# Effect of the Roughness of Faying Surface on the Early Process of Diffusion Welding†

## — Study of the Early Process of Diffusion Welding by Means of the Electric Resistance Measurement (Report Ⅱ) —

by

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**Abstract**

*The early process of diffusion welding of aluminum, titanium and copper whose faying surfaces have been finished by polishing with emery paper of various grades (600 ~ 1500) have been investigated with the electric resistance measurement. A couple of the base metal was brought into contact in a vacuum and the electric resistance across the bonding interface was measured while the couple was heated at the rate of 15°C/min. The obtained electric resistance in the heating process is analysed by using the contact parameter $W(= n \cdot S_M/S)$ which is derived on the basis of the constriction resistance theory. Here $S_M$ is the total area of metal-to-metal contact spots, n their number per a unit area and S the apparent contact area.*

*For all the bonding process of aluminum, titanium and copper, the electric resistance across the bonding interface decreased in its initial value and approached the resistivity of the base metal more rapidly in the heating process as the faying surface became roughened. According to an analysis based on the constriction resistance theory, the contact parameter in the heating process for all the base metals increased with roughening the faying surface.*

*These results indicate that the disruption of oxide film on the faying surface, which prevents the formation of the metal-to-metal contact (as reported in a previous paper), is promoted and so the area and/or number of metal-to-metal contact spots increase as the faying surface becomes roughened. This fact can be accounted for by the model that the deformation of micro-asperities on the faying surface leads to the disruption of oxide film and the degree of the deformation increases as the faying surface becomes roughened.*

**KEY WORDS:** (Diffusion Welding) (Surface Preparation) (Contact Resistance) (Aluminum) (Titanium) (Copper)

## 1. Introduction

It was shown in a previous paper[1)] that the oxide film on the faying surface is a most important factor preventing the formation of metal-to-metal contact in the early process of diffusion welding. The roughness of faying surface has been regarded as another important factor affecting the bonding process by several authors[2,3)]. In the present investigation, the effect of the roughness of faying surface on the early process of diffusion welding has been examined using the electric resistance measurement as described in the previous paper[1)]; a couple of base metals whose faying surfaces were finished with emery paper of various grades were brought into contact at a given welding pressure in a vacuum and the electric resistance across the bonding interface was measured in the heating process of the couple from room temperature. Base metals used were aluminum, titanium and copper. The oxide films of aluminum and titanium are very stable, while that of copper is not so stable as aluminum and titanium. The effect of the faying surface roughness on the variation of the electric resistance is analysed on the basis of the constriction resistance theory.

## 2. Experimental Details

Base metals used were commercially pure aluminum, titanium and copper whose chemical compositions were the same as those reported in the previous paper[1)]. The dimensions of the base metal and the welding procedure were also the same as those reported in the previous paper[1)].

In order to investigate the effect of the roughness of the faying surface on the bonding process, the faying surface was finished by grinding on emery paper of 600, 800 and 1500 grade. **Table 1** shows parameters of the roughness of aluminum faying surfaces where $H_{max}$ and $H_{ave}$ are the maximum and mean height of

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Table 1 Parameters of the roughness of aluminum faying surfaces finished by polishing with emery paper of various grades, where $N$, $H_{max}$ and $H_{ave}$ denote the number of micro-asperities per a unit length, the maximum and average height of the micro-asperities, respectively.

| Grade of Emery Paper | $N(cm^{-1})$ | $H_{max}(\mu m)$ | $H_{ave}(\mu m)$ |
|---|---|---|---|
| 1500 | 670 | 1.1 | 0.34 |
| 800 | 545 | 1.3 | 0.40 |
| 600 | 490 | 2.6 | 0.71 |

micro-asperities and $N$ is the number of micro-asperities per a unit length. As the faying surface becomes finer (the grade of emery paper increases), the height of micro-asperities ($H_{max}$ and $H_{ave}$) decreases and their number per a unit length ($N$) increases. The height and number of micro-asperities on the titanium and copper faying surfaces depend on the roughness similarly to those of the aluminum faying surface. The electric resistance measurement was carried out using the conventional potentiometric method as reported in the previous paper[1].

