

# Diffusion Bonds between Molybdenum and Titanium

Hirohisa MASUMOTO\*, Kazumasa NISHIO\*\*, Shizuo MUKAE\*\*\*  
Akihiro ASADA\* and Mitsuaki KATOH\*\*

## Abstract

In this study, the effects of the bonding conditions and the postheat treatment on the bondability of the bonds of molybdenum and molybdenum alloy to titanium and titanium alloy have been investigated. Results obtained are summarized as follows:

1) In case of the bond of molybdenum to titanium, the diffusion layers formed on the bonded zone were both  $\beta$  phase and  $\alpha+\beta$  phase. Kirkendall effect was observed at the bond interface between molybdenum and titanium, and the voids were formed in diffusion layer.

2) The bond strength of the bond of molybdenum to titanium depended on the bonding temperature and the maximum bond strength of 440 MPa was obtained at 850°C for the bonding time of 1ks and 1.8 ks, and tension fracture occurred in titanium base metal. However, the bond strength decreased as the bonding temperature became higher.

3) When bonds having the maximum bond strength were heated at 700°C, the bond strength was not affected by the heating time up to 72 ks. However, it decreased with the increase of holding time at 900°C and 1000°C.

4) Rotating bending fatigue limits of the bonds of Mo/Ti, TZM/Ti, Mo/Ti-6Al-4V and TZM/Ti-6Al-4V were the value of 40%~50% of each bond strength.

Key Words; Diffusion bonding, Molybdenum, Titanium, Bond strength, Fatigue limit, Mill

## 1. Introduction

Some intermetallic compounds are well known to have excellent performance such as high temperature strength and superconductivity<sup>1)</sup>, they are considered to be advanced materials. However, because of the poor workability, improvement of processability has been investigated<sup>1)2)</sup>. Rolling and hot isostatic pressure, HIP<sup>3)</sup>, can be applied to work the intermetallic compound powder. Producing composites of the intermetallic compound with refractory metals can be performed by vacuum roll bonding<sup>4)</sup>. In the rolling of these materials, since the rolls are needed to be heated at a high temperature, the roll materials must be provided with high resistance to heat. Materials with high strength at elevated temperatures are ceramics and refractory metals. In this study, molybdenum was marked as a researching target because of high heat conductivity, good workability and a low thermal expansion coefficient. Rolling must be carried out in a vacuum or inert gas atmosphere, because molybdenum has a poor resistance to oxidation at high temperature. Furthermore, since molybdenum is low in toughness, the rolls were designed to use it only as an overlay material on the outside of the roll. The materials in the central part of the roll must be provided with high corrosion resistance to cooling water besides high toughness. In order to make such a composite roll, bondabilities of materials for the rolls were studied. In preliminary experiments of bonding of molybdenum to pure

\* Kurume Institute of Technology      \*\* Kyushu Institute of Technology

\*\*\* Kitakyushu Technology Center Co., LTD

平成8年9月20日受理

iron, nickel (VNiB), titanium (TB24H), and various types of stainless steel, the bond strength was the highest value for the bonding to titanium. Thus, the materials for the rolls were titanium or titanium alloy as the central part materials of the rolls, and the bondabilities of these metals were studied.

Available reports on bonding of molybdenum were mainly concerned with the bonding of molybdenum to molybdenum<sup>5)</sup>, bonding of molybdenum to different metals were studied on application of brazing<sup>6)</sup> and diffusion bonding<sup>7)9)</sup>. Enjyo et al. applied diffusion bonding into the bonding of molybdenum to Hastelloy X<sup>7)</sup>.

However, the reports on evaluation of the bond strength are scarcely available on the bonding of molybdenum to titanium. Therefore, this study has been intended to examine the effects of bonding conditions on the bonding performance of the bonds of molybdenum to titanium. The effects of postheating temperature is an important factor in practical application on bond strength and fatigue strength of the bonded materials have been studied.

## 2. Materials and Experimental Procedure

Table 1 shows the chemical compositions of a pure molybdenum, commercial bar of 10mm in diameter, and a commercial pure titanium. The surfaces bonded were prepared by polishing with #1200 emery paper and ultrasonic cleaning in acetone. Roughness of the surface, Rz, was about 0.5  $\mu\text{m}$  for molybdenum and about 0.8  $\mu\text{m}$  for titanium. Bonding was performed by using the same apparatus as the previous reported<sup>9)</sup>, which was carried out in a vacuum of  $8 \times 10^{-3}$  Pa at a predetermined temperature after heating at the rate of 5 °C/s. Bonding were carried out under various bonding conditions, that is, the bonding pressure,  $P_b$ , of 5.6 MPa, and the bonding temperature being changed from 600°C to 1200°C and also the bonding time,  $t_b$ , after reaching the bonding temperature being varied several levels from 0.1 ks to 36 ks.

