**Interreactions of TiAl3 Thin Film on Bulk γ-TiAl and on Bulk α2-Ti3Al Alloys at 700–1000°C**

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Interreactions of diffusion couples of TiAl3 film on bulk γ-TiAl and TiAl3 film on bulk α2-Ti3Al are investigated at high temperature. Experimental results show that TiAl3 layer and TiAl3/γ-TiAl mixed layers are observed at the interfaces of TiAl3 film/bulk γ-TiAl and TiAl3 film/bulk α2-Ti3Al diffusion couples, respectively, at 700–1000°C. In addition, the growth rates of TiAl3 and γ-TiAl product layers comply well with a parabolic law. The growth activation energy, \( Q_k \), and \( C_1/C_2 \) values of γ-TiAl and TiAl3 phases in TiAl3 film/bulk α2-Ti3Al system are 163.4 kJ/mol and 147.9 kJ/mol, respectively. These \( Q_k \) values are similar in magnitude with those of TiAl3 phase formation in Ti-Al thin film diffusion systems. In this study, TiAl3 formation is suggested to have been nucleated at the interface during the heating prior to reaching the set temperature.

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**Keywords:** sputtering, intermetallics, diffusion couple, kinetics, γ-TiAl and α2-Ti3Al

1. Introduction

Titanium aluminides such as γ-TiAl and α2-Ti3Al alloys are high temperature structural intermetallics with rapidly growing technological importance. They have the characteristics of high temperature stability, good creep resistance and relatively high yield strength. Their superior properties have found applications in aerospace and automotive applications.4) The interdiffusion and interreaction phenomena of the Ti-Al diffusion couple system have previously been studied in detail.4) As shown by these studies, phenomena occurring in thin film diffusion couples are very different from those observed in bulk couples. This comes from the fact that thin films contain more interfaces and surfaces than bulk specimens. Additionally, the thickness of thin films is usually limited to a few thousand nanometers. Hence, these inherent characteristics of thin films are often responsible for the particular behaviors occurring there.

Among the various titanium aluminides in the Ti-Al binary alloys, it has been reported that TiAl3 is thermodynamically more stable and kinetically more favorable to form first than the other titanium aluminides in the bulk or thin film interreactions of Ti and Al diffusion couples.5) Diffusion tests in the Ti-Al bulk couple system have indicated that the growth of the TiAl3 layer obeys the parabolic time dependence. In addition, the growth of the TiAl3 phase in the Ti-Al thin film couple system obeys the diffusion controlled kinetics with activation energies varying from about 150 to 190 kJ/mol according to different researchers.6) To our best knowledge, most investigations on phase interreactions in the Ti-Al system have concentrated on the TiAl3 formation of the thin film diffusion couple or the bulk diffusion couple. In the case of the diffusion couple of TiAl3 thin film on γ-TiAl or on α2-Ti3Al bulk alloys, their interreactions to form TiAl2 and γ-TiAl phases at high temperature have not previously been reported.

In this study, γ-TiAl and α2-Ti3Al intermetallics were sputtered with a pure Al thin film. A subsequent interdiffusion treatment at 600°C was conducted, in which an adhesive TiAl3 layer forms between the Al film and γ-TiAl or α2-Ti3Al. Therefore, simple diffusion couples of TiAl3 thin film on γ-TiAl bulk alloy or on α2-Ti3Al bulk alloy are obtained. We investigate the further interreactions of these simple diffusion couples at 700–1000°C, including the phase formation sequence and kinetics. At the same time, based on the measured data of the thicknesses of formed phases in these diffusion couples, the activation energies of phases formation can also be calculated.

2. Experimental Procedures

The Ti-50 at%Al (γ-TiAl) and Ti-25 at%Al (α2-Ti3Al) alloys were prepared as ingots from the raw materials of titanium (99.7%) and aluminum (99.98%) by a vacuum arc remelter (VAR). The ingots were re-melted at least six times. After homogenization of the ingots at 1000°C for 100 h, square specimens of 10 × 10 × 1 mm3 were sectioned by a diamond saw and ground to a final polishing of 0.3 μm alumina, then ultrasonically cleaned with acetone, ethanol and deionized water and then blown dry before sputtering. The sputtering target of 99.98% pure aluminum was 50 mm in diameter and 5 mm in thickness.