## 3. Results and Discussion

### 3.1 Effect of the roughness of faying surface on the bonding process of aluminum

A couple of aluminum base metals were brought into contact in a vacuum at the welding pressure of 0.2kg/mm$^2$ and then heated from room temperature to 640°C at the rate of 15°C/min. **Figure 1** shows the effect of the faying surface roughness on the variation of the electric resistance $\rho$ across the bonding interface in the heating process. In this figure, the electric resistance $\rho$ in the cooling process after the heating up to 640°C is also shown. The electric resistance $\rho$ in this cooling process was nearly equal to the resistivity of the base metal within experimental error(±10%) as reported in the previous paper[1]. As shown in the figure, the initial value of the electric resistance $\rho$ decreased as the faying surface became rougher. And the variation of the electric resistance $\rho$ in the heating process was influenced remarkably by the roughness of the faying surface; when the roughened faying surface was used, the electric resistance $\rho$ decreased remarkably in the temperature range from room temperature to 220°C where no decrease in $\rho$ was observed when the fine faying surface was used. In case where the roughened faying surface was used, the variation of the electric resistance $\rho$ with temperature can be divided into

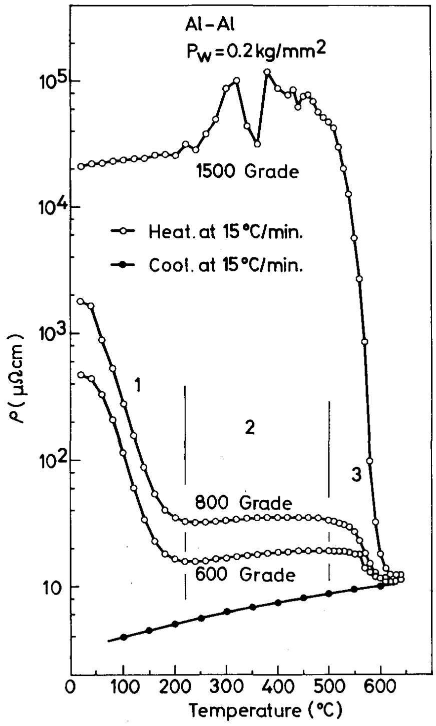


Fig. 1 Variation of electric resistance $\rho$ across the bonding interface of aluminum with temperature in the heating process(—○—) of the bonding interface and in the cooling process (—●—) after the heating process up to 640°C. The faying surfaces were finished by polishing with emery paper of 1500, 800 and 600 grade. The heating and cooling rate were 15°C/min, and the welding pressure $P_w$ was 0.2kg/mm$^2$.

three stages as shown in Fig. 1; stage 1 from room temperature to 220°C where the electric resistance $\rho$ decreased largely, stage 2 from 220°C to 500°C where $\rho$ hardly decreased and stage 3 from 500°C to 630°C where $\rho$ decreased largely. In case where the fine faying surface was used, large decrease in $\rho$ was observed only in stage 3.

In the bonding process of aluminum, the oxide film on the faying surface interferes with the formation of metal-to-metal contact as reported in the previous paper[1]. Thus it is not necessarily clear from what stage the metal-to-metal contact occurs. In order to make clear the existence of the metal-to-metal contact in the temperature ranges of stage 1, 2, and 3, the dependence of the electric resistance $\rho$ on temperature was investigated in cooling processes subsequent to the heating process up to the temperature range of stage 1, 2 and 3. As shown in **Figs. 2** and **3**, the electric resistance $\rho$ in all the cooling processes from stage 1, 2 and 3 decreased with decreasing temperature. In the heating process of the bonding interface, the increase in contact area or the disruption of oxide film may occur, but in the cooling process such change in the

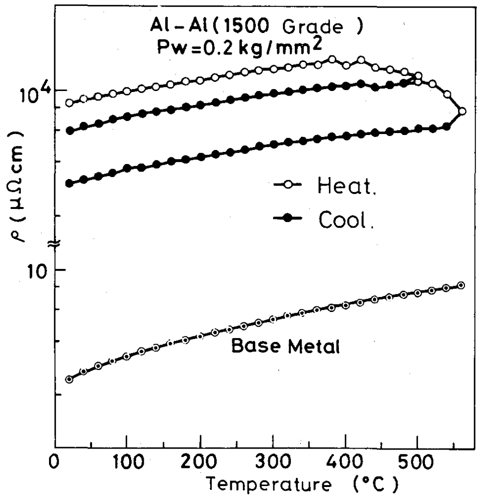


Fig. 2 Temperature dependence of the electric resistance $\rho$ of aluminum in cooling processes (—●—) of the bonding interface after heating (15°C/min) up to the temperature range of stage 3. The faying surfaces were finished with emery paper of 1500 grade. The resistivity of the base metal is also shown (—⊙—).

