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Effect of $\alpha \leftrightarrows \beta$ Transformation on the Diffusion Welding of Titanium†

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Abstract

An investigation has been made into the effect of $\alpha \rightleftarrows \beta$ transformation on the diffusion welding of titanium with particular reference to the transformation-induced superplasticity. The welding has been carried out in vacuo at a constant welding temperature in α or β phase region, and under thermal cycling (845°C $\rightleftarrows$ 920°C) through the transformation temperature.

The diffusion-welding process of titanium has developed more rapidly at welding temperatures in β phase region than in α phase. The increase in joint strength for early process of welding has been accelerated by the transformation-induced superplasticity. This effect of the superplasticity has been explained by the acceleration of the accomodation at bonding interface which requires the deformation of microasperities on faying surfaces. On the other hand, grain growth across bonding interface has not been so much promoted by the transformation-induced superplasticity.

KEY WORDS: (Diffusion Welding) (Titanium) (Transformation) (Superplasticity) (Diffusion)

1. Introduction

For the diffusion welding of metal, atomic diffusion and plastic deformation at high temperatures play an important role in the annihilation of microvoids at bonding interface and attainment of intimate contact between faying surfaces[1]. It is said that the atomic diffusion and plastic deformation are enhanced markedly by an allotropic transformation[2,3,4]. Therefore the diffusion welding of metal which has allotropic transformation is considered to be accelerated by taking advantage of the allotropic transformation.

Titanium has an allotropic transformation ($\alpha \rightleftarrows \beta$ transformation) at 882°C[5]. Several investigations[6,7,8] have already been reported on the diffusion welding of titanium. However, very little is known about the effect of the $\alpha \rightleftarrows \beta$ transformation on the diffusion-welding process.

In the present investigation, the diffusion welding of titanium has been carried out in the temperature range from 820°C to 940°C, and the effect of the $\alpha \rightleftarrows \beta$ transformation on the microstructure of bonding zone and joint strength has been investigated. The diffusion welding of mild steel has also been carried out in order to compare the effect of $\alpha \rightleftarrows \gamma$ transformation of steel with that of $\alpha \rightleftarrows \beta$ transformation of titanium.

2. Experimental Details

Base metals used in the present investigation were prepared from commercially pure titanium and mild steel. Their chemical compositions are shown in Table 1.

Table 1 Chemical compositions of base metals used (wt%).

Titanium

C	Fe	N	O	H	Ti
0.018	0.036	0.0057	0.083	0.0026	Bal.

Iron

C	Si	Mn	P	S	Fe
0.019	0.012	0.29	0.010	0.013	Bal.

The base metal used for the observation of microstructure of bonding zone was cube 3 ~ 4 mm in edge length, and that for tensile test of joint was cylindrical rod 20 mm in diameter and 37 mm in edge length.

The welding of joint for the microstructure observation was carried out with a high temperature optical microscope equiped with a compressing device. That of joint for the tensile test was carried out with a vacuum welding chamber installed with a radiant resistance heater of molybdenum foil and hydraulic press[9]. The faying surfaces were finished by grinding with 1500 grade emery paper unless otherwise stated and degreased by washing in

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acetone. After the washing in acetone the base metals were placed in the welding chamber with the faying surfaces in contact and the welding chamber was evacuated to pressures below 10^{-4} mm Hg. Then the bonding zone was heated and the pressure was applied onto the bonding interface. Temperature of the bonding zone was monitored with a thermocouple percussion-welded in the vicinity of bonding interface. The temperature of the bonding zone was controlled to an accuracy of ± 5°C.

Etchant for the observation of the microstructure of bonding zone was mixed acid (HF 5%, HNO_3 10% and H_2O 85%) for titanium and (HNO_3 5% and n-$C_5H_{11}OH$ 95%) for mild steel. Tensile test on joints was carried out at the strain rate of $0.03sec^{-1}$ at room temperature. Specimens for the tensile test were prepared by machining joints after welding. The gauge length and diameter of the specimen were 37 mm and 7 mm, respectively.

