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Interface microstructure and formation mechanism of diffusion-bonded joints of TiAl to steel 40Cr ①

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[Abstract] TiAl intermetallics was diffusion bonded to steel 40Cr in vacuum furnace. The results show that at the TiAl-40Cr interface the mixture reaction layer of Ti_3Al+ FeAl+ $FeAl_2$ is formed close to the TiAl base, TiC layer is formed in the middle and obvious decarbonized layer is formed closest to the steel 40Cr side. The whole reaction process can be divided into three stages. In the first stage, TiC layer is formed at the interface TiAl/40Cr, as well, decarbonized layer occurs on the steel 40Cr side. In the second stage, TiAl, $FeAl_2$ and FeAl are formed adjacent to TiAl, in the mean, the continuous diffusion of Al atoms from TiAl to 40Cr gives rise to the formation of Ti_3Al. In the last stage, the thickness of each reaction layer increases with bonding time according to a parabolic law. The growth energy Q and the growth velocity K_0 of reaction layer Ti_3Al+ FeAl + $FeAl_2$+ TiC in the diffusion-bonded joints of the TiAl base alloy to steel 40Cr are 203.017 kJ/mol and 6.074 mm^2/s, respectively, and the growth formula (thickness of reaction layer) is $y^2 = 6.074\times 10^{-6}\exp(-203\,017.48/RT)t$. By virtue of this formula, the growth of reaction layer Ti_3Al+ FeAl+ $FeAl_2$+ TiC can be presetted and controlled.

[Key words] TiAl intermetallics; interface microstructure; formation mechanism; growth energy; growth velocity
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1 INTRODUCTION

In recent years, considerable interest has been given to TiAl intermetallics because of its unique properties such as low density, good stiffness, high elevated-temperature strength, and excellent oxidation resistance[1~4]. TiAl intermetallics has been considered ideal new high temperature structural materials with potential applications in spacecraft and aircraft for both military and civil purposes[5, 6]. The effective utilization of TiAl intermetallics needs to develop reliable joining techniques, especially joining techniques of TiAl intermetallics to other materials[7~10]. The concept of utilizing TiAl intermatallics and steel 40Cr to attain missile and tank engine turbo components by bonding process is a new approach[11]. This paper aims to demonstrate the feasibility of diffusion bonding of TiAl to steel 40Cr, and the focus is placed on the interface microstructure and formation mechanism of diffusion-bonded joints of TiAl to steel 40Cr.

2 EXPERIMENTAL

The chemical compositions of TiAl intermetallics and steel 40Cr used are given in Table 1. Both TiAl intermetallics and steel 40Cr were cut into specimens of dimension d 10 mm × 30 mm. The bonded surfaces were ground flat by 1000# grinding paper and polished by diamond paste and cleaned in ethanol and acetone prior to diffusion bonding. Diffusion bonding experiments were conducted under a vacuum of 3×10^{-4} Pa. The cross-sections of the bonded TiAl/40Cr joints were prepared for metallographic analysis by standard polishing techniques. The microstructures of the TiAl/40Cr joints were examined by metallographic microscopy and scanning electron microscopy (SEM, S-570). The composition analysis of the reaction products was performed by electron probe X-ray microanalysis (EPMA, JXA8600). The kinds and crystal structures of the reaction products were identified from the fracture surfaces of the joints by XRD(JDX-3 530M).

3 RESULTS AND DISCUSSION

Fig. 1 shows an optical micrograph of the cross-section of the TiAl/40Cr joint diffusion-bonded at 1 373 K and 20 MPa for 3.6 ks. Obviously, three kinds of reaction layers were observed between TiAl and 40Cr. For the sake of convenience, the reaction layer with black phase adjacent to TiAl is called layer I, and the reaction layer with grey phase adjacent to 40Cr layer III, and the reaction layer in the middle layer II.

Fig. 2 shows the back-scattered electron image and the concentration profiles of major elements

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Table 1 Chemical compositions of materials(mole fraction, %)

Material	Al	Ni	Cr	Nb	Ti	Fe	Si	C	Mn
TiAl	47.2	1.17	0.56	0.11	51.0	–	–	–	–
40Cr	–	0.18	0.95	–	–	base	0.27	0.40	0.65

across the interface of the TiAl/ 40Cr. It can be found that a certain amount of diffusion occurs between steel 40Cr and TiAl, and two mutual diffusion layers are formed near the interface.