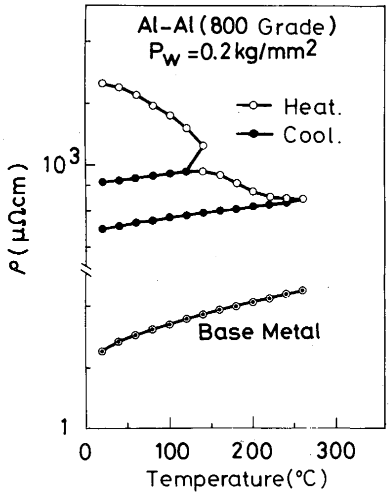


Fig. 3 Temperature dependence of the electric resistance $\rho$ of aluminum in cooling processes of the bonding interface after heating (15°C/min) up to the temperature ranges of stage 1 and 2. The faying surfaces were finished with emery paper of 800 grade.

contact state will not occur at temperatures much lower than the starting temperature of the cooling process. Therefore in the cooling process, if the metal-to-metal contact does not exist, the dependence of electric resistance $\rho$ on temperature will be determined by the resistivity of the oxide film; the electric resistance across the bonding interface will increase with decreasing temperature since the resistivity of the aluminum oxide decreases with the rise of temperature[4]. Clearly, this is in conflict with the results shown in Figs. 2 and 3.

On the other hand, when the metal-to-metal contact exists and the electric resistance across the bonding interface is caused by the constriction resistance $\rho_C$ at metal-to-metal contact spots, the electric resistance $\rho$ is given approximately by[1]:

$$\rho=\rho_C+\rho_M \tag{1}$$

$$=\left(\frac{\sqrt{\pi}}{2}\sqrt{\frac{S}{n\cdot S_M}}+1\right)\rho_M$$
$$=\left(\frac{\sqrt{\pi}}{2}W^{-\frac{1}{2}}+1\right)\rho_M, \tag{2}$$

where

$$W=n\cdot S_M/S. \tag{3}$$

Here $\rho_M$ is the resistivity of base metal, $S_M$ the total area of metal-to-metal contact, $S$ the apparent contact area (cross-sectional area of base metal), and $n$ the number of metal-to-metal contact spots per a unit area. In this case, the electric resistance $\rho$ is proportional to the resistivity of base metal as given by eq. (2). Therefore in the cooling process the electric resistance $\rho$ will decrease with decreasing temperature similarly to the resistivity of base metal. Such temperature dependence of the electric resistance $\rho$ is consistent with the results shown in Figs. 2 and 3. Consequently, it can be concluded that the metal-to-metal contact spot exists in the temperature range of stage 1, 2 and 3. And the electric resistance across the bonding interface is considered to be caused by the constriction resistance at the metal-to-metal contact spot.

In order to examine the variation of area or number of metal-to-metal contact spots in the heating process, the temperature dependence of the electric resistance $\rho$ shown in Fig. 1 is analysed using the contact parameter $W$ given in eq. (2). If the electric resistance across the bonding interface is caused by only the constriction resistance, the contact parameter $W$ is proportional to the area or number of metal-to-metal contact spots per a unit area as given by eq. (3). As described in the previous paper[1], the experimental value of contact parameter (estimated from the experimental electric resistance $\rho$ using eq. (2) ) gives the upper limit to the true value of ( $n\cdot S_M/S$ ).