3. Results and Discussion

The temperature range where the base metal of titanium underwent the $\alpha \rightleftarrows \beta$ transformation was estimated using electrical resistivity measurement. Figure 1 shows a variation of the electrical resistivity of base metal with heating and cooling at the constant rate of 32°C/min. As shown in the figure, a conspicuous change in the electrical resistivity was observed in the temperature range of 875° ~ 910°C for heating and of 890° ~ 850°C for cooling. This indicates that the base metal underwent the $\alpha \rightleftarrows \beta$ transformation in these temperature ranges. The temperature ranges of the transformation were almost constant

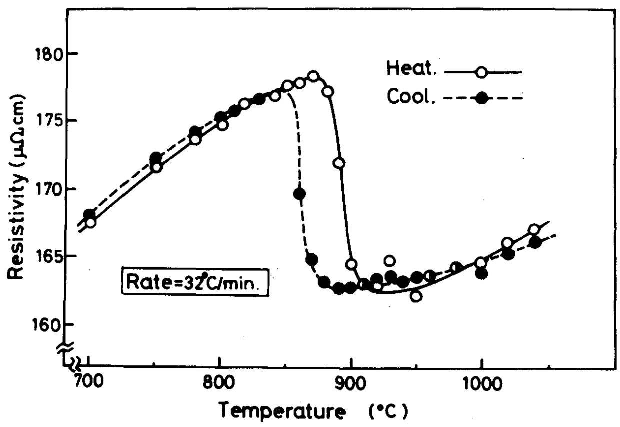


Fig. 1 Variation of electrical resistivity of the titanium base metal with heating and cooling at the constant rate of 32°C/min.

for heating and cooling rates of 15 ~ 32°C/min. From these results the welding was carried out at temperatures lower than 870°C for the test in α phase region and higher than 920°C for that in β phase region.

3.1 Effect of $\alpha \rightleftarrows \beta$ Transformation on the Microstructure of Bonding Zone

Photo. 1 (a), (b) and (c) show the microstructures of bonding zones obtained at welding temperatures in α and β phase region. As shown in Photo. (a) and (b), grain growth across bonding interface did not occur and many voids remained at the bonding interface at welding temperatures in α phase region. On the other hand, at the welding temperature of 920°C (β phase region), grain

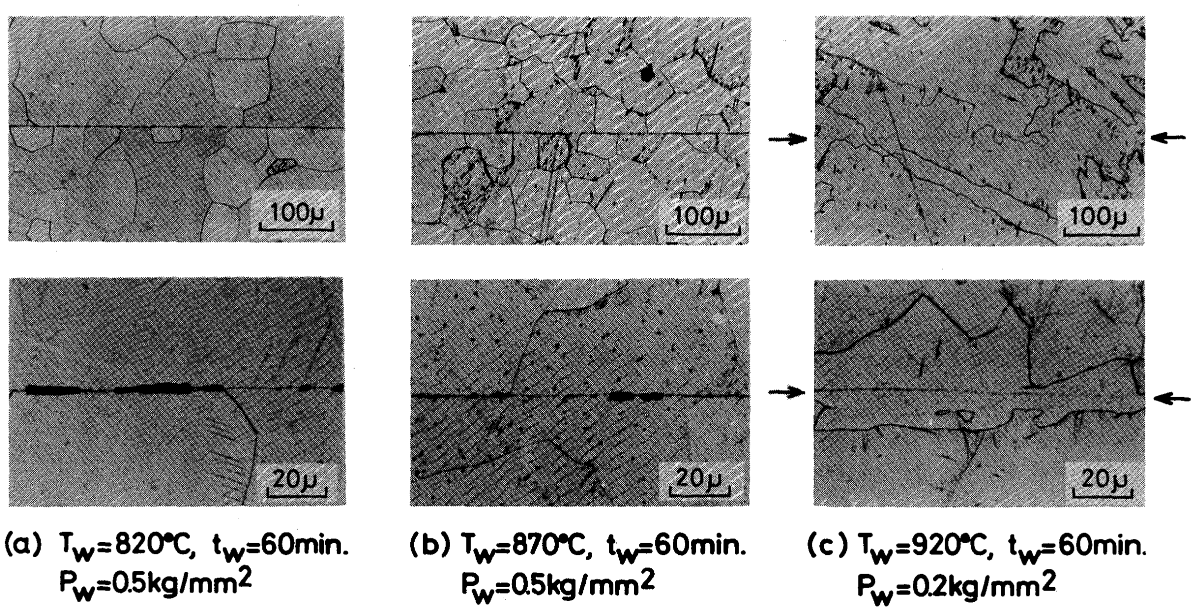


Photo. 1 Microstructures for the bonding zone of titanium. T_W, t_W and P_W denote welding temperature, time and pressure, respectively.

growth occured completely across the bonding interface, though several voids remained at the bonding interface. These facts indicate that the diffusion-welding process of titanium develops more rapidly in β phase region than in α phase.

