Tensile Properties of Diffusion Bonds between TiAl Intermetallic Compound and Titanium Alloy

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To investigate the feasibility of joining the TiAl intermetallic compound to titanium alloys, the diffusion bonding of TiAl to Ti-17 alloys (Ti-Al-Cr-Mo-Sn-Zr, near β -phase alloy) was performed, and the effects of joining parameters on the joint strength and the diffusion phase at the bonding interface were examined.

The major results are as follows:

- (1) For diffusion bonding of TiAl to Ti-17, joints which fractured at the TiAl base metal on the tensile test were obtained in case where the thickness of the diffusion phase at the bonding interface exceeded 10 μm .
- (2) The observation of the diffusion phase revealed that a solid solution of TiAl matrix containing the alloying elements of Ti-17 such as Cr, Mo, Zr and Sn, and a small amount of Ti_3Al particles were formed, while no lamellar Ti_3Al detrimental to the joint strength was detected. This result can be interpreted by taking into account the effects of Cr and Mo on the Ti-Al phase diagram.
- (3) The bonding temperature to give the maximum tensile strength of the TiAl to Ti-17 joint was found to be higher than those of TiAl to pure titanium joint and TiAl to Ti-6Al-4V alloy joint.

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1. Introduction

Attention has been paid to TiAl intermetallic compound (TiAl, hereinafter) since it can be used as aerospace materials etc.,¹⁻⁶⁾ especially at high temperatures. The specific gravity of TiAl (*ca.* 3.8) is about the half of the Ni based super alloys, and its specific strength is almost the same as or even larger than that of the Ni alloys. However, TiAl has poor workability as intermetallic compounds does in general, which leads to the difficulty in forming a complicated configuration. Accordingly, it can be one of the major impacts to expand the usage if the bonding technology of TiAl to other metals and alloys is established more thoroughly.

Efforts have been made by the authors⁷⁾ from a practical point of view on the diffusion bonding of TiAl to Ti alloys, where the bonding strength and related factors for the combination of TiAl to pure Ti (the α -type) (TiAl/Ti, hereinafter) and TiAl to Ti-6Al-4V alloy (the $\alpha + \beta$ type) (TiAl/Ti-6Al-4V, hereinafter) were investigated, and it was found that lamellar Ti_3Al was formed at the bonding interface for the both types of bonding combinations, and the joint strength was significantly reduced by its formation.

One of the joint microstructures that ensure the joint strength not less than that of the base metal might be a firm solid solution strengthening phase at the joint interface.

On the other hand, undesirable joint is broken up at the interface because of the formation of brittle microstructure. Diffusion bonding of the combination of TiAl and Ti or Ti-6Al-4V does not yield a remarkable joint strength as the diffusion of Ti and Al causes the formation of brittle Ti_3Al . Therefore, the joint strength can be improved by suppressing the formation of lamellar Ti_3Al structure.

It may be one of the most ordinary ways to use an intermediate layer which can form solid solution with TiAl

and Ti alloys, though such a metal is not easy to find. It can be also proposed to find out an alloy, in which the alloying elements can form solid solution with the base metal and delay the diffusion of Ti atoms. As realized from Fick's first law of diffusion, the transport of mass through unit area in unit time is proportional to the concentration gradient.⁸⁾ Based on this knowledge, it is essential to decrease the concentration gradient of Ti so that the formation of intermetallic compounds such as Ti_3Al can be suppressed. It is also suggested that the joint strength can be increased because of the formation of solid solution with other alloying elements.

On the other hand, the increase in concentration gradient is reported to be effective to reduce the formation and the growth of intermetallic compounds from theoretical analysis.⁹⁾

Therefore, in this study, in order to investigate the effects of the concentration gradient to the formation of intermetallic compound was also examined.

In this study, the diffusion bonding of TiAl to Ti-17 alloy (near β type; Ti: 83 mass%Ti) (TiAl/Ti-17, hereinafter) has been carried out, and the results obtained from the tensile test and microstructure observation have been compared with previous results of TiAl/Ti (100 mass%Ti) or TiAl/Ti-6Al-4V (90 mass%Ti).

2. Experimental Method

The chemical compositions of TiAl and Ti-17 used in this study are shown in Tables 1 and 2. The specimens were prepared as shown in Fig. 1. The surface to be bonded was finished by grinding on Emery paper of #400 to #2000 grades and subsequent buff-polishing. The parameters for the diffusion bonding experiments are listed in Table 3. The post bonding heat treatment (PBHT) conditions are also shown in Table 3, which were performed after the diffusion bonding done at a bonding temperature of 1223 K and a

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Table 1 Chemical composition of TiAl compound used.