Since in bonding above 900°C titanium deformed remarkably, the work was carried out by applying pressure for 0.1ks initially and after continuing the heating under no-load. The composite rolls are intended to use the hot rolling, therefore, the effects of holding time and temperature on the bond strength were examined for the practical use. The heating temperature,  $T_h$ , was varied from 700°C to 1000°C and the holding time,  $t_h$ , was changed from 0.06 ks to 72 ks. The bond strength was evaluated by tensile test and Ono type rotating bending fatigue test in air at room temperature. Microstructures observation of the bond region were observed after etching of the titanium part with an etchant of a 1 : 1 : 3 mixture of fluoric acid, hydrochloric acid and glycerin. The shape of tensile testing specimen was 7.5 mm in diameter and 20 mm in gage length. The fatigue test specimens were fabricated to have a parallel part of 6 mm diameter and 10 mm length. The bond region was positioned at the center of parallel part of both types of the specimens. Tensile tests were carried out at the tensile rate of 0.025mm/s.

## 3. Experimental results and discussion

### 3.1 Diffusion behavior in the bonds of molybdenum and titanium

#### 3.1.1 Microstructures in bonds

Figure 1 shows the microstructures in the vicinity of bond interface of the bonds of molybdenum to titanium joined at the temperature of 800°C (as shown in Figure 1(a)) and 1000°C (as shown in Figure 1(b)) lower than the  $\beta$  transus (882°C) of titanium<sup>10)</sup>. The time for bonding was 1.8 ks. The vicinity of bonds consisted of two phases, hereafter, these will be named the molybdenum side as diffusion layer I and the titanium side as diffusion layer II. In the case of bonding at 800°C, both diffusion layers I and II were not detected in some bond zone. These areas were thought to be non-bond regions. Such a non-bond part disappeared gradually in bond area at bonding temperature

Table 1 Chemical compositions of molybdenum and titanium used

	(mass%)						
	Fe	C	N	O	Si	Ti	Mo
Ti	0.053	0.007	0.0075	0.098	-	Bal.	-
Mo	0.002	0.014	0.0009	0.075	0.004	-	Bal.

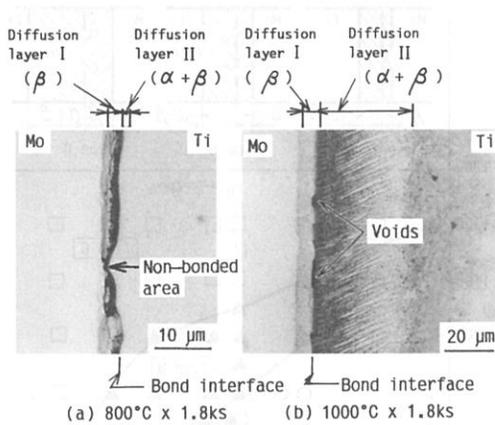


Fig. 1 Microstructures of bonded zone of joints of molybdenum to titanium

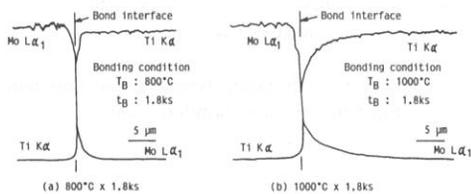


Fig. 2 Results of EPMA analysis near bonded zone of joints of molybdenum to titanium

wider as much as about 40 μm. EPMA line analysis was made in the vicinity of the bond interface, showing in Figure 1.

Figure 2 shows the result. In every bonding condition the amount of titanium diffused into molybdenum was very small. Molybdenum diffused into titanium in the vicinity of bond interfaces, after bonding at 800°C the diffusion distance amounted as much as several micron meters, the extent of diffusion of molybdenum in bonding at 1000°C was wider than the above case, being about 45 μm. This suggests that there was a large difference on diffusion behavior of Mo above and below the β transus. In order to examine the difference of growth of diffusion layers caused by the difference of phases or temperature, the relation between the width of diffusion layers and the square root of bonding time,  $\sqrt{t_B}$ , was examined. The width of diffusion layer was correlated linearly with  $\sqrt{t_B}$  for every temperature. The slope of straight lines,  $K_T$ , became larger with elevation of temperature.

Figure 3 shows the relation between the slope,  $K_T$ , and the bonding temperature, which was expressed as two straight lines separated by the β transus. The straight line for higher temperature than the β transus is located above that of lower temperature than the β transus. It suggests the important contribution of the types of phase on the growth of diffusion layer.