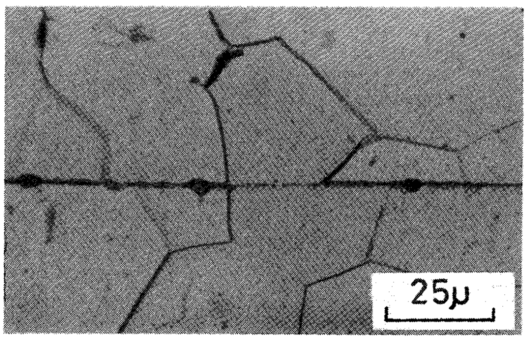
The diffusion coefficient of titanium increases markedly with the transformation from α to β phase[10, 11]. In order to examine the effect of the diffusion on bonding process, the amount of diffusion "A" during welding was estimated by eq. (1) as follows.

$$A=\int_0^{t_w} D\,d\tau=\int_0^{t_w} D_0 \exp\left(-E/(k\,T_w)\right) d\tau \qquad (1),$$

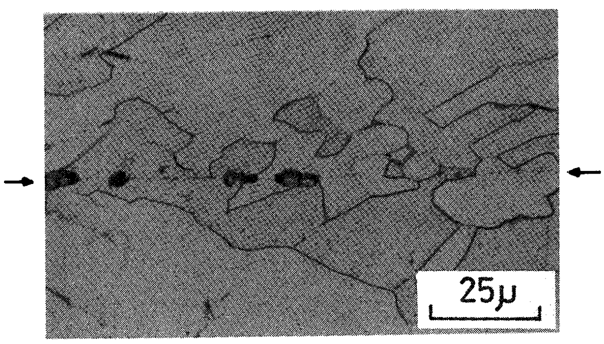
where D is the self diffusion coefficient, E the activation energy of self diffusion, D_0 constant, k the Boltzmann constant, and t_w and T_w are respectively welding time and temperature. When the welding temperature is constant, eq. (1) becomes

$$A=D\cdot t_w=D_0\cdot \exp\left(-E/(k\,T_w)\right)\cdot t_w \qquad (2).$$

Photo. 2 (a) and (b) show the microstructures of bonding zones obtained under the conditions where the value of A given by eq. (2) is nearly equal[10, 11]. As shown in the photographs, even though the value of A is nearly equal, no grain growth across the bonding interface occured in α phase region, whereas it occured in β phase regoin.



(a) T_W=870°C, t_W=600min, P_W=0.2kg/mm^2



(b) T_W=920°C, t_W=1min, P_W=0.2kg/mm^2

Photo. 2 Microstructures for the bonding zone of titanium. The welding times for (a) and (b) were selected so that the value of A given by eq. (2) were equal.

The self diffusion coefficient of iron decreases with the transformation from α to γ phase in contrast to the $\alpha \rightleftarrows \beta$ transformation of titanium. Photo. 3 (a) and (b) show the bonding zones of mild steel obtained at a welding temperature in α phase and γ phase region. The value of A for the bonding zone shown in (a) is 50 times as large as that shown in (b). At the welding temperature of 920°C grain growth occured completely across the bonding interface as shown in (b) whereas it did not occur at 850°C as shown in (a). Thus the bonding process of mild steel proceeds more rapidly in γ phase region than α phase region even though the amount of diffusion during welding is smaller. These facts indicate that the difference in the grain growth across bonding interface between α phase and β phase region can not be attributed to the difference in the amount of diffusion during welding.