**Figure 4** shows the variation of contact parameter $W$ in the heating process. When the roughened faying surface was used, large increase in the contact parameter was observed in stage 1, but in stage 2 the increase in $W$ was much smaller. Thus metal-to-metal contact spot increased largely in its area and number in stage 1, while in stage 2 their increase was much smaller. As the faying surface became finer, the contact parameter decreased in its initial value and the increment of the contact parameter in the temper-

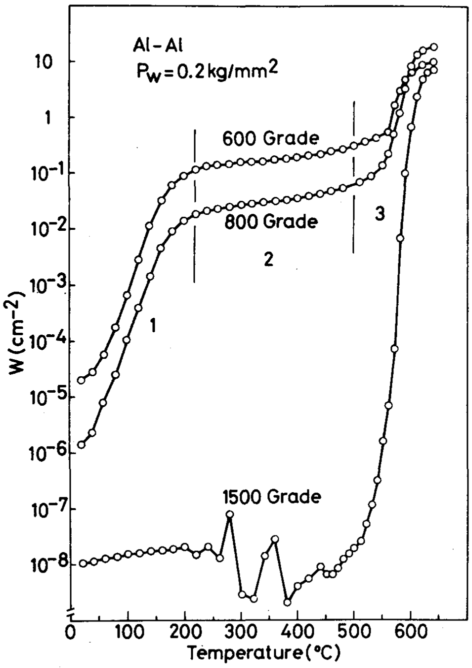


**Fig. 4** Variation of the contact parameter $W$ of aluminum bonding interface estimated from $\rho$ shown in Fig. 1.

ature range of stage 1 became smaller.

The total contact area to bear a given welding pressure (including the contact spot where the contact occurs between the oxide film) does not depend on the roughness of faying surface. As the faying surface becomes roughened, the number of total contact spots will decrease since the number of micro-asperities decreases as shown in Table 1. On the other hand, the area or number of metal-to-metal contact spots increased with roughening the faying surface as shown in Fig. 4. As pointed out in the previous paper[1], the oxide film on the faying surface is a most important factor interfering with the formation of metal-to-metal contact. These facts indicate that the disruption of the oxide film which results in the formation of metal-to-metal contact is promoted as the faying surface becomes roughened.

In order to investigate the mechanism of the disruption of the oxide film, the faying surface was observed with scanning electron microscope after the bonding interface was heated to the temperature range of stage 1 and 2. **Figure 5** shows the faying surfaces finished with emery paper of 600 grade. As shown in this figure, dark bands which intersect the grooves caused by grinding on emery paper were observed on the faying surfaces subjected to the heating process up to stage 1 and 2. In the diffusion welding of the present investigation, the base metals were so arranged that the grooves on the faying surfaces intersected at nearly right angle with each other.

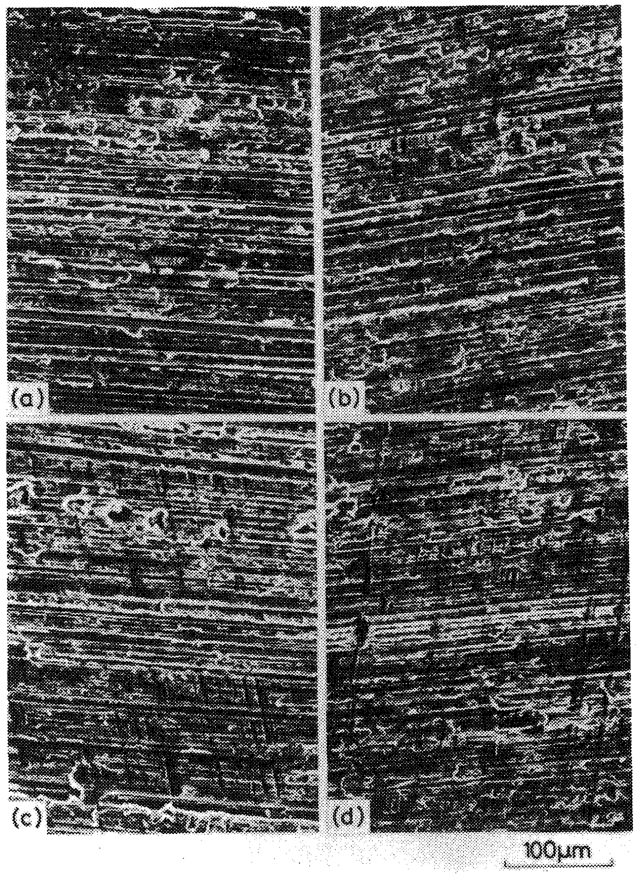


**Fig. 5** Change in the morphology of aluminum faying surfaces (finished with 600 grade emery paper) which was caused by the heating of the bonding interface up to 160°C(b), 220°C(c) and 460°C(d) at the welding pressure of 0.2kg/mm$^2$ (as-polished(a) ).