X-ray diffraction pattern was obtained in the vicinity of bond interface joined under a condition of 1200°C × 10 ks to analyze the bond microstructure. Peaks were identified as Mo, αTi phase, and βTi phase in the bonded region. In the binary Mo-Ti system the β phase was observed in the case containing molybdenum more than 12 mass% and the α + β phase in the case less than 12 mass%<sup>11)</sup>. Furthermore, the formation of the β phase in the bonds was thought due to molybdenum being the β phase stabilizer of titanium, and both Mo and Ti making a solid solution mutually over all range. The concentration of molybdenum at the interface between diffusion layer I and II was about 12

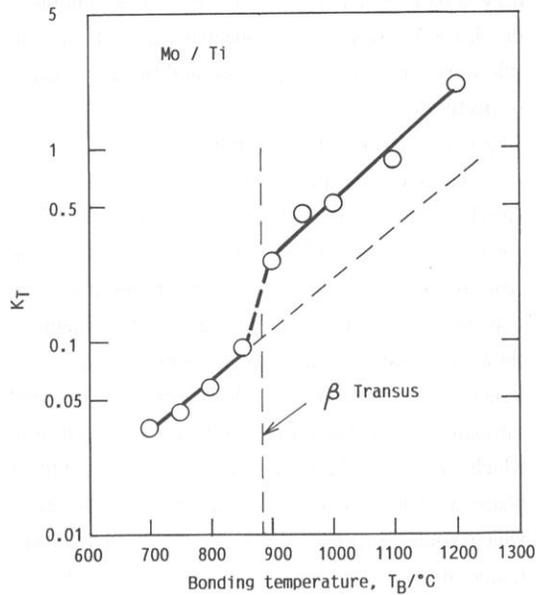


Fig. 3 Relation between  $K_T$  and bonding temperature

than 800°C. In bonding at 1000°C, diffusion layers I and II were observed over all in the bond area and small voids were detected at the bond interface. The width of diffusion layer I was about 6 μm, while that of diffusion layer II was

mass% on EPMA analysis. From the above mentioned, the diffusion layers of molybdenum side and titanium side were considered the  $\beta$  phase and the  $\alpha+\beta$  phase, respectively.

3.1.2 Effects of bonding condition on bond structure

The microstructure and void formation varied largely with the bonding temperature and time. Thus, the microstructure in bonds was classified into three types from the viewpoints of the formation states of the  $\beta$  phase and the position of void formed. Figure 4 shows the result. The type A represents a microstructure in which the  $\beta$  phase was not detected throughout the bonded area, the type B a structure in which voids were observed along the interfaces of the  $\beta$  phase and the  $\alpha+\beta$  phase, and the type C a structure in which voids were in the  $\beta$  phase. Bonding at lower temperature and shorter time produced the A type microstructure. On the other hand, bonding at higher temperature and longer time produced the C type microstructure. Bonding at an intermediate region produced the B type microstructure. In order to make

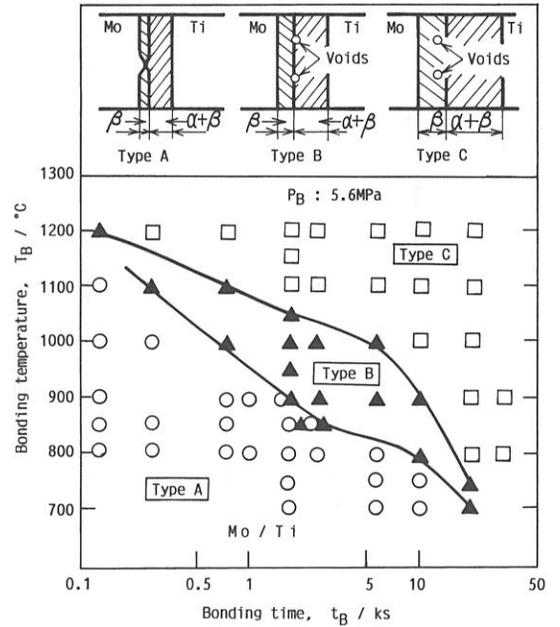
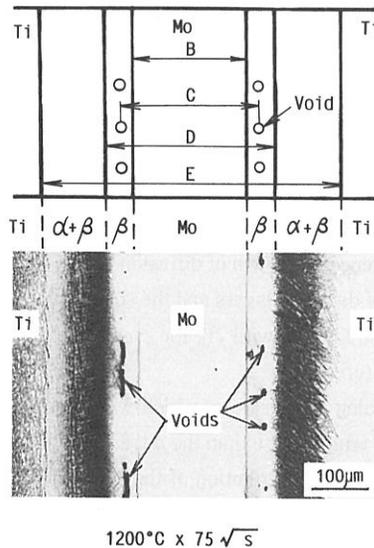
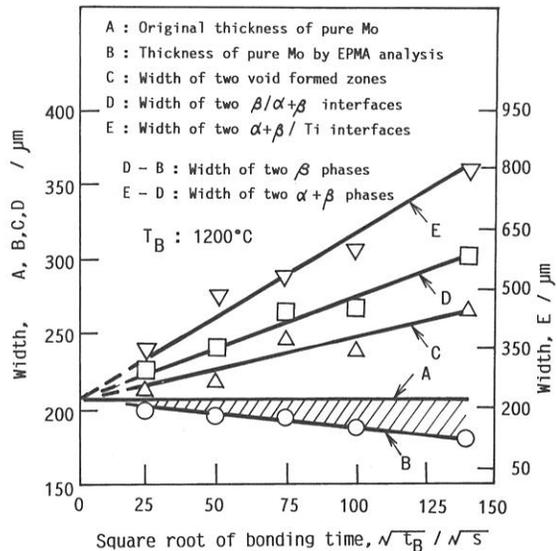


Fig. 4 Effects of bonding temperature and bonding time on near bonded zone



(a) Microstructure and schematic diagram of bonded zone



(b) Relation between square root of bonding time and width of diffusion layers

Fig. 5 Schematic diagram of bond microstructure and relation between bonding time and width of diffusion layers

clear observation on the states of diffusion phases and voids, a diffusion couple of titanium/ 205  $\mu\text{m}$  thick molybdenum / titanium was made. In this case, a foil of tungsten, 25  $\mu\text{m}$  thick and 3 mm in width, was inserted as the marker in the center part of bonding interface of the couple. After bonding the intervals of each phase was measured by taking pictures of the interface microstructure.