The Al films were sputter-deposited on all the surfaces of the γ-TiAl and α2-Ti3Al specimens using an r.f. magnetron sputtering apparatus with a turbo-pumped vacuum system at a base pressure of about 6.65 × 10−8 Pa. The working pressure was set at 6.65 × 10−4 Pa with ultra high purity argon. The r.f. power was 100 W and the substrate was unheated during the Al sputtering. Al films were deposited on specimens with their thickness measured by α-step (Veeco Dektak® ST). A subsequent interdiffusion treatment was carried out at 600°C for 24 h in a high vacuum furnace that reached about 3.99 × 10−5 Pa. After interdiffusion treatment, the specimens were then further heated in a muffle furnace at temperatures ranging from 700–1000°C for 30 min to 300 h in ambient atmosphere.
Fig. 1 SEM cross-sectional morphologies of Al-sputtered specimens after interdiffusion treatment at 600°C for 24 h in a vacuum. (a) γ-TiAl with 5 μm Al film and (b) α₂-Ti₃Al with 3 μm Al film.

Fig. 2 SEM cross-sectional images of γ-TiAl specimens with 5 μm Al films which have been interdiffusion treated, and then heated at 800°C in air for (a) 1 h (b) 5 h (c) 10 h (d) 80 h (e) 200 h and (f) 300 h. The EDS analysis for the composition of points 1~5 shown in (a) is listed in Table 1.
An X-ray diffractometer (XRD, Philips PW1729) with Cu Kα radiation at 30 kV, 20 mA and 4° 2θ/min scanning rate was used to identify the phases of sputtered-films formed by the interdiffusion treatment and the following interreaction tests. The cross-sectional microstructures of specimens were observed by means of a Leo 1530 scanning electron microscope (SEM) coupled with energy dispersive spectrometry (EDS). The layer thickness of formed phase was determined by the measured function of the SEM, using the average of ten measurements. Some of the samples were examined by electron probe microanalyzer (EPMA, JEOL JXA-8600 SX) to measure the chemical compositions of phases formed by sputtering, interdiffusion treatment and interreaction tests.

3. Results and Discussion

3.1 Interdiffusion treatment of as-sputtered Al films with bulk γ-TiAl and α2-Ti3Al alloys

Al films with different thicknesses of 1~5 μm were sputtered on the γ-TiAl and α2-Ti3Al alloys. The appropriate thickness of Al film can be controlled accurately according to the sputtering rate of Al film as about 0.35 nm/s.15,16) However, intrinsic stress in the film increases with increasing the film thickness, resulting in poor adhesion of coating to substrate. Once the thickness of Al film is over 5 μm, small parts of the film spall out from the γ-TiAl and α2-Ti3Al specimens after the interdiffusion treatment. Hence, in this study, the thicknesses of as-sputtered Al films are all less than 5 μm. The as-sputtered Al film reveals a crystalline structure in terms of XRD pattern.15)

The interdiffusion treatment at 600°C for 24 h can not only increase the adhesion of Al film with substrates but also promote the formation of TiAl3 phase, as shown in Fig. 1.15,16) Figures 1(a) and (b) show the cross-sectional SEM morphologies of Al-sputtered γ-TiAl and α2-Ti3Al, respectively, after interdiffusion treatment at 600°C for 24 h in a vacuum. From Fig. 1, a TiAl3 layer on the outer surface of the substrate can be seen, which has a uniform thickness with no cracks or voids at the interface. Thus, the interdiffusion treatment is beneficial to increase the bonding of the films and substrates.

<table>
<thead>
<tr>
<th>Compositional Location</th>
<th>Ti (at%)</th>
<th>Al (at%)</th>
<th>phase</th>
</tr>
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<tr>
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<td>75.35</td>
<td>TiAl3</td>
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<tr>
<td>Point 2</td>
<td>25.16</td>
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</tr>
<tr>
<td>Point 3</td>
<td>33.44</td>
<td>66.56</td>
<td>TiAl2</td>
</tr>
<tr>
<td>Point 4</td>
<td>48.65</td>
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<tr>
<td>Point 5</td>
<td>50.25</td>
<td>49.75</td>
<td>γ-TiAl</td>
</tr>
</tbody>
</table>