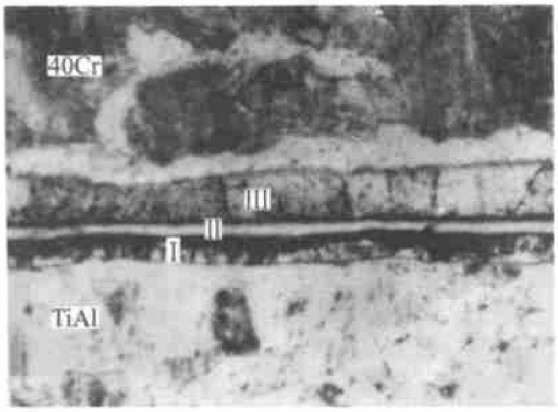

Fig. 1 Optical microstructure of cross-section of TiAl/40Cr joint diffusion-bonded at 1 373 K and 20 MPa for 3.6 ks

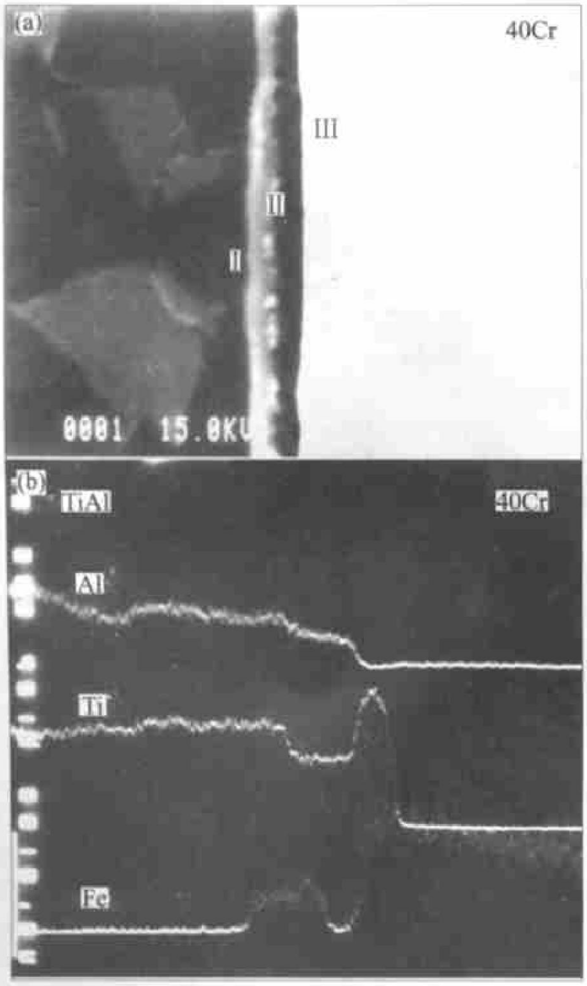

Fig. 2 Back-scattered electron image and concentration profiles of major elements across interface of TiAl/40Cr at 1 373 K and 20 MPa for 3.6 ks

While layer III which can be clearly seen from optical microstructure is not observed in Fig. 2. As well, there exists a plateau in the element dispersion curve, which indicates that some metallic compound films are formed in the diffusion layer.

Fig. 3 shows the XRD patterns from the fracture surfaces of the TiAl/ 40Cr joint bonded at 1 373 K for 3.6 ks. Obviously, the phases identified from the surface are TiC, Ti_3Al, FeAl and $FeAl_2$. Therefore, there are four kinds of reaction products or formed phase in the diffusion-bonded joints of TiAl to 40Cr.

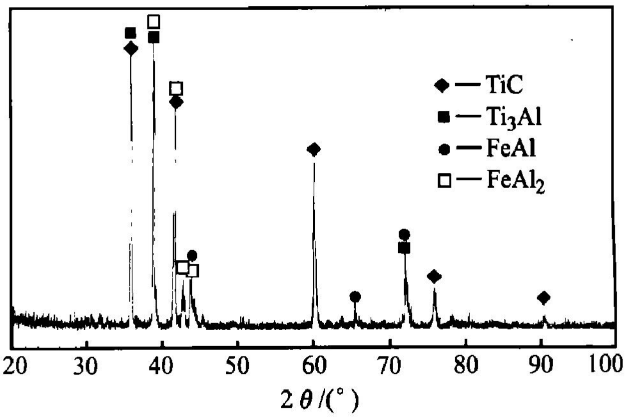

Fig. 3 XRD patterns from fracture surfaces of TiAl/ 40Cr joint bended at 1 373 K and 20 MPa for 3.6 ks

Table 2 shows the chemical compositions of the zones in reaction layer of TiAl/ 40Cr interface. It can be seen from the table that the stoichiometric proportion of Ti to C is approximately 1∶1 in layer II. Based on this and XRD results mentioned above, it is inferred that reaction layer II is TiC, but it should be noted that there is a certain amount of Fe in TiC. Similarly, according to the table and XRD results, reaction layer I is Ti_3Al+ FeAl+ $FeAl_2$, reaction layer III is a decarbonised layer. Thus, the interface microstructure of diffusion-bonded joints of TiAl to steel 40Cr is TiAl/Ti_3Al + FeAl + $FeAl_2$/TiC/ decarbonised layer/ 40Cr.