Therefore the dark bands observed on the faying surface are regarded as the region where micro-asperities are deformed by virtue of being micro-asperities on the other faying surface, i.e., the contact region. As shown in Figs. 5(b) and (c), the number and area of the contact region increased with the rise of temperature in stage 1. On the other hand, the contact region was hardly increased in stage 2. These changes in the number and area of the contact region agree well with those of metal-to-metal contact spots derived from the electric resistance measurement. These facts indicate that in stage 1 the deformation of micro-asperities on the faying surface causes the disruption of the oxide film which results in the formation of metal-to-metal contact. This conclusion is supported by the fact that the increment of the contact parameter in stage 1 increased as the faying surface became roughened. On the other hand, in stage 2, the area or number of metal-to-metal contact spots is not considered to increase remarkably because the degree of the deformation of micro-asperities scarecely increases.

### 3.2 Effect of the roughness of faying surface on the bonding process of titanium

A couple of titanium base metals were brought into contact at the welding pressure of 0.1kg/mm$^2$ and heated in a vacuum from room temperature to 1000°C at the rate of 15°C/min. **Figure 6** shows the effect of the faying surface roughness on the variation of the electric resistance $\rho$ across the bonding interface in the heating process. In this figure, the electric resistance $\rho$ in the cooling process after the heating process up to 1000°C is also shown. As described in the previous paper[1], the electric resistance $\rho$ in this cooling process is nearly equal to the resistivity of the base metal within experimental error. As shown in this figure, the electric resistance across the bonding interface decreased in its initial value as the faying surface became roughened. In contrast to the bonding process of aluminum, no new stage was observed in the bonding process of titanium when the roughened faying surface was used. The decrement of the electric resistance $\rho$ in stage 1 became much smaller as the faying surface became roughened. On the other hand, the roughness of faying surface had little effect on the variation of the electric resistance $\rho$ in stage 2 and 3.

In order to make clear the existence of the metal-to-metal contact, the temperature dependence of the electric resistance $\rho$ was investigated in cooling processes as mentioned in §3.1. **Figure 7** shows the electric resistance $\rho$ as a function of temperature in the cooling process from the temperature range of stage 1 and 2. As shown in this figure, in the cooling process from the temperature range of stage 1, the electric resistance across the bonding interface increased with decreasing temperature similarly to the resistivity of the titanium oxide[5]. This result indicates that the electric resistance $\rho$ in stage 1 is influenced significantly by the resistivity of the oxide film. On the other hand, in the cooling process from the temperature range of stage 2, the electric resistance $\rho$ decreased with decreasing temperature. This indicates that the metal-to-metal contact forms in stage 2.

The fact that the electric resistance $\rho$ of titanium is influenced more significantly by the resistivity of the oxide film than that of aluminum can be interpreted as follows: The resistivity of the titanium oxide is much lower than that of the aluminum oxide while the resistivity of the titanium base metal is about ten times as large as that of the aluminum as shown in Figs. 1 and 6. Therefore even if the thickness of the oxide film is equal and the contact state in the bonding interface is the same, the electric currents which flow the contact spot including the oxide film is larger in the titanium bonding interface than in the aluminum. Consequently, the electric resistance across the bonding interface of titanium is influenced more significantly by the resistivity of the oxide film compared with that of aluminum.

In order to examine the change in the area and number of metal-to-metal contact spots, the variation of electric resistance $\rho$ shown in Fig. 6 is analysed by using the contact parameter $W$ as described in §3.1.

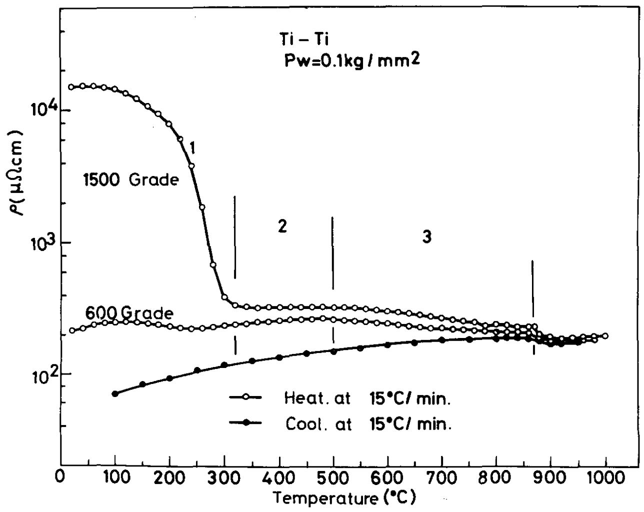


**Fig. 6** Variation of the electric resistance $\rho$ of titanium with temperature in the heating process of the bonding interface. The faying surfaces were finished by polishing with 1500 and 600 grade emery paper.