	Al	Fe	V	B	O	N	Ti
mass%	32.5	1.85	1.65	0.087	0.049	0.0113	Bal.
at%	46.0	1.265	1.24	0.31	0.117	0.031	Bal.

Table 2 Chemical composition of Ti-17 used (mass%).

	Al	B	C	Cr	Cu	Fe	Mn	Mo	N	O	Sn	Y	Zr	Ti
Ti-17	5.03	0.001	0.019	3.82	0.002	0.072	0.005	3.83	0.004	0.10	1.90	0.001	1.59	Bal.

Table 3 Main conditions of diffusion bonding.

Bonding temperature (K)	Bonding pressure (MPa)	Bonding time (ks)	PBHT temperature (K)	PBHT time (ks)	Vacuum atmosphere (Pa)
973–1348	4.9	3.6	—	—	6.7×10^{-3}
1123–1273	9.8				
1223	4.9	3.6	1223–1473	1.8–14.4	2.2×10^{-3}

*PBHT: Post Bonding Heat Treatment

Fig. 1 Specimen configuration for diffusion bonding.

Fig. 2 Relationship between bonding temperature and tensile strength. (Bonding time: 3.6 ks)

bonding pressure 4.9 MPa for a bonding time of 3.6 ks.

Examination was also performed to obtain the relationship between the thickness of the diffusion phase and the joint strength.

The evaluation of the joint strength was made by using tensile test at a cross head speed of 1 mm/min. The microstructure of the joint was examined by observing with optical microscope, scanning electron microscope (SEM), SEM-EDX and EPMA.

3. Experimental Results

Figure 2 shows the tensile strength of TiAl/Ti-17 joint as a function of bonding temperature. In this experiment, the bonding time (= 3.6 ks) and the bonding pressure (= 4.9 or 9.8 MPa) were kept constant. For comparison, the previous results of diffusion bonding of TiAl/Ti and TiAl/Ti-6Al-4V⁷⁾ were also shown. As can be seen, the joint strength of TiAl/Ti-17 increased with bonding temperature, and reached at almost the same level as the tensile strength of TiAl at 1273 K when the bonding pressure was 9.8 MPa and joints bonded at the bonding temperature was fractured at the TiAl base metal.

The temperature range that allowed the diffusion bonding of the TiAl/Ti-17 shifted to the higher side than those to obtain TiAl/Ti and TiAl/Ti-6Al-4V joints. The bonding temperature to obtain the maximum tensile strength of the TiAl/Ti-17 joint at the constant bonding pressure of 4.9 MPa and bonding time of 3.6 ks, became higher by more than 150 K compared with that of TiAl/Ti joint.

The tensile strength of the joints of TiAl/Ti and TiAl/Ti-6Al-4V decreased with increasing bonding temperature after attaining the maximum value, and fracture occurred at the bonding interface in all the specimens. A similar phenomenon was observed in the joints of TiAl/Ti-17. However, it was difficult to perform the diffusion bonding at temperatures higher than 1473 K because of large deformation of Ti-17 alloy.

In order to investigate the effects of temperature on the joint strength and the diffusion phase formed at the bonding interface, the PBHT was given to the TiAl/Ti-17 joint which was bonded at comparatively low temperatures. The results are shown in Fig. 3, where the joint tensile strength remains constant at higher temperatures than 1273 K, and fracture occurred at the TiAl base metal. This phenomenon is

Fig. 3 Relationship between PBHT temperatures and tensile strength. (T_B : 1223 K, P_B : 4.9 MPa, t_B : 3.6 ks, PBHT time: 3.6 ks)

Fig. 5 Relationship between tensile strength and thickness of diffusion phase.

Fig. 4 Microstructures of TiAl/Ti-17 joints with PBHT temperature. (T_B : 1223 K, P_B : 4.9 MPa, t_B : 3.6 ks, PBHT time: 3.6 ks)

different from those of TiAl/Ti and TiAl/Ti-6Al-4V joints.

Figure 4 shows the microstructures of TiAl/Ti-17 joints receiving the PBHT under the same conditions as shown in Fig. 3. In the figure, a diffusion phase was observed at the bonding interface. The thickness of the diffusion phase increased with increasing the PBHT temperature.

Figure 5 shows the relationship between tensile strength and thickness of the diffusion phase. The joints having tensile strength not less than that of the TiAl base metal were obtained in case where the thickness of the diffusion phase exceeded 10 μm .

4. Discussion

As shown in the preceding chapter, a favorable joint, with which was fractured at the TiAl base metal on the tensile test, was obtained for the joint of TiAl/Ti-17, while no such joints

were observed for TiAl/Ti joint or TiAl/Ti-6Al-4V.