Figures 5 (a) and (b) show the microstructure in the vicinity of bond interface of the couple heated at 1200°C, the schematics of the measured positions in each phase, and the relation between interspacing of each phase and the square root of heating time  $\sqrt{t_B}$ . In figures A is the distance of markers both tungsten foil, B is the widths of pure molybdenum after bonding, C is the interspacing of formed voids, D is the distances of boundaries between the  $\beta$  and the  $\alpha + \beta$  phases, and E is the distance of boundaries between the  $\alpha + \beta$  phase and titanium. Except for A, all others are mean values which were obtained at thirty positions within the area of about 3mm at the center of a specimen. The distance A is constant at 205  $\mu\text{m}$  regardless of the heating time. The width B of pure molybdenum decreased linearly with an increase of  $\sqrt{t_B}$ . On the other hand, the distance D increased linearly with an increase of  $\sqrt{t_B}$ . As a result, it was found that the  $\beta$  phase is formed on both sides of the original surfaces. And also E increases linearly with an increase of  $\sqrt{t_B}$ . Especially, growth of the  $\alpha + \beta$  phase region, that is, the distance between E and D, is very fast compared with growth of the  $\beta$  phase region the distance between D and B. For instance, when  $\sqrt{t_B}$  was 100  $\text{s}^{1/2}$ , width of the  $\alpha + \beta$  and the  $\beta$  phase about 335  $\mu\text{m}$  and 75  $\mu\text{m}$ , respectively. And also it was found that distance between voids formed both side, C, increased linearly with  $\sqrt{t_B}$ . From the above, it was found that the  $\beta$  phase in the bonds was formed by mutual diffusion of molybdenum and titanium and the  $\alpha + \beta$  phase was produced molybdenum diffusing into titanium. Since the growth of the  $\alpha + \beta$  phase was faster than that of  $\beta$  phase, the amount of molybdenum diffusing into titanium from the  $\beta$  phase was large and Kirkendall voids were generated in the bond region.

### 3.2 Bond strength of joints

Figure 6 shows the effects of the bonding temperature on the bond strength. The broken lines in the figure shows the tensile strength of titanium heated under the simulating condition of bonding. In bonding below 600°C, the joints separated readily at the bond interface when they were taken out from the bonding apparatuses. Bonding could be obtained above 700°C to give a bond strength of about 100MPa. The bond strength increased with increase of bonding temperature in the range below the  $\beta$  transus, showed the maximum value when bonded at 850°C, and tensile fracture occurred in titanium base metal. In bonding above the  $\beta$  transus, the bond strength decreased remarkably with increase of the bonding temperature, being about 200 MPa at 1200°C.

Figure 7 shows an SEM image of the tensile fracture surface in molybdenum matrix and the microstructure in the vicinity of fractured position of the joint. The bonding temperature was 800°C and 900°C, and the bonding time was 1.8 ks. Fractured surface of the joints at 800°C exhibited a parallel ridges resulting from scratches in grinding. From the microstructural observation in the vicinity of fractured positions, fracture mainly initiated from the bond interfaces, partly from within molybdenum matrix and the interface of molybdenum and the  $\beta$  phase. Moreover, a lot of subcracks were observed inside molybdenum. The cause for initiation of cracks inside molybdenum may be the grain boundary originating embrittlement due to results

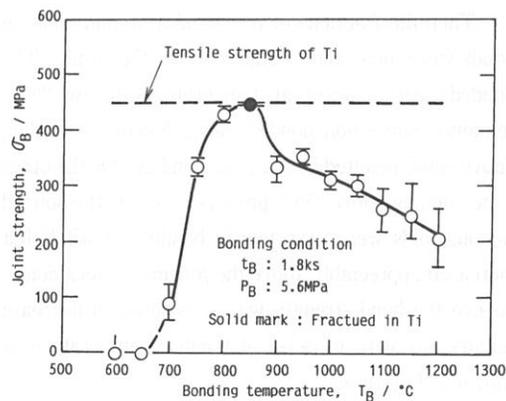


Fig. 6 Effect of bonding temperature on joint strength of the joints of molybdenum to titanium