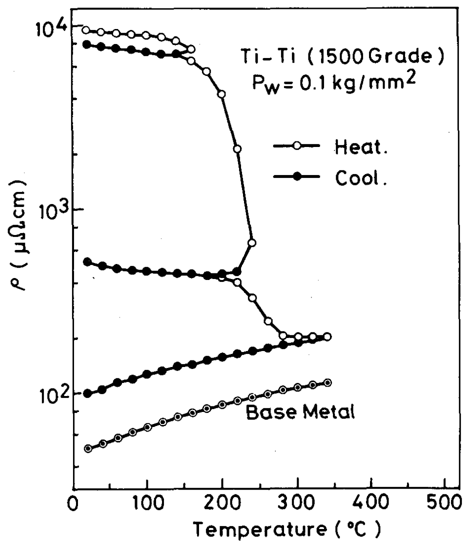


**Fig. 7** Temperature dependence of the electric resistance $\rho$ of titanium in cooling processes of the bonding interface after heating (15°C/min) up to the temperature ranges of stage 1 and 2. The faying surfaces were finished by polishing with 1500 grade emery paper.

**Figure 8** shows the contact parameter as a function of temperature. As shown in this figure, the contact parameter at room temperature and in the heating process increased as the faying surface became roughened. Because the electric resistance $\rho$ is influenced significantly by the oxide film, the contact parameter $W$ estimated from the electric resistance $\rho$ overestimates the area and number of metal-to-metal contact spots. However, as described in §3.1, the total contact area (including the contact spot where the contact occurs between the oxide films) should not increase as the faying surface becomes roughened. Consequently, unless the area and/or number of metal-to-metal contact spots increase, the contact parameter $W$ will not increase as the faying surface becomes roughened; accordingly in the bonding process of titanium the disruption of the oxide film is promoted and so the metal-to-metal contact increases as the faying surface becomes roughened.

The change in the morphology of the faying surface which arised in the heating process of the bonding interface was investigated with SEM. As shown in **Fig. 9**, the faying surface of titanium (finished with emery paper of 600 grade) was almost unchanged by the heating process up to 500°C. On the other hand, as shown in Figs. 4 and 8, the contact parameter $W$ in stage 1 and 2 of titanium is about two orders of magnitude larger than that of aluminum. These results suggest that the degree of the deformation of micro-asperities to disrupt the oxide film is much smaller in the titanium bonding process than in the aluminum or the contact parameter of titanium shown in Fig. 8 overestimates largely the area and number of metal-to-metal contact.

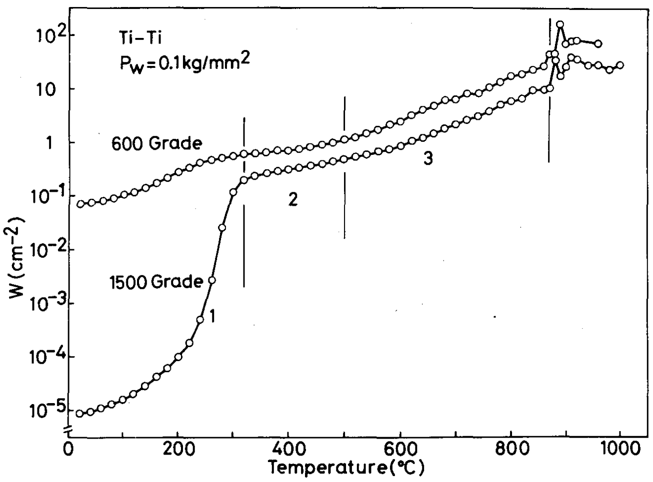


**Fig. 8** Variation of the contact parameter $W$ of the titanium bonding interface estimated from $\rho$ shown in Fig. 6.