The tensile strength of TiAl/Ti or TiAl/Ti-6Al-4V decreased with increasing bonding temperature after the maximum strength and fracture occurred at the bonding interface. On the other hand, the joint tensile strength of TiAl/Ti-17, which was almost equal to that of TiAl base metal, remained the same at the higher PBHT temperature range from 1273 to 1473 K, and fracture occurred at TiAl base metal.

The mechanism to improve tensile strength by choosing Ti-17 instead of Ti or Ti-6Al-4V as a titanium alloy and the diffusion behavior of Ti atoms in the TiAl/Ti-17 joint are discussed below.

4.1 Metallographic analysis on the improvement of tensile strength

As previously reported by the authors,⁷⁾ the tensile strength

Fig. 6 Results of EPMA line analysis.

of the joints of TiAl/Ti and TiAl/Ti-6Al-4V was affected strongly by the formation of lamellar Ti_3Al intermetallic compound at the bonding interface. In the present experiment, the lamellar phase at the bonding interface was not observed. It is important to discuss the strengthening mechanism of the joints with this fact.

Therefore, at first, the diffusion phase at the bonding interface of TiAl/Ti-17 joint was analyzed by EPMA line analysis using the specimens in which the maximum thickness of diffusion phase was attained. Figure 6 shows one of the typical results of EPMA line analysis in the vicinity of bonding interface. In this figure, a smooth gradient of concentration is observed in each element, but a plateau of the lines which suggests the formation of compound, for example Ti_3Al , is not observed. Therefore, the diffusion of the atoms coexisting in Ti-17, *e.g.*, Mo, Cr, Zr and Sn, can proceed by keeping a smooth concentration gradient during the diffusion process. One of the strengthening mechanism of the diffusion phase at the bonding interface of TiAl/Ti-17 joint is considered to be solid solution strengthening of the matrix alloy.

The results of SEM-EDX analysis at the reaction phase are shown in Fig. 7. From Fig. 7(a), bonding was considered to accomplish almost perfectly. From Fig. 7(b), white phase and black phase can be observed. The components of the white phase [No. 1 shown in Fig. 7(b)] are Ti, Al, Cr, Mo, etc. which are the major elements of Ti-17, while the black phase [No. 2 shown in Fig. 7(b)] is considered to be Ti-Al alloy which contains small amounts of other elements.

From the observation of above mentioned white phase, one of the strengthening mechanisms of the reaction phase at the bonding interface is considered to be solid solution strengthening of matrix. Other than these phases, white particles were observed. From the SEM-EDX analysis of the white particle

[No. 3 shown in Fig. 7(c)] observed with a higher magnification than that of Fig. 7(b), it was considered to be Ti_3Al . These Ti_3Al particles are dispersed in the matrix phase.

Comparing with the lamellar Ti_3Al layers observed in TiAl/Ti and TiAl/Ti-6Al-4V joints, the dispersion of a small amount of Ti_3Al particles in the matrix phase observed in TiAl/Ti-17 should be preferable from a standpoint of tensile strength properties.

Accordingly, it is concluded that strengthening factors of the diffusion phase at the interface of TiAl/Ti-17 joints are composed of two phases that are solid solution strengthening phase of the TiAl matrix and a small amount of Ti_3Al particles, which in turn can improve tensile strength properties when Ti-17 is used.

Furthermore, in this case, the formation of Ti_3Al phase was substantially suppressed and a small amount of Ti_3Al was observed at the diffusion phase. The interpretation by the phase diagram is discussed below. Figure 8 shows the Ti-Al binary phase diagram.¹⁰⁾ R. Kainuma *et al.*¹¹⁾ studied the phase equilibria among several phases in Ti-Al base ternary alloys. They reported that the addition of Cr, Mo to Ti-Al alloy could shift the $\alpha_2 + \gamma/\gamma$ boundary towards the TiX side at 1273 K in the Ti-Al phase diagram shown in Fig. 8. Applying their finding to the present study suggests that the γ rich phase will increase, while α_2 phase decreases, during the diffusion process to TiAl side of Cr and Mo which are major elements of Ti-17. This explanation is well consistent with the experimental results mentioned above.

4.2 Diffusion behavior of Ti atoms in TiAl on TiAl/Ti-17 joint

As mentioned in Fig. 2, the bonding temperature of the TiAl/Ti-17 joint at a constant bonding parameter increased by more than 150 K compared with that of TiAl/Ti joint.

Fig. 7 Results of SEM-EDX analysis. (T_B : 1223 K, P_B : 4.9 MPa, t_B : 3.6 ks, PBHT temperature: 1473 K, PBHT time: 14.4 ks)

Fig. 8 Equirbrium phase diagram of Ti-Al.