It has been reported by several authors[3,4] that the $\alpha \rightleftarrows \beta$ transformation of titanium induces superplasticity. However the grain growth across the bonding interface can be accomplished by undergoing the $\alpha \rightleftarrows \beta$ transformation without the effect of the superplasticity as shown in Photo. 4. That is, Photo. 4 shows a microstructure of bonding zone obtained under the condition of zero welding pressure and the thermal cycling through the transformation temperature shown in Fig. 2, after a preliminary welding in α phase (welding temperature, pressure and time were 840°C, 0.5 kg/mm^2 and 5 min, respectively). In this case the bonding process is not considered to be influenced by the transformation-induced superplasticity because the welding pressure is zero. Nevertheless, the grain growth occured certainly across the bonding interface as shown in Photo. 4.

As shown in Photo. 5 no grain growth across bonding interface occured in α phase, even though the welding deformation (defined as a reduction in the length of base metals) was increased up to 12% by raising the welding pressure. In contrast to this in β phase region the grain growth occured completely across the bonding interface for welding deformations less than $2 \sim 4\%$ as shown in Photo. 1. These facts indicate that the grain growth across the bonding interface induced by the transformation can not be explained only by a decrease in flow stress due to the transformation-induced superplasticity. The acceleration of the grain growth across the bonding interface by the transformation may rather be explained as an effect of activated interface between α and β phase which migrates across bonding interface at the transformation.

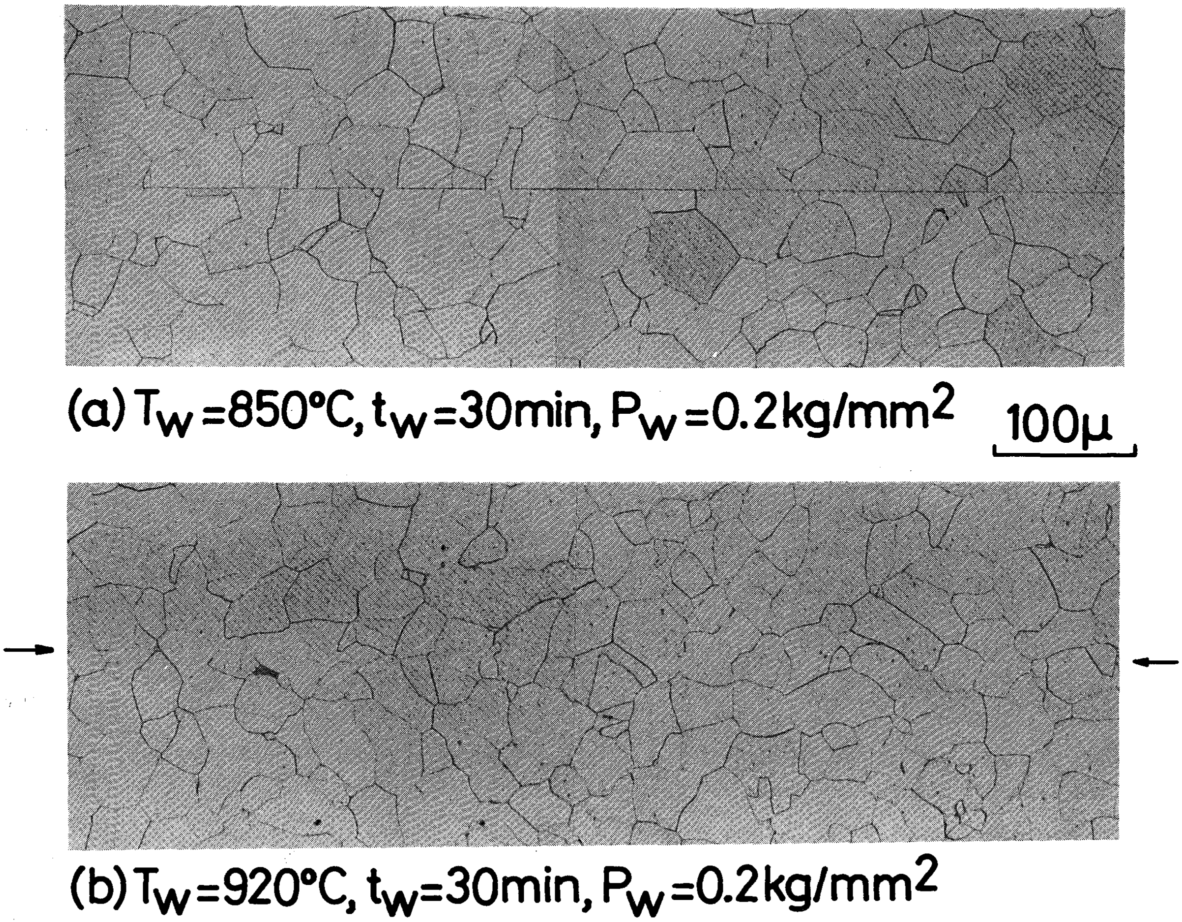
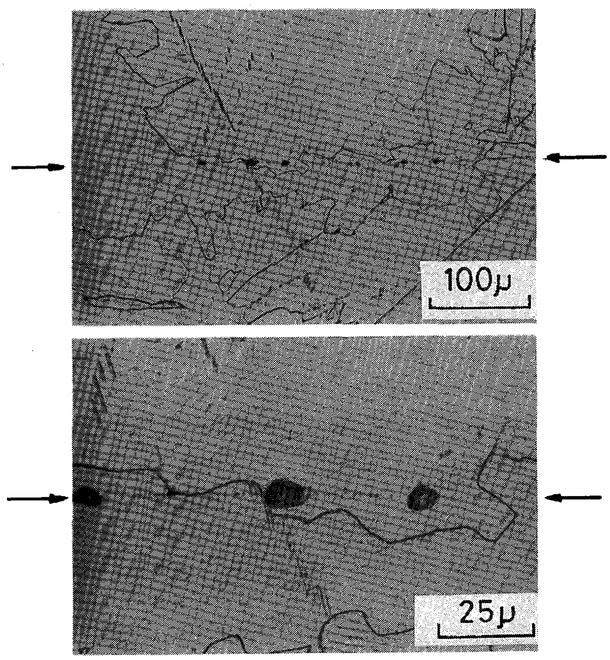