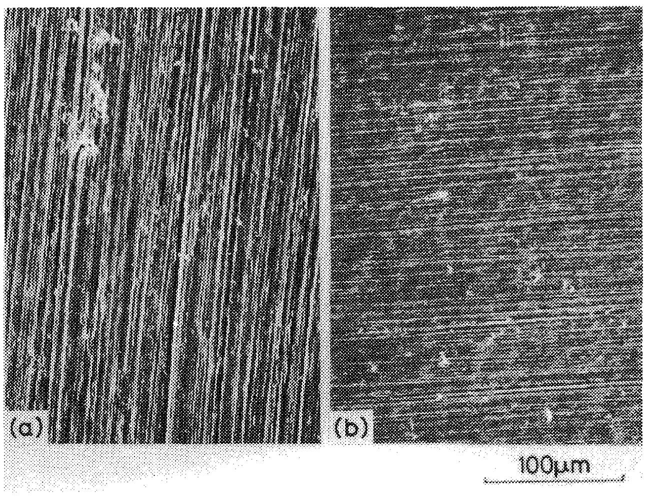


**Fig. 9** Titanium faying surfaces (finished by polishing with 600 grade emery paper) in the as-polished state(a) and after the heating of the bonding interface up to 500°C(b) at the welding pressure of $0.1kg/mm^2$.

### 3.3 Effect of the roughness of faying surface on the bonding process of copper

**Figure 10** shows the variation of the electric resistance $\rho$ across the bonding interface of copper in the heating process as described in §3.1 (heating rate $= 15°C/min$, welding pressure $= 0.2kg/mm^2$). As shown in this figure, the electric resistance $\rho$ decreased in its initial value and approached the resistivity of the base metal at lower temperature as the faying surface became roughened.

In order to make clear the existence of the metal-to-metal contact, the temperature dependence of the electric resistance $\rho$ was investigated in cooling processes subsequent to the heating process up to stage 1, 2 and 3. **Figure 11** shows the variation of the electric resistance $\rho$ in the cooling process in case where the faying surface was oxidized in air for 20min at 220°C after the finishing with emery paper of 1500 grade. As shown in this figure, the electric

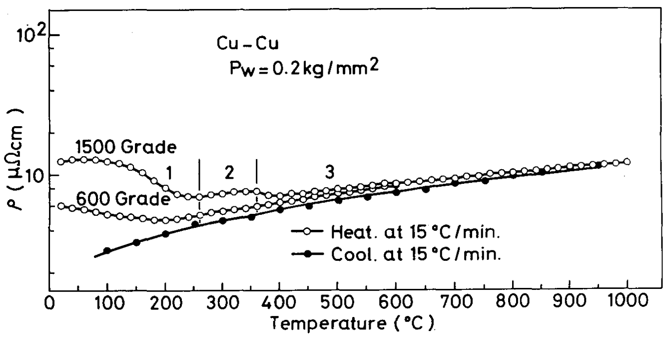


**Fig. 10** Variation of the electric resistance $\rho$ of copper in the heating process of the bonding interface. The faying surfaces were finished with 1500 and 600 grade emery paper.

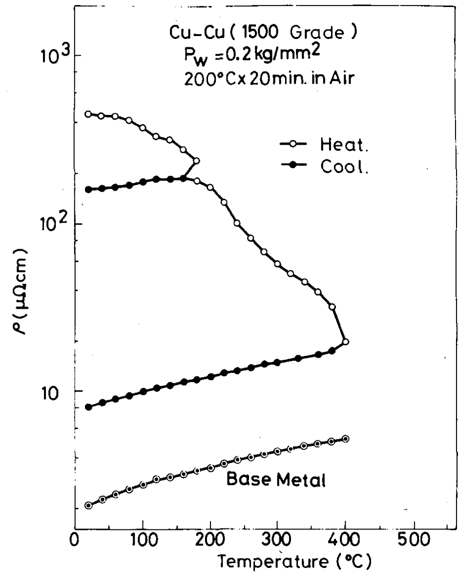


**Fig. 11** Temperature dependence of the electric resistance $\rho$ of copper in cooling processes of the bonding interface after the heating up to the temperature ranges of stage 1 and 3. The faying surfaces were oxidized in air at 200°C for 20min after polishing with 1500 grade emery paper.