Fig. 3  SEM cross-sectional morphologies of γ-TiAl specimens with 5 μm Al films heated at high temperatures in air for (a) 900°C–30 min (b) 900°C–10 h (C) 1000°C–30 min and (d) 1000°C–10 h. The specimens were interdiffusion treated in high vacuum before the interreaction.
and also beneficial to investigate the subsequent interreaction tests between the TiAl$_3$ thin film and its substrates. Therefore, TiAl$_3$ film/bulk $\gamma$-TiAl and TiAl$_3$ film/bulk $\alpha_2$-Ti$_3$Al diffusion couples are formed via interdiffusion treatment. According to an effective heat of formation model using the solid-state diffusion theory, the predicted first phase formed in Al film/$\gamma$-TiAl film and in Al film/$\alpha_2$-Ti$_3$Al film diffusion couples is TiAl$_3$. In Fig. 1, the formation of TiAl$_3$ phase continues until all the sputtered Al film is exhausted during the 600°C–24 h interdiffusion treatment. This indicates that the thickness of TiAl$_3$ layer formed by interdiffusion is dependent on the thickness of sputtered Al film. From Fig. 1(a), with a 5 µm sputtered-Al film before the interdiffusion treatment, the thickness of TiAl$_3$ layer is about 8 µm. In contrast, from Fig. 1(b), with a 3 µm sputtered-Al film before the interdiffusion treatment, the thickness of TiAl$_3$ layer is only about 4 µm. Clearly, the growth rate of the TiAl$_3$ layer on $\gamma$-TiAl is higher than that on $\alpha_2$-Ti$_3$Al, which shows that the Al-atom diffusion in $\gamma$-TiAl is faster than that in $\alpha_2$-Ti$_3$Al during the 600°C interdiffusion. This feature agrees with the reported results of Ref. 14), in which the interdiffusion coefficient of Al-atoms was determined by calculating the Al tracer in $\gamma$-TiAl and $\alpha_2$-Ti$_3$Al single-phase bulk diffusion couples. Moreover, from many reported diffusion couples tests in the Ti-Al system, the TiAl$_3$ layer is observed to grow rapidly and complies with the parabolic time dependence. In our cases, we suggest that the TiAl$_3$ growth in Fig. 1 is also following the parabolic law, although its growth kinetics is not investigated in this study.

### 3.2 Interreaction in between TiAl$_3$ film and bulk $\gamma$-TiAl at 800~–1000°C

It has been reported that, in the TiAl$_3$ and $\gamma$-TiAl diffusion couple, the TiAl$_2$ phase can be formed first by the interreaction at high temperature. In order to understand the subsequent phase formation developed between bulk $\gamma$-TiAl and TiAl$_3$ thin film, specimens of Fig. 1(a) were heated at 800°C, 900°C and 1000°C for different time intervals in the ambient atmosphere. Figure 2(a) shows the SEM cross-sectional microstructure of the specimen heated at 800°C for 1 h. From Fig. 2(a), the TiAl$_3$ outer layer (points 1 and 2 of Fig. 2(a)) and the TiAl$_2$ inner layer (point 3 of Fig. 2(a)) coexist, as shown by the accompanying EDS analysis, which is listed in Table 1. The appearance of a TiAl$_2$ layer indicates that the TiAl$_3$ film has interreacted with bulk $\gamma$-TiAl at 800°C, indicated by the Ti-Al phase diagram.

With increasing interreaction time at 800°C, the thickness of the TiAl$_3$ layer decreases whereas that of the TiAl$_2$ layer increases, as shown in Figs. 2(b) and (c). This is because of the solid-state diffusion between thin film TiAl$_3$ and bulk $\gamma$-TiAl at high temperature. From Fig. 2, comparing the thickness of the TiAl$_2$ layer to that of the TiAl$_3$ layer, the TiAl$_3$ layer will be exhausted completely within approximately 80 h at 800°C. Meanwhile, the thickness of TiAl$_2$ layer reaches its maximum of about 15 µm at 80 h, as shown in Fig. 2(d). In addition, Figs. 2(d), (e) and (f) reveal that, not only has the TiAl$_2$ formed, but also a stable Al$_2$O$_3$ layer adheres on the outer surface of the specimen at 800°C. In Fig. 2, the Al$_2$O$_3$ layer is not completed during the initial period, but becomes a continuous layer with further heating time. This stable Al$_2$O$_3$ layer becomes a good barrier against the inward oxygen attack, resulting in the significantly improved oxidation resistance of $\gamma$-TiAl at high temperature. The formation of an Al$_2$O$_3$ layer needs a supply of Al atoms from the TiAl$_3$ layer, or from the TiAl$_2$ layer after the TiAl$_3$ layer has been exhausted. At the same time, Al
The atoms of the TiAl$_2$ layer also diffuse into the γ'-TiAl substrate, as shown in points 4 and 5 of Fig. 2(a) with EDS analysis listed in Table 1.