Photo. 3 Microstructures for the bonding zones of mild steel.



T_W=920°C ⇌ 845°C, t_W = 30min, P_W= 0 kg/mm^2

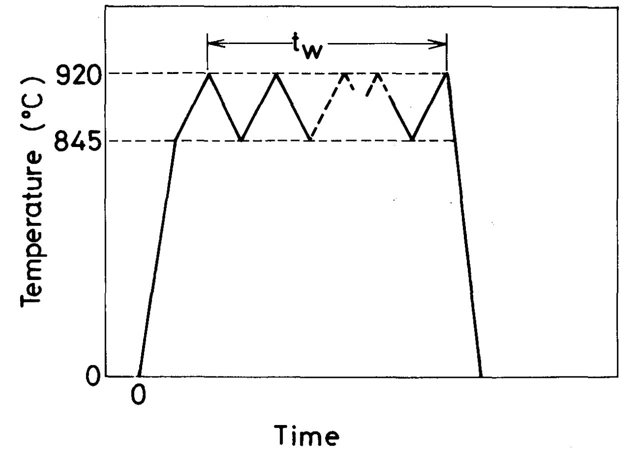


Fig. 2 Schematic diagram of welding thermal cycle.

Photo. 4 Microstructures for the bonding zone obtained under the thermal cycling shown in Fig . 2 under zero welding pressure after preliminary welding (T_W = 840°C, t_W = 5 min, P_W = 0.5 kg/mm^2). The welding time was 30 min and the number of the thermal cycle was 7.