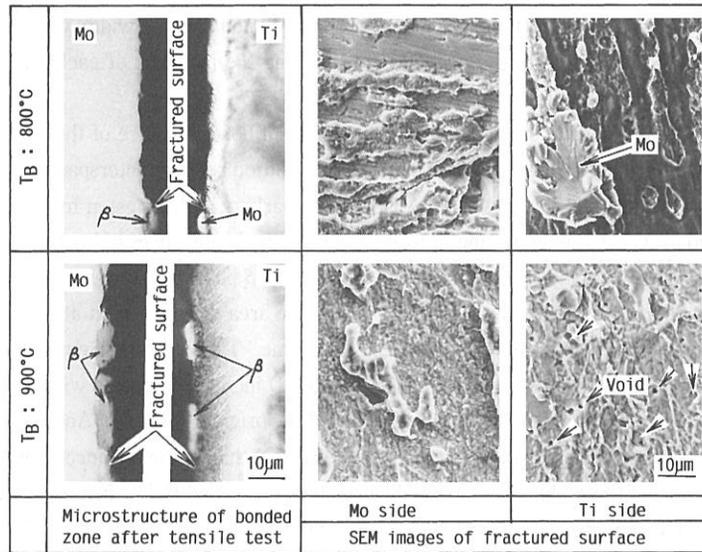


Fig. 7 Scanning electron micrographs of fractured surface and microstructures of fractured zone of the joint of molybdenum to titanium

of titanium diffusing toward grain boundaries. In the bonds joined at  $900^\circ\text{C}$ , tensile fracture occurred mainly at the site of void<sup>12)</sup> formation and interfaces of molybdenum and the  $\beta$  phase, tensile fracture originating from polishing scratches was not noticed on the fractured surfaces. Since grain boundary diffusion was accelerated with increasing of bonding temperature, the proportion of fracture occurred in the molybdenum matrix was considered to increase with increasing of bonding temperature. As shown in Figure 4 on the bonding time of 1.8 ks, the microstructure of B and C types devolved in the bond zone, bonding at temperatures above  $900^\circ\text{C}$  and the voids acting as the initiation sites and propagation paths of fracture appeared in the bonded regions. Fracture in tensile deformation of the B-type bond region occurred at the positions similar to the bonds joined at  $900^\circ\text{C}$  and that of the C-type occurred at void formation site. From the above mentioned the decrease of bond strength was caused by void formation rather than embrittlements due to grain boundary diffusion of titanium.

Then the fractions of non-bond area and voids in bonds were measured. Figure 8 shows the result. The bonded region joined at temperatures below  $800^\circ\text{C}$  remained some non-bonded parts, however, bonding above  $800^\circ\text{C}$  resulted in complete bonding. On the other hand bonding above  $850^\circ\text{C}$  produced voids in the bonded region, voids were very few in bonding at  $850^\circ\text{C}$  but increased appreciably above the  $\beta$  transus. As a consequence the bond strength was considered to decrease remarkably with increase of bonding temperature as shown in Figure 6.

Figure 9 shows the effects of bonding time,  $\sqrt{t_B}$ , on the bond strength between molybdenum and titanium. The bond strength of joints bonded at  $800^\circ\text{C}$  and  $850^\circ\text{C}$

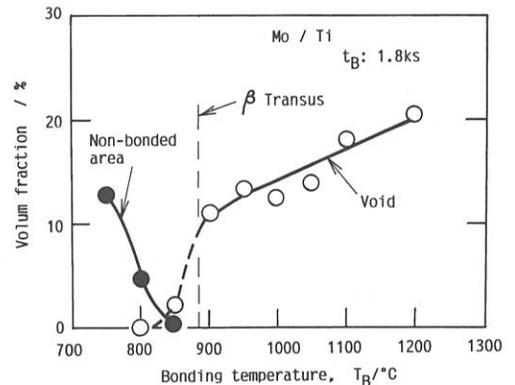


Fig. 8 Effect of bonding temperature on volume fraction of non-bonded area and voids bonded at 1.8ks

just below the  $\beta$  transus temperature increased linearly with increase of  $\sqrt{t_B}$  for a bonding time less than 1 ks. It was suggested that the bond strength was strengthened with progress of diffusion of Mo and Ti. Bonding time longer than 1ks brought a bond strength higher than 400 MPa and tensile fracture occurred in the titanium base metal. In the short bonding time at 800°C and 850°C, the later was obtained higher bond strength than the former. And also tensile fracture occurred in titanium base metal when the bonding time was short less than 3.6 ks. Observations of the fractured surfaces and positions revealed the scratches by grinding on the part of the fractured surface for a short time of bonding and the fracture occurred at the interfaces between molybdenum and titanium. Long bonding time eliminated the grinding scratches and increased the fraction of fracture from the void formation faces.

