.40	1.55	36.21
Sublayer 1,4	Bright (3,4)	63.93	20.00	2.47	13.60
	Grey (5,6,7)	68.74	27.57	0.81	2.89
Sublayer 2,3	Bright (8,9)	51.48	24.37	1.78	22.37

Note: # refers to the phase denoted by the number shown in figure 3.

Figure 4 shows schematically the liquid formation process during the bonding of TiAl with Ti-Cu insert foil. The dark area represents the liquid phase formed during bonding and the arrows indicate the diffusion direction of Cu atoms. TiAl-1 and TiAl-2 represent TiAl parent material adjacent to Cu foil and Ti foil respectively. Considering the composition C_{bl} in table 1,

which represents the starting composition at which liquid phase begins to be formed at the bonding temperature. For Ti-Cu foil combination, the composition is about Ti-17wt%Cu or Cu-2wt%Ti. So as shown in figure 4(b), it is reasonable to deduce that the liquid phase appears at first at both the surfaces of Cu foil during heating because Ti atoms could diffuse from Ti

foil and TiAl parent material into Cu foil. Subsequently Ti atoms diffuse continuously into Cu foil through the existing liquid which leads to the increase in thickness of the liquid phase and the decrease in thickness of Ti foil as shown in figure 4(c). At this stage, Cu atoms diffuse only into the adjacent parent material TiAl-1 which is indicated by the arrows in figures 4(c) and (d). With the progress of the interdiffusion between Ti and Cu foils, the whole insert foil transforms into liquid state, as shown in figure 4(e), then Cu atoms diffuse both into TiAl-1 and TiAl-2. It means that the solid-liquid diffusion process of Cu atoms into TiAl-1 happens earlier than that into TiAl-2, which results in that the thickness of sublayer 1 is a

little thicker than that of sublayer 4. Finally the interdiffusion between the liquid phase and the TiAl parent materials leads to the formation of sublayers 1 and 4 in the parent materials and the formation of sublayers 2 and 3 at the interface. Certainly, with decreasing of Cu content in the liquid phase, the melting point of the liquid phase is increased which leads to isothermal solidification of the liquid phase at the bonding temperature and the interlayer is formed in the joined zone, as shown in figures 4(e) and (f). During the diffusion process, TiAl would slightly dissolve into the liquid phase, which helps to increase the thickness of the liquid phase.

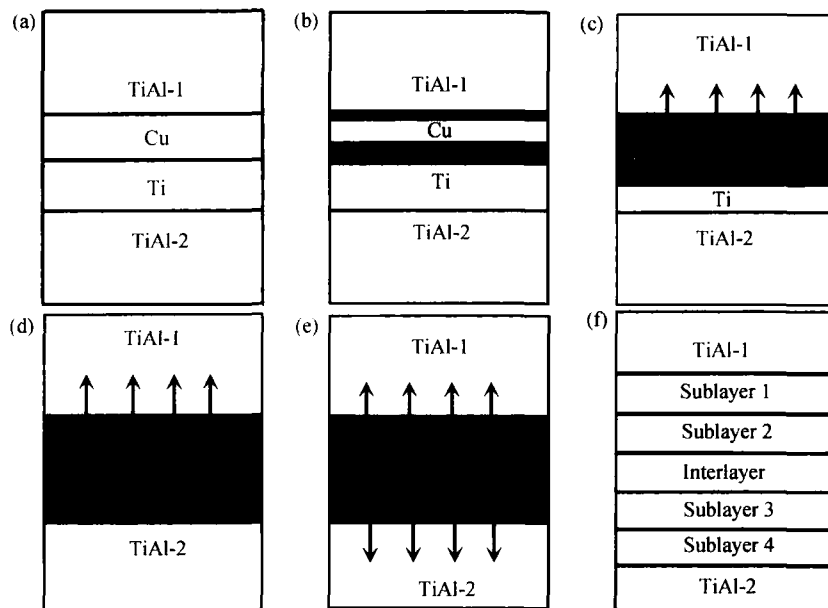


Figure 4 Process of liquid formation in the joint produced with Ti-Cu insert metal: (a) initial assembly of the parent material; (b) primary occurrence of the liquid phase; (c) dissolution of Cu foil and existence of retained Ti foil; (d) dissolution of retained Ti foil; (e) diffusion of Cu atoms into TiAl after liquidation of the insert metal, (f) resulting structure of the joint.