Table 2 Chemical compositions of zones in reaction layer of TiAl/ 40Cr interface at 1 373 K and 20 MPa for 3.6 ks (mole fraction, %)

Zone	Ti	Fe	Cr	Nb	Al	C
I	40.53	24.32	3.04	0.11	31.82	0.17
II	56.6	4.44	0.97	0.12	0.72	37.15
III	0.97	93.63	1.35	0.08	3.85	0.13

Fig. 4 shows the interface reaction mechanism for diffusion-bonded TiAl/40Cr joints. The whole reaction process can be divided into three stages. In the first stage (see Fig. 4(b)), in respect that the atomic radius of C atom is smaller and its diffusion velocity is higher, C atoms first diffuse quickly from 40Cr to TiAl. In the mean time, Ti and Al atoms diffuse from TiAl to 40Cr, and then TiC layer is formed at the interface of TiAl/40Cr according to reaction 1. As well, the diffusion of C atoms gives rise to the occurrence of decarbonised layer on the steel 40Cr side. At this time, the interface microstructure of TiAl/40Cr steel is TiAl/TiC/decarbonised layer/40Cr. In the second stage (see Fig. 4 (c)), Fe atoms diffuse from 40Cr to TiAl continuously. When the concentration of Fe atoms rises to a certain amount in TiAl, $FeAl_2$ and FeAl are formed adjacent to TiAl according to reactions 2 and 3. In the mean, the continuous diffusion of Al atoms from TiAl to 40Cr forms Ti_3Al according to reaction 4. Thus, the interface microstructure of diffusion-bonded joints of TiAl to steel 40Cr turn into TiAl/Ti_3Al+ FeAl+ $FeAl_2$/TiC/decarbonised layer/40Cr. Finally, the thickness of each reaction layer increases with bonding time according to a parabolic law.

$$Ti + C \rightarrow TiC \quad (1)$$

$$Al + Fe \rightarrow FeAl_2 \quad (2)$$

$$FeAl_2 + Fe \rightarrow FeAl \quad (3)$$

$$TiAl \rightarrow Ti_3Al + Al \quad (4)$$

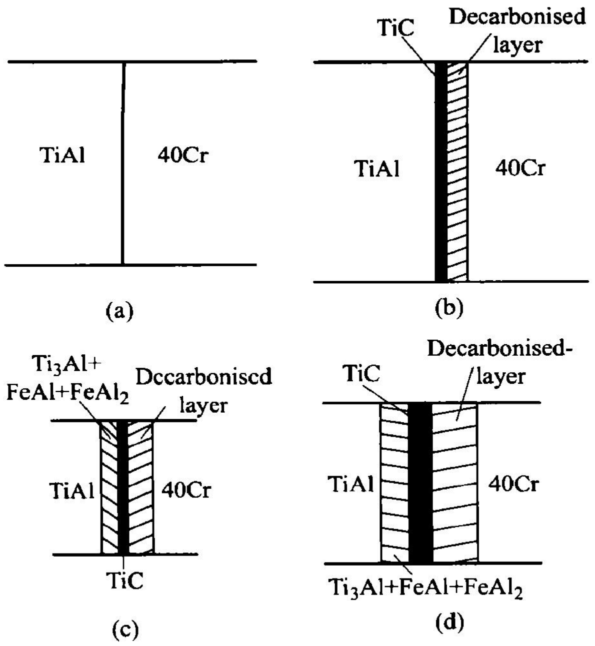

Fig. 4 Interface reaction model for TiAl/40Cr joints

(a) —Close contact of TiAl to 40Cr;
(b) —Occurrence of TiC layer and decarbonised layer;
(c) —Occurrence of Ti_3Al+ FeAl+ $FeAl_2$;
(d) —Growth of each reaction layer

From Ref. [11], the growth of reaction layer Ti_3Al+ FeAl+ $FeAl_2$+ TiC is expressed by formulas (5) and (6). As a calculating result, the growth energy Q and the growth velocity K_0 of reaction layer Ti_3Al+ FeAl + $FeAl_2$ + TiC in the diffusion-bonded joints of TiAl base alloy to 40Cr steel are 203.017 kJ/mol and 6.074 mm^2/s, respectively, and the growth formula is formula (7). By virtue of formula (7), the growth of reacting layer Ti_3Al+ FeAl+ $FeAl_2$+ TiC can be presetted and controlled.

$$y^2 = Kt \quad (5)$$

$$K = K_0 \exp(-Q/RT) \quad (6)$$

$$y^2 = 6.074 \times 10^{-6} \exp(-203\,017.48/RT)\,t \quad (7)$$

where y is thickness of the reaction layer, m; t is bonding time, s; T is bonding temperature, K; K is growth velocity of reaction layer, m^2/s; K_0 is growth constant, m^2/s; Q is growth energy, kJ/mol; R is gas constant, 8.314 J/(K·mol).

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