From Fig. 2, the TiAl$_2$ layer stops its growth at 800°C–80 h, and starts to become thinner with further heating time. After 800°C–300 h, as shown in Fig. 2(f), the TiAl$_2$ layer is reduced to about 8 μm in thickness, and will be exhausted eventually. This is because Al atoms in the TiAl$_2$ layer must diffuse outward to form the Al$_2$O$_3$ layer, as well as diffuse inward to increase the Al content in the γ'-TiAl substrate. Figures 3(a) and (b) show SEM cross-sectional morphologies of specimens of Fig. 1(a) heated at 900°C in air for 30 min and 10 h, respectively. Clearly, the TiAl$_2$ layer shown in Fig. 3(a) is thicker than that in Fig. 2(a). The TiAl$_3$ and TiAl$_2$ layers coexist in Fig. 2(c), but only the TiAl$_2$ layer is observed in Fig. 3(b). This feature accounts for the fact that growth rate of the TiAl$_2$ layer increases significantly with increasing temperature, while the TiAl$_3$ is completely exhausted within 2 h at 900°C but within 80 h at 800°C.

The specimen was heated at 1000°C in air for 30 min.
and 10 h, as shown in Figs. 3(c) and (d), respectively, the TiAl layer is estimated to have been exhausted within 1 h. In addition, according to the thickness of TiAl layer shown in Fig. 3(d), the exhausting time of TiAl layer at 1000°C is estimated to be shorter than 15 h. From Figs. 2 and 3, the dependence of the thicknesses of TiAl and TiAl layers vs. interreaction time for TiAl film on bulk γ-TiAl heated at 800°C, 900°C and 1000°C can be plotted, as shown in Figs. 4(a), (b) and (c), respectively. From Fig. 4, the growth of the TiAl layer can be described by the diffusion-controlled model within the initial interreaction (<80 h at 800°C, <10 h at 900°C and <5 h at 1000°C), as discussed further in Section 3.4.

3.3 Interreaction between TiAl3 film and bulk α2-Ti3Al at 700–1000°C

In order to realize the phase formation sequence between bulk α2-Ti3Al and TiAl thin film, specimens of Fig. 1(b) were heated at 800°C for 30 min–300 h, and their cross-sectional SEM images with accompanying EDS analyses are shown in Fig. 5 and Table 2, respectively. From Fig. 5(a) of 800°C–1 h, the TiAl2 and γ-TiAl layers were formed between the TiAl3 and α2-Ti3Al layers where a mixture layer of TiAl3/TiAl2/γ-TiAl/α2-Ti3Al coexists. The EDS results of points 2 and 3 confirm the formation of TiAl2 and γ-TiAl phases. It has been reported that TiAl3 and γ-TiAl phases can be formed simultaneously at the interface of TiAl3 and α2-Ti3Al in a Ti-Al bulk diffusion couple. After 5 h heating in air, the TiAl3 is exhausted and the thicknesses of TiAl2 and γ-TiAl layers increase, as shown in Fig. 5(b). With further heating time, the thickness of TiAl2 decreases gradually, as compared with Figs. 5(b) and (c). The TiAl2 layer will be exhausted completely at 80 h, as shown in Fig. 5(d). At this time, a mixture layer of Al2O3/γ-TiAl/α2-Ti3Al is observed. An adhered Al2O3 layer is formed on the outer surface of γ-TiAl layer, as shown in Fig. 5(e), and it provides excellent improvement in the oxidation resistance of the α2-Ti3Al alloy at high temperature. From the EDS analysis of Fig. 5(a), in the α2-Ti3Al substrate, the Al content is higher at the position nearer the γ-TiAl layer, as indicated in points 4 and 5 of Fig. 5(a). While the heating time reaches 300 h, there is a Ti-Al-O compound existing within the γ-TiAl layer, as shown in Fig. 5(f). This feature implies that the γ-TiAl beneath the protective Al2O3 layer will be destroyed by this Ti-Al-O compound with longer heating time.