When Ti-Ni or Ti-Fe foil combination is used to join TiAl, the liquid formation process is quite different. The process of liquid formation is schematically shown in **figure 5**. The dark area represents the liquid phase formed during bonding and the arrows indicate the diffusion direction of Ni or Fe atoms. Based on the binary phase diagrams, C_{bl} is Ti-10wt%Ni or Ni-46wt%Ti for Ti-Ni foil combination and Ti-17wt%Fe or Fe-36wt%Ti for Ti-Fe foil combination. It is suggested that liquid phase would primarily appear only in Ti foil near to the interface between the insert metals. Compared with figure 4, the differences locate in the following aspects: (1) liquid phase originated from Ti foil; (2) there is a retained Ni- or Fe-rich foil when the Ti foil transforms into liquid state (figure 5(c)). So the diffusion process of Ni or Fe atoms into TiAl-2 occurs earlier than that into TiAl-1, which leads to the thickness of sublayer 4 is much thicker than that of

sublayer 1.

4 Conclusions

TLP bonding of TiAl has been successfully performed and defect-free joints have been fabricated using the insert metal of Ti combined with Cu, Ni or Fe foils. Based on investigation and discussion on the interface structure of the joints, following conclusions could be drawn:

(1) The joined zone can be roughly divided into five sublayers, *i.e.* two diffusion zones, two interfacial zones and an interlayer. The interface structure of the joint differs with the insert foils.

(2) The formation process of transient liquid phase is different with the insert foils, which has great effect on the diffusion behavior of the MPD atoms. It is convinced that such a difference leads to the different interface structure of the joints. When Ti-Cu foil combi-

nation is used to join TiAl, the transient liquid phase appears at first in Cu foil, which leads to the thickness of the diffusion layer in TiAl parent material adjacent to Cu foil thick than that of the opposite diffusion layer. On the contrary, if Ti-Ni or Ti-Fe foil combina-

tion is employed to join TiAl, the transient liquid phase tends to appear primarily in Ti foil, which increases the thickness of the diffusion layer in the TiAl parent material adjacent to Ti foil.

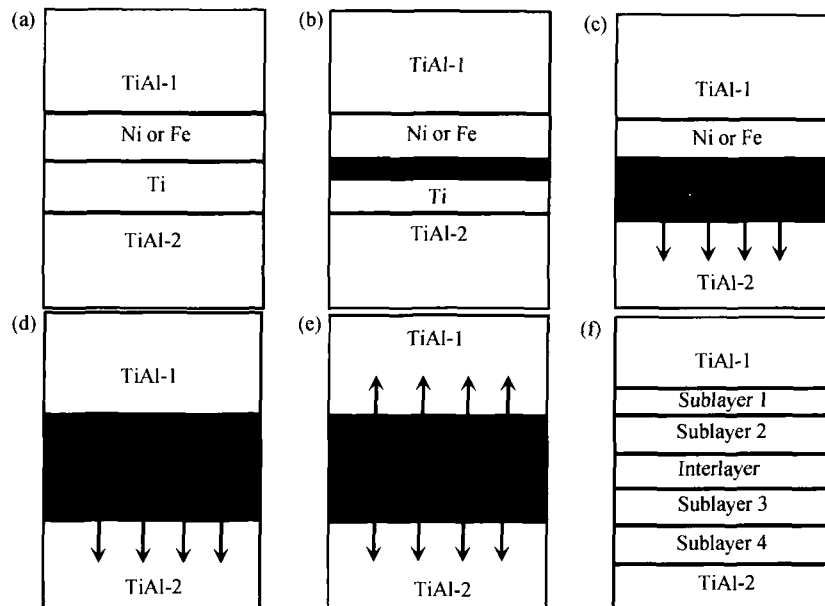


Figure 5 Process of liquid formation in the joint produced with Ti-Ni or Ti-Fe insert metal: (a) initial assembly of the parent material; (b) primary occurrence of the liquid phase; (c) dissolution of Ti foil and existence of retained Ni or Fe foil; (d) dissolution of retained Ni or Fe foil; (e) diffusion of Ni or Fe atoms into TiAl after liquidation of the insert metal, (f) resulting structure of the joints.

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