In bonding at 900°C, higher than the  $\beta$  transus, the bond strength of 300 MPa was obtained even for a shorter bonding time of 0.18 ks, and also it showed about 290 MPa after extremely longer bonding time more than 30 ks, which indicated little effects of bonding time. It was considered that the results was to promote the adhesion at the bond interface due to high deformability of titanium and enhancing diffusion of molybdenum within titanium, bond strength of about 300 MPa was higher than that of the joints bonded at a temperature just below the  $\beta$  transus for a short bonding time of 0.18 ks. The fractured surface in this case revealed the ridge pattern originating from grinding scratches. As shown in Figure 3, however, voids tended to be formed in the bond regions after bonding time longer than 1.8ks and the fracture occurred from the formed void parts. The area fractions of grinding scratches and voids throughout the bonded areas were measured by the point counting method with SEM micrographs on the fractured surfaces of the materials bonded with bonding time of 0.18 ks, 1.8 ks, and 30 ks. In a short time bonding less than 0.18 ks, the non-bonded parts were about 20%. In the case of bonding time between 1.8 ks and 30 ks, voids were about 11% and 15% respectively. But non-bonded area could not be observed in both cases. In the case of bonding at 900°C a shorter bonding time was not sufficient for bonding and a longer bonding time produced voids in the bonded regions, therefore satisfactory strength comparable to the strength of titanium base metal was not obtained over all range of employed bonding time. Moreover, it was thought that in the case of bonding at 900°C the bond strength did not decrease for a shorter time longer than 1.8 ks since the area fraction of voids did not increase appreciably after bonding in the range from 1.8 ks to 30 ks.

### 3.3 Fatigue strength of joints

Figure 10 shows the S-N curves of joints bonded under the condition of 850°C×1.8 ks which produced the highest bond strength. The marks ● and ○ represent the fracture position, the former is in the base metal of titanium and the later at the bond interface. In the range of cycle stresses from 250MPa to 300MPa, fracture tended to occur in the titanium matrix. In the case of fracture within cycling less than  $10^4$  cycles fracture occurred exclusively in the bonds while after more than  $10^6$  cycles fracture occurred partly in titanium. From observation of the fractured surfaces using SEM, fracture in the vicinity of the bonded region occurred at the formed void site as well as the tensile fracture, at the interfaces between molybdenum and the  $\beta$  phase, and partly in the molybdenum matrix. The slope of S-N curve was moderate and the fatigue strength at  $10^7$  cycle number (called fatigue limit) showed about 220 MPa. Since the fatigue strength of annealed pure titanium was about 230 MPa, the bond strength of molybdenum and

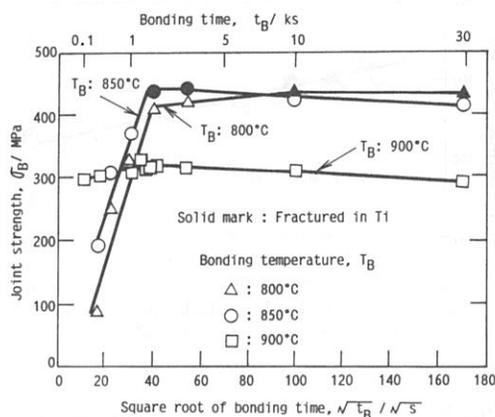


Fig. 9 Relation between square root of bonding time and joint strength of the joints of molybdenum to titanium

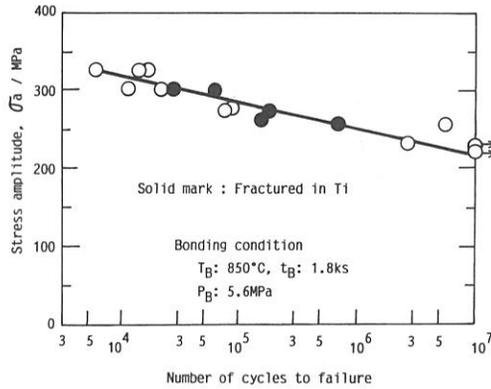


Fig. 10 S-N curve of the joints of molybdenum to titanium bonded at 850°C×1.8ks

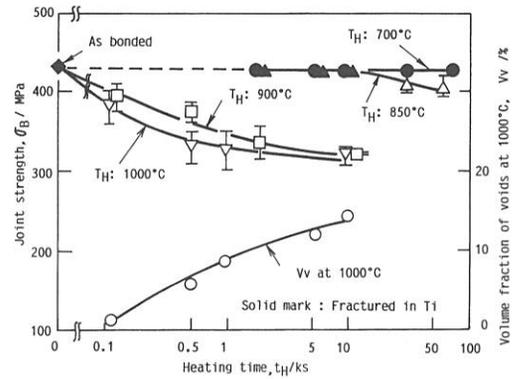


Fig. 11 Effect of postheat treatment on joint strength of the joint of molybdenum to titanium bonded at 850°C×1.8ks

titanium joined under the highest bond strength was nearly equal to the fatigue strength of pure titanium.

### 3.4 Effect of heating treatment on bond strength

Bond between molybdenum and titanium, showed a bond strength which was comparable to the matrix strength of titanium at 800°C and 850°C a little lower than the  $\beta$  transus. In order to applicate for a hot working rolls, it is necessary to examine the effects of heat treatment on the bond strength. Therefore, the effects of heat treatment on the bond strength were examined using the joints bonded the condition of 850°C×1.8 ks which brought the bond strength equal to the strength of titanium base metal.