Figure 6 shows the SEM cross-sectional morphologies of Fig. 1(b) specimens heated at 700°C (Figs. 6(a) and (b)) and 900°C (Figs. 6(c) and (d)) in air for 30 min and 10 h, respectively. From the inserted photo of Fig. 6(a), very thin layers of TiAl2 and γ-TiAl phases are formed at the interface of TiAl3 film and α2-Ti3Al substrate in which the TiAl2 and γ-TiAl phases are formed at the same time. Figure 6(b) shows a sandwich layer of TiAl3/TiAl2/γ-TiAl/α2-Ti3Al at 700°C for 10 h heating. This microstructure coincides with Fig. 5(a),
which was heated at 800°C for 1 h. Figure 6(c) shows that TiAl2/γ-TiAl/α2-Ti3Al layers are coexisting without a TiAl3 layer after 900°C–30 min interreaction. With further heating time, only the γ-TiAl layer remains at 900°C–10 h, as shown in Fig. 6(d). Figures 7(a), (b) and (c) show the dependence of the thicknesses of TiAl3, TiAl2 and γ-TiAl phases vs. interreaction time for TiAl3 film on bulk α2-Ti3Al heated at 700°C, 800°C and 900°C, respectively. From Fig. 7, the growth of TiAl2 and γ-TiAl layers is also in agreement with diffusion-controlled behavior within 10 h at 700°C, 5 h at 800°C and 30 min at 900°C for TiAl3 formation; and within ≥80 h at 700°C, 80 h at 800°C and 10 h at 900°C for γ-TiAl formation, as discussed further in Section 3.4.
3.4 Interreaction kinetics of phase formation between TiAl3 film/bulk γ-TiAl and TiAl3 film/bulk α2-Ti3Al systems

Figures 4 and 7 show the thicknesses of the TiAl3, TiAl2 and γ-TiAl layers vs. interreaction time at high temperature in TiAl3 film/bulk γ-TiAl and TiAl3 film/bulk α2-Ti3Al, respectively. From Figs. 4 and 7, the curves of TiAl2 and γ-TiAl thicknesses vs. heating time exhibit a complete interreaction and are suitable for investigating the kinetics of phase formation in this study. The TiAl2 and γ-TiAl curves shown in Figs. 4 and 7 begin from the origin, increase rapidly in the initial heating time and reach the curve maximum. After reaching their maxima, the TiAl2 and γ-TiAl curves decrease gradually because the Al-atoms diffuse outward to form the Al2O3 layer and diffuse inward to increase the Al concentration in the substrate. Obviously, only the portion of TiAl2 and γ-TiAl curves from the origin to their maximum is related to the phase formation and can be used to analyze the growth kinetics, as shown in Fig. 8 for TiAl2 formation and in Fig. 9 for γ-TiAl formation. In Figs. 8(a) and (b), the dependence of the TiAl2 layer thickness is plotted against the square root of the interreaction time for TiAl3 film on γ-TiAl bulk alloy and for TiAl3 film on α2-Ti3Al one, respectively. The heating temperatures are 800 °C, 900 °C and 1000 °C for Fig. 8(a), and 700 °C and 800 °C for Fig. 8(b). In all heating temperatures of Fig. 8, each set of data points can be fitted well to straight lines. This characteristic behaves a diffusion-controlled process for TiAl2 phase growth and complies fairly well with the parabolic law. The same situation also occurs in Fig. 9 for γ-TiAl formation in TiAl3 film on bulk α2-Ti3Al system. Therefore, the growth constants from the slopes of these straight lines can be determined, as discussed in detail below. Notice also from Fig. 8, that all fitted straight lines do not intercept the origin of the plot. This may be because a few TiAl2 phases have nucleated at the interface before the specimens were heated up to the set temperature. However, all straight lines shown in Fig. 9 pass near the origin of the plot. This feature indicates that γ-TiAl formation may be not nucleated during the heating and it only needs a little incubation time at the set temperature, which is quite different from the behavior of TiAl2 formation at the same temperature.

From Figs. 8 and 9, the growth kinetics of TiAl2 and γ-TiAl phases in TiAl3 film/bulk γ-TiAl and in TiAl3 film/bulk α2-Ti3Al all belong to diffusion-controlled process. There are Arrhenius plots of the growth constant, k, which is defined by \( W = k \sqrt{t} \), where \( W \) is the thickness of product layer and t the interreaction time. Hence, the growth constants can be determined from the slopes of the straight lines shown in Figs. 8 and 9. The temperature dependence of k can be expressed by the Arrhenius equation:

\[
k^2 = k_o^2 \exp\left(\frac{Q_k}{RT}\right)
\]