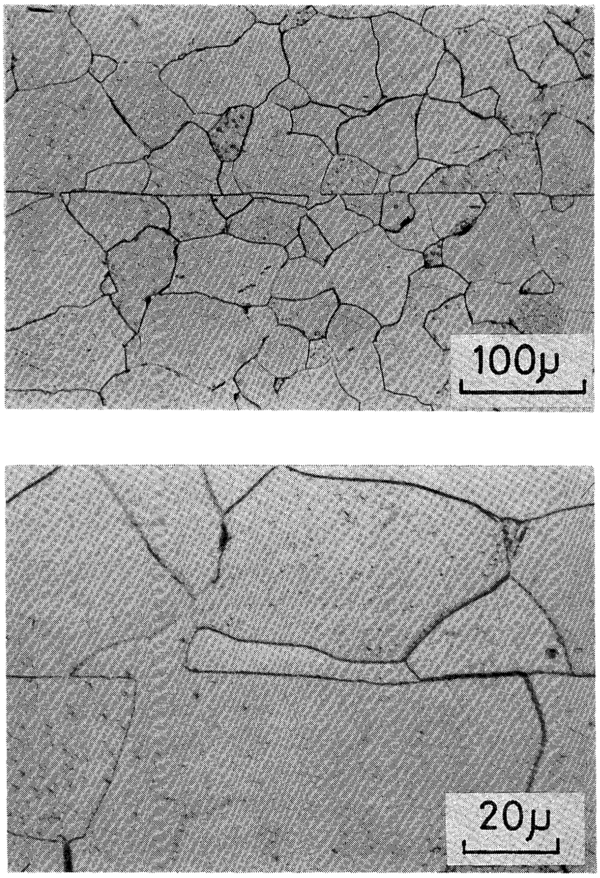


Photo. 5 Microstructures for the bonding zone of titanium. T_W, t_W and P_W were 870°C, 60 min and 0.1 kg/mm^2, respectively.

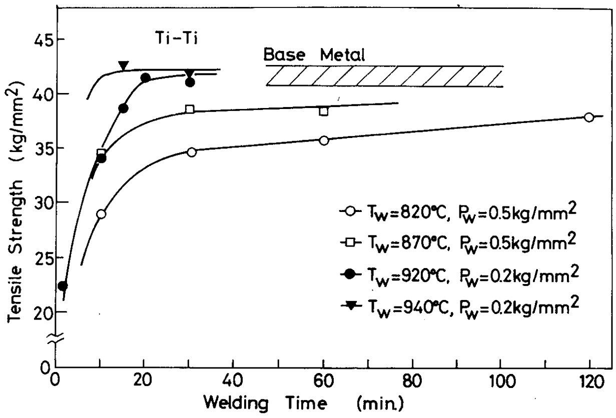


Fig. 3 Tensile strength of joint as a function of welding time at various welding temperatures and pressures.

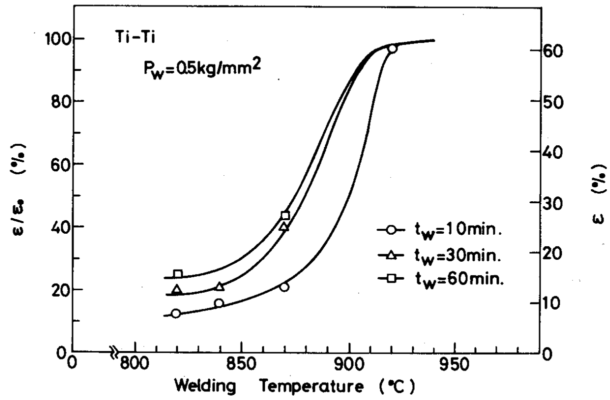


Fig. 4 Elongation of joint as a function of welding temperature.

3.2 Effect of $\alpha \rightleftarrows \beta$ Transformation on Joint Strength

Figure 3 shows tensile strength of joint as a function of welding time at various welding temperatures and pressures. As shown in the figure, the tensile strength of joint which was enough to fracture at base metal was obtained for welding times more than 20 min at 920°C above the transformation. On the other hand, joints obtained at welding temperatures below the transformation fractured at the bonding interface for the welding time of 60 min (870°C) and 120 min (820°C). Figure 4 shows the elongation of joint on tensile test as a function of welding temperature. As shown in the figure, the elongation of joint increased markedly with the rise of temperature at the $\alpha \rightleftarrows \beta$ transformation. Thus the bonding process develops more rapidly at temperatures in β phase region than those in α phase region in accord with the result described in the preceding section.