Figure 11 shows effects of heat treatment time on the bond strength. Tensile fracture occurred in titanium after soaking at 700°C for a long period of 72 ks. And also, after heating at 850°C for less than 3.6 ks, fracture occurred in titanium. Heating time being over 10 ks, small voids were observed at the bond interface a part of which caused initiation of fracture. However, the bond strength above 400 MPa was obtained even for a long soaking time more than 60 ks. Thus, the effects of heat treatment time on the bond strength were small at heating temperatures below the  $\beta$  transus in this work. On the other hand, soaking at the temperatures above the  $\beta$  transus such as 900°C or 1000°C decreased the bond strength with increasing the heating time. In heating at the temperature above 900°C for 1.8 ks, the bond strength decreased to until that of materials as joined at 900°C and 1000°C for 1.8 ks. Voids were observed on the tensile fractured surfaces of the joints heated over 900°C. The fraction of voids formed in the bond zone at the heating temperature of 1000°C was increased. The results were shown as  $\circ$  marks in figure, the volume fraction of voids,  $V_v$ , increased with an increase of a heating time. Decreasing the bond strength of joints heated at temperatures above 900°C with the bonding time was thought to be a result of increase of voids by long time heating.

### 3.5 Bonds of molybdenum or TZM alloy to Ti-6Al-4V alloy

It was verified that the bond strength could be as strong as that of titanium base metal under the optimum bonding condition on bonding of molybdenum to titanium. Therefore bondability was examined with Ti-6Al-4V alloy which has more excellent mechanical properties than titanium for the purpose of producing high strength composites. And also with TZM alloy having higher ductility and strength than molybdenum at elevated temperature was performed. Table 2 shows the chemical composition of the Ti-6Al-4V alloy and TZM alloy.

Figure 12 shows the relation between the bond strength and the bonding temperature on the bonding of molybdenum to the Ti-6Al-4V alloy and the TZM alloy, and titanium to the TZM alloy. The broken lines in figure show the tensile strength of titanium, Ti-6Al-4V alloy, molybdenum and TZM alloy which were subjected much the same heat treatment as bonding. The tensile strength of Ti-6Al-4V alloy decreased a little by heat treatment at 1000°

C, but both of molybdenum and TZM alloy were few change about 750 MPa and 900 MPa by changing the heating temperature respectively. In bonding of titanium to TZM alloy the bond strength showed the peak value at 850°C alike bonding of titanium and molybdenum, but decreased appreciably above 900°C. In this case obtained the results of microstructure observation and EPMA line analysis the same tendency as the bonding of titanium and molybdenum. Bonds of Ti-6Al-4V alloy to molybdenum or TZM at the bonding temperatures from 850°C to 900°C produced a bond strength comparable to base metal of molybdenum and TZM alloy, and in particular, bond strength of the joints with molybdenum was obtained about 750MPa in the bonding at 850°C, and the fracture occurred in the molybdenum base metal. Bonding with TZM alloy brought a strength higher than 900 MPa and the fracture occurred partly in the TZM alloy matrix. Bonding above 950°C led to some decrease of the bond strength, in this case the tensile fracture occurred at the bond interface and voids were observed on the fractured surface. In order to examine why the bond strength did not decreased remarkably in the owing with Ti-6Al-4V unlike with titanium, diffusion experiment was performed. As a result, in the joining with titanium the width of diffusion layer and the void formed in the bond zone were very few in comparison with titanium, which is thought to be the cause of preventing remarkable decrease of the bond strength. The joints bonded under the condition of 850°C×1.8 ks were tested a fatigue strength by Ono type rotation bending fatigue testing machine.

Figure 13 shows the relation between tensile strength and fatigue limit of joints. The fatigue limit was about 50% of the bond strength of the joints between titanium and molybdenum or Ti-6Al-4V alloy and in the bond between TZM alloy and Ti-6Al-4V alloy showed somewhat lower about 40%.

#### 4. Conclusions

In this study, the effects of the bonding conditions and the postheat treatment on the bondability of the bonds of molybdenum to titanium and ether alloys have been investigated. Results obtained are summarized as follows;

1) In case of the bond of molybdenum to titanium, the diffusion layers formed on bonded zone were both  $\beta$  phase and

Table 2 Chemical compositions of molybdenum alloy and titanium alloy used

	(mass%)								
	Al	V	Fe	C	N	O	Si	Ti	Mo
Ti-6Al-4V	6.48	4.28	0.280	0.006	0.004	0.080	0.05	Bal.	-
T Z M	-	-	0.085	0.0017	0.028	0.002	0.001	-	Bal.