where \( Q_k \) is the activation energy of phase growth, \( k_o^2 \) is a pre-exponential factor and \( R \) is the gas constant. The logarithm of the growth constant k is plotted as a function of reciprocal temperature (1/T), as shown in Fig. 10. Figure 10 shows that the straight lines can be fitted well to the data points, thus the growth of TiAl2 and γ-TiAl is thermally activated, but with different \( Q_k \) and \( k_o^2 \). From Fig. 10, the parameters \( Q_k \) and \( k_o^2 \) were calculated from eq. (1) and are listed in Table 3. From Table 3, for the TiAl3 film/bulk γ-TiAl diffusion couple, the \( Q_k \) of TiAl2 phase formation is about 158.9 kJ/mol, and the \( k_o^2 \) is approximately 3.9 \( \times 10^{-8} \) m/s at 800~1000 °C. In the case of TiAl3 film/bulk α2-Ti3Al diffusion couple, the \( Q_k \) and \( k_o^2 \) of γ-TiAl and TiAl2 phases formation are about 163.4 kJ/mol and

Table 3 Data of various product phases in Ti-Al diffusion couples.

<table>
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<tr>
<th>Formed Phase</th>
<th>Diffusion couples</th>
<th>( Q_k ) (kJ/mol)</th>
<th>( k_o^2 ) or ( D_o ) (cm²/s)</th>
<th>Temperature range (°C)</th>
<th>Reference No.</th>
</tr>
</thead>
<tbody>
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<td>TiAl3</td>
<td>bulk Al-bulk Ti</td>
<td>179.5 ± 5</td>
<td>8 ( \times 10^{-3} )</td>
<td>580-640</td>
<td>6</td>
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<tr>
<td>TiAl2</td>
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<td>238.5 ± 10</td>
<td>—</td>
<td>784-958</td>
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<tr>
<td></td>
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<tr>
<td></td>
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4.8 × 10^{-8} \text{m}^2/\text{s}, and 147.9 kJ/mol and 1.6 × 10^{-8} \text{m}^2/\text{s} at 700 to 900°C, respectively. Data obtained from this study and more obtained from published reports are listed in Table 3 for comparison.

From Table 3, the $Q_k$ values of TiAl$_2$ and $\gamma$-TiAl phases formation in this study are very similar in magnitude with those of the TiAl$_3$ phase in the Ti-Al thin film diffusion systems,

4. Conclusions

In this study, TiAl$_3$ film/bulk $\gamma$-TiAl and TiAl$_3$ film/bulk $\alpha_2$-Ti$_3$Al diffusion couples are obtained by sputtered-Al film on $\gamma$-TiAl or $\alpha_2$-Ti$_3$Al substrates and then annealing at 600°C for 24h. Subsequent interreaction at 700 to 1000°C for 30min to 300h in the ambient atmosphere shows that TiAl$_2$ layer and TiAl$_2$/$\gamma$-TiAl mixed layers are observed at the interfaces of TiAl$_3$ film/bulk $\gamma$-TiAl and TiAl$_3$ film/bulk $\alpha_2$-Ti$_3$Al diffusion couples, respectively. All growth kinetics of TiAl$_2$ and $\gamma$-TiAl phase formation obey a parabolic law. Hence, the growth activation energy, $Q_k$, of product phases, as well as their pre-exponential factor, $k_o^2$, can be determined by an Arrhenius equation. Experimental results show that $Q_k$ of TiAl$_2$ phase formation is about 158.9 kJ/mol with $k_o^2$ of 3.9 × 10^{-8} \text{m}^2/\text{s} in TiAl$_3$ film/bulk $\gamma$-TiAl system at 800 to 1000°C, and those of $\gamma$-TiAl and TiAl$_2$ phases formation are 163.4 kJ/mol and 147.9 kJ/mol with $k_o^2$ of 4.8 × 10^{-8} \text{m}^2/\text{s} and 1.6 × 10^{-8} \text{m}^2/\text{s} in the TiAl$_3$ film/bulk $\alpha_2$-Ti$_3$Al system at 700 to 900°C, respectively. In this study, the $Q_k$ values of TiAl$_2$ and $\gamma$-TiAl phase formation are similar to the reported $Q_k$ values of TiAl$_3$ phase formation in Ti-Al thin film diffusion couples. At the same time, none of the fitted straight lines of TiAl$_3$ thickness vs. the square root of the interreaction time intercepts the origin of the plot. This implies that only a few TiAl$_3$ phases had nucleated at the interface prior to the specimen being heated up to the set temperature. However, all fitted straight lines of $\gamma$-TiAl thickness vs. the square root of the interreaction time for the TiAl$_3$ film on $\alpha_2$-Ti$_3$Al alloy pass near the origin of the plot. This indicates that $\gamma$-TiAl formation may be not nucleated during the heating and it needs only a brief incubation time at the set temperature.

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