In order to examine the bonding state which caused such difference in joint strength as described above, fractured surfaces of joints obtained by tensile test was observed with a scanning electron microscope. As shown in Photo. 6, dark region and light region were observed on the fractured surface. In the dark region, grooves caused by grinding with emery paper were observed and so this is considered to correspond with region where real contact between faying surfaces is not achieved. On the other hand, in the light region where no groove could be observed, the real contact between faying surfaces is considered to be attained. Figure 5 shows a relationship between

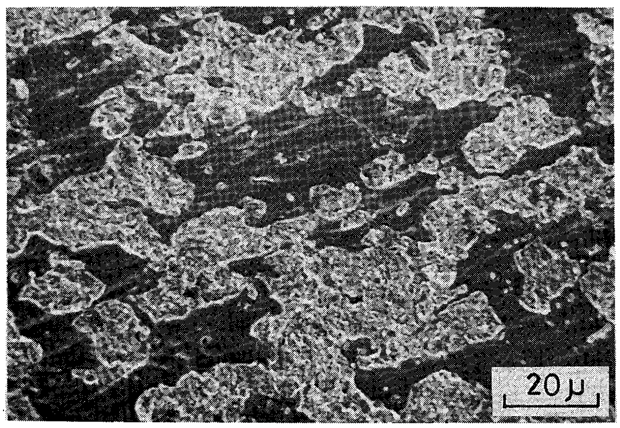


Photo. 6 Secondary electron image of a fractured surface of joint obtained from tensile test. T_W, t_W and P_W for the joint were 820°C, 10 min and 0.5 kg/mm^2, respectively.

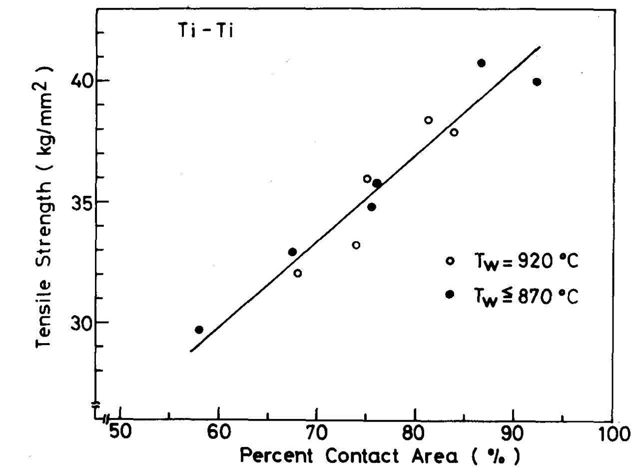


Fig. 5 Relationship between tensile strength of joint and percent contact area at bonding interface.

tensile strength of joint and percent contact area. As shown in the figure a linear relation existed between the joint strength and percent contact area independently of welding temperature. This indicates that the large increase in the joint strength by the transformation is due to the increase in real contact area at bonding interface.

In order to exactly examine the effect of undergoing the transformation on the joint strength, welding was carried out under the thermal cycling through the transformation temperature shown in Fig. 2. Figure 6 shows the elongation of joint obtained at 920°C and under the several thermal cyclings (1 cycle/5 min). At a same welding time, the amount of diffusion A for the welding at 920°C is larger than that for the welding under the thermal cycling since the diffusion coefficient of β phase is higher than that of α phase. As shown in the figure, the

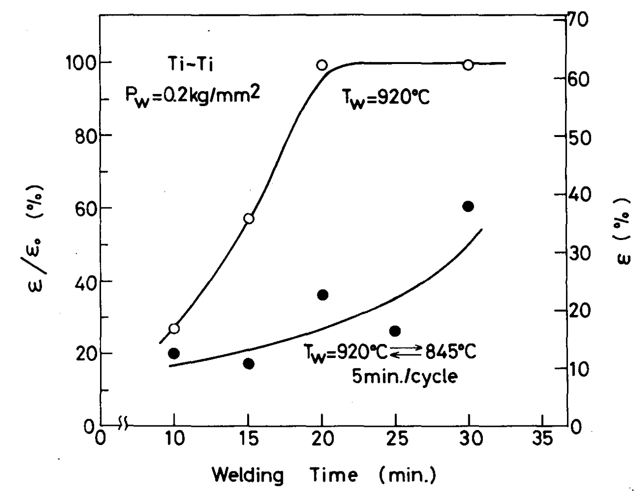


Fig. 6 Elongation of joint as a function of welding time for joints obtained at the constant temperature of 920°C and under thermal cycling through the transformation temperature shown in Fig. 2.

elongation of joint at the welding temperature of 920°C was larger than that obtained under the thermal cycling. The difference between them was small for comparatively short welding times, but increased as the welding time increased. This fact suggests that the effect of the difference in the amount of diffusion on the real contact area can be compensated with undergoing the transformation for early process of welding, but it becomes more difficult as the welding time increases. That is, the increase in real contact area in early process of welding is promoted by undergoing the transformation.