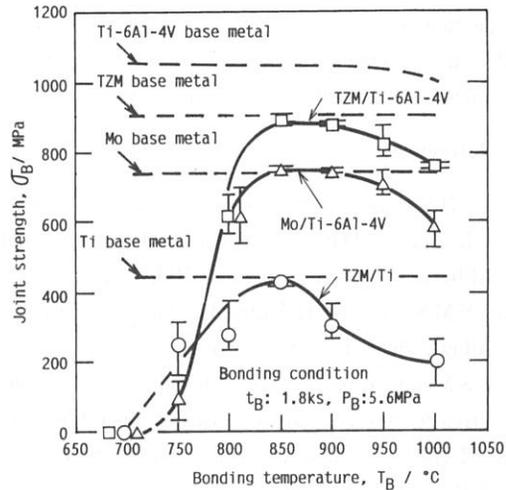


Fig. 12 Effect of bonding temperature on joint strength of the joints of TZM/Ti, Mo/Ti-6Al-4V and TZM/Ti-6Al-4V

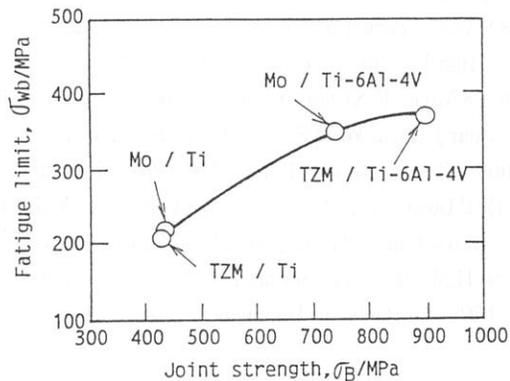


Fig. 13 Relation between fatigue limit and joint strength of the joints

- $\alpha + \beta$  phase. Kirkendall effect was observed at the bond interface between molybdenum and titanium, and the voids were formed in diffusion layer.
- 2) The bond strength of the bond of molybdenum to titanium depended on the bonding temperature and the maximum bond strength of 440 MPa was obtained at 850°C for the bonding time of 1 ks and 1.8 ks, and tension fracture occurred in titanium base metal. However, the bond strength decreased as the bonding temperature became higher.
  - 3) When bonds having the maximum bond strength were heated at 700°C, the bond strength was not affected by the heating time up to 72 ks. However, it decreased with the increase of holding time at 900°C and 1000°C.
  - 4) Rotating bending fatigue limits of the bonds of Mo/Ti, TZM/Ti, Mo/Ti-6Al-4V and TZM/Ti-6Al-4V were the value of 40%~50% of each bond strength.

### References

- 1) J.H.Westbook, "Intermetallic Compounds", John Wiley & Sons, (1967)
- 2) K.Aoki and O.Izumi, "Improvement in Room Temperature Ductility of the  $L_{12}$  Type Intermetallic Compound  $Ni_3Al$  by Boron Addition" Trans., JIM, 43-12(1979), 1190-1196
- 3) S.M.Sastry and H.A.Lipsitt, "Ordering Transformation and Mechanical Properties of  $Ti_3Al$  and  $Ti_3Al-Nb$  Alloy", Met. Trans. 8A(1977) 1543
- 4) S.Mukae, K.Nishio, M.Katoh, T.Inoue and N.Hatanaka, "Development of Vacuum Roll Bonding Apparatus and Production of Clad Metals", Quar.J.Japan Weld Soc., Vol.9-1 (1991), 17-23 (in Japanese)
- 5) T.Hashimoto and K.Tamura, "Diffusion Bonding of Molybdenum" Quar.J.Japan Weld Soc., Vol.37-12 (1926), 1345-1352 (in Japanese)
- 6) H.Ohmura and T.Yoshida, "Dissolution and Deposit of Base Metal in Brazing to Dissimilar Materials and its Application (Part 6)", Quar.J.Japan Weld Soc., Vol.2-2(1984), 293-301 (in Japanese)
- 7) T.Enjyo, M.Oouchi, S.Nasu, K.Ikeuchi and Y.Arata, "Diffusion Welding of Molybdenum to Hastelloy Alloy X", Quar.J.Japan Weld Soc., Vol.46-9 (1977), 660-665 (in Japanese)
- 8) W.Werdecker and F.Aldinger; The Bonding of Refractory Metals by Hot Isostatic Pressing, High Temperatures -High Pressures, Vol.14-2 (1982), 183-197
- 9) S.Muae, K.Nishio, H.Baba, M.Suenaga and Y.Ishihara, "Solid State Bonding of Ductile Cast Irons (Report 1)", Quar.J.Japan Weld Soc., Vol.4-1 (1986), 66-73 (in Japanese)
- 10) T.B Massalski, etc; Binary Alloy Phase Diagrams, Vol.1 and Vol.2(1986), ASM
- 11) P.Duwez; Effect of Rate of Cooling on the Alpha-Beta Transformation in Titanium and Titanium-Molybdenum Alloys, Trans., AIME, Journal of Metals, (1951), 765-771
- 12) H.Masumoto, M.Serino, K.Nishio, A.Asada and S.Mukae, "Formation of Diffusion Layer and Bond Strength of Diffusion Bonds of Aluminum Bronze to Stainless Steel", Trans. Japan Welding Society, 24-1 (1993), 63-69