From the results of diffusion bonding experiment of TiAl/Ti-17, it was observed that the solid solution phase and Ti_3Al particles were formed and the formation of lamellar Ti_3Al was suppressed. Therefore, in order to clarify the diffusion behavior of Ti atom on TiAl/Ti-17 joint, diffusion coefficient and activation energy were measured and discussed as below.

Although even the diffusion coefficient is not very easy to obtain, a rough estimation of the value is given by the following equation:¹²⁾

Fig. 9 Relationship between temperature and diffusion coefficient.

$$X = (2D_t)^{1/2}$$
$$D = D_0 \exp(-Q/RT)$$

where X is diffusion distance, and t the treatment time.

The diffusion coefficient of Ti atoms onto TiAl at the bonding interface of TiAl/Ti-17 joint was measured by the post bonding heat treatment experiment. In this case, each diffusion distance X of Ti atoms was measured with EPMA line analysis curves. Therefore, the value is different from the thickness of diffusion phase. The relationship between temperature and diffusion coefficient is shown in Fig. 9. From this figure and the above Arrhenius equation, the following values were obtained:

$$D_0 = 3.26 \times 10^{-4} \text{ (m}^2\text{/s)}$$
$$Q = 501 \text{ (kJ/mol)}$$

where D_0 is the pre-exponential factor and Q is activation energy of Ti onto TiAl of TiAl/Ti-17 joint.

As reference, the minimum values of D_0 and Q reported in the tracer diffusion of Ti atoms in TiAl/Ti¹³⁾ are as follows:

$$D_0 = 7.66 \times 10^{-4} \text{ (m}^2\text{/s)}$$

$$Q = 311 \text{ (kJ/mol)}$$

Comparing the present results with the literature data, the apparent diffusion coefficient of Ti atoms in Ti-17 onto TiAl was found to be smaller than that in Ti. It is clear that diffusion of Ti atoms onto TiAl in TiAl/Ti alloy joint was suppressed by replacing Ti or Ti-6Al-4V to Ti-17 as Ti alloy. This kind of interpretation can well correspond to the above mentioned experimental facts shown in Fig. 2.

The formation of lamellar Ti₃Al will discuss below. In Fig. 2, the bonding temperature at the constant bonding parameters in tensile strength of TiAl/Ti joints was higher by about 100 K than that of TiAl/Ti-6Al-4V joint. The larger concentration gradient for TiAl to pure Ti than that for TiAl to Ti-6Al-4V which contains 6%Al is considered to decrease the formation and the growth of intermetallic compounds. The fact is well coincident with the theoretical analysis on the formation of intermetallic compounds described in the introduction.⁹⁾ This discussion is only valid in case when it is assumed that the addition of 4%V does not affect the binary Ti-Al phase diagram largely.

On the other hand, the bonding temperature in the TiAl/Ti-17 joints was higher above 150 K than that of TiAl/Ti joints at constant bonding pressure of 4.9 MPa and bonding time of 3.6 ks (Fig. 2). In this case, the phase diagram of Ti-17 may substantially change the original phase diagram, because of the alloying elements of 4%Cr, 4%Mo, 2%Sn and 2%Zr. Therefore, the formation rate of Ti₃Al compound in TiAl/Ti-17 and TiAl/Ti cannot be discussed only from the viewpoint of the concentration gradient.

5. Conclusion

It is essential to improve the joint strength of diffusion bonding between TiAl intermetallic compound and titanium alloys. In this study, the diffusion bonding between TiAl and Ti-17 alloys was performed and the effects of joining factors on the joint strength and the diffusion phase at the bonding interface were examined.

The major findings are as follows:

- (1) For diffusion bonding between TiAl and Ti-17, a favorable joint, with which the fracture occurred at the TiAl part during the tensile test, was obtained in case where the thickness of the diffusion phase at the bonding interface exceeded 10 μm.
- (2) As a result of the observation on the reaction phase, solid solution of TiAl matrix containing the coexisting elements of Ti-17 such as Cr, Mo, Zr and Sn, and a small amount of Ti₃Al particles were observed. However, lamellar Ti₃Al was not observed. These phases are considered as one of the strengthening factors of the joints.
Furthermore, the fact that the formation of TiAl(γ) rich phase occurred more easily while the Ti₃Al(α₂) decreased, can be well interpreted by taking the increase of Cr and Mo in the Ti-Al phase diagram into account.
- (3) The bonding temperature to give the maximum tensile strength of TiAl/Ti-17 joint increased by more than 150 K compared with those of TiAl/Ti and TiAl/Ti-6Al-4V joints at the constant bonding pressure and bonding time.

The apparent diffusion coefficient of Ti atoms in Ti-17 to TiAl was found to be smaller than that with pure Ti to TiAl.

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