Peterson[2] has suggested that the self diffusion of titanium is much enhanced by undergoing the transformation. If such enhancement of self diffusion by the transformation is important for the bonding process, the whole bonding process is influenced effectively by undergoing the transformation in contrast to the result shown in Fig. 6. That is, the self diffusion plays an important role rather in later process of bonding such as the annihilation of microvoid[1]. Consequently, the enhancement of self diffusion by the transformation is not considered as an important factor for the increase in real contact area due to undergoing the transformation.

Figure 7 shows the variation of joint strength with the number of thermal cycle (the welding time and pressure

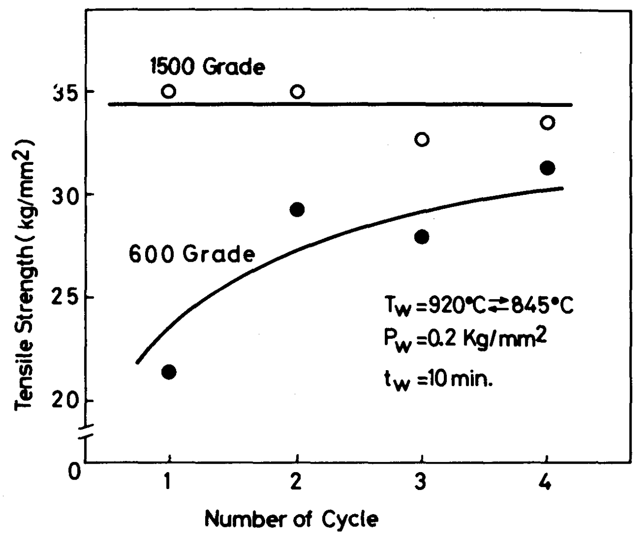


Fig. 7 Tensile strength of joint as a function of the number of thermal cycle shown in Fig. 2. The faying surfaces were finished by grinding with 1500 grade (——○——) and 600 grade emery paper (——●——).

were kept to be constant). As shown in the figure, the joint strength did not increase with the rise of the number of thermal cycle when the faying surfaces were finished by grinding with 1500 grade emery paper. On the other hand, when the faying surfaces were finished by grinding with 600 grade emery paper, the joint strength increased with the increase in the number of thermal cycle. That is, the increase in real contact area is promoted more effectively by undergoing the transformation as the faying surface becomes rougher. As described above, the effect of undergoing the transformation was valid rather in early process of welding. These facts suggest that the initial accomodation at bonding interface which requires the deformation of microasperities on faying surfaces is accelerated by undergoing the transformation. The acceleration of the accomodation at bonding interface can be explained by the transformation-induced superplasticity that permits the deformation of microasperities at lower flow stress.

4. Summary

The effect of $\alpha \rightleftarrows \beta$ transformation on the diffusion welding of titanium was investigated chiefly by the observation of microstructure for the bonding zone and tensile test of joint. Welding in vacuo was carried out at a constant welding temperature in α or β phase region, or under thermal cycling through the transformation temperature. The results obtained are summarized as follows:

(1) Grain growth across bonding interface was accomplished much more rapidly at welding temperatures in β phase region than in α phase, and accelerated by undergoing the transformation during welding. These effects of the transformation on the grain growth can not be attributed to the difference in the diffusion coefficient between α and β phase, or to the transformation-induced superplasticity.

(2) Joint strength increased more rapidly at welding temperatures in β phase region than in α phase region. The difference in the joint strength is ascribed to the difference in real contact area at bonding interface.

(3) Increase in joint strength in the early process of welding was accelerated by undergoing the transformation during welding. This result is accounted for by the effect of the transformation-induced superplasticity that permits more rapid initial accomodation at bonding interface.

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