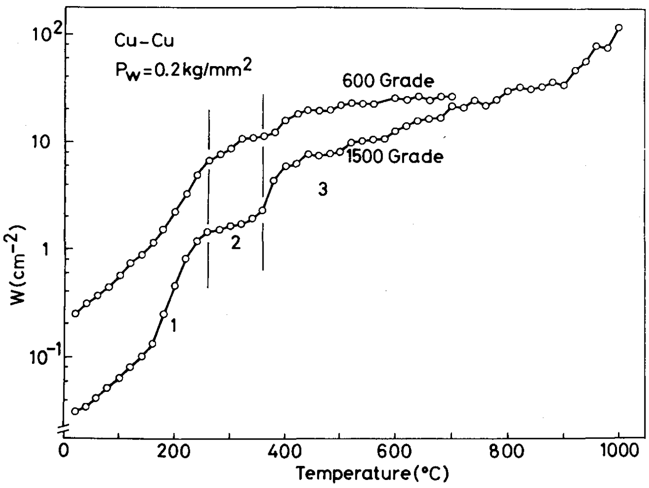


**Fig. 12** Variation of the contact parameter $W$ of the copper bonding interface estimated from $\rho$ shown in Fig. 10.

resistance $\rho$ in the cooling processes decreased with decreasing temperature, even though the thickness of the oxide film was increased by the oxidation treatment. This result indicates that the metal-to-metal contact spot exists in the bonding interface and the electric resistance across the bonding interface is mainly caused by the constriction resistance at metal-to-metal contact spots[6].

**Figure 12** shows the variation of the contact parameter $W$ of copper obtained from the electric resistance $\rho$ shown in Fig. 10. As shown in this figure, the increase in the contact parameter was accelerated as the faying surface became roughened.

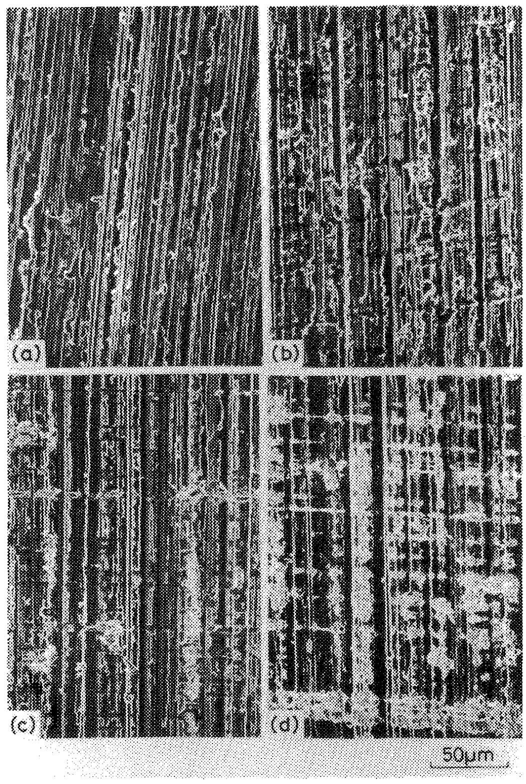


**Fig. 13** Change in the morphology of copper faying surfaces (finished with 600 grade emery paper) which was caused by the heating of bonding interfaces up to 260°C(b), 360°C(c) and 450°C(d) at the welding pressure of 0.2kg/min$^2$ (as-polished(a) ).

The change in the morphology of the faying surface which arised in the heating process of the bonding interface was investigated with SEM for comparison with the variation of the contact parameter $W$. **Figure 13** shows the faying surfaces (finished with emery paper of 600 grade) after the heating process up to the temperature range of stage 1,2 and 3. As shown in Fig. 13(b), many dark bands where micro-asperities were deformed were observed on the faying surface after the heating process up to the final temperature of stage 1(260°C). These dark bands are regarded as contact regions similarly to those observed on the aluminum faying surface (see Fig. 5). When the bonding interface was heated up to the final temperature of stage 2(360°C), the contact region hardly increased compared with those on the faying surface heated to 260°C as shown in Figs. 13(b) and (c). On the other hand, after the heating process up to the temperature range of stage 3, light bands which exhibited a dimpled appearance were observed as shown in Fig. 13(d). These light bands are considered to be the region where strong bonds are attained. As described in the previous paper[1], the initiation of stage 3 is related to the reverse reaction of the eutectoid reaction ($Cu_2O \rightarrow Cu + CuO$) or the change in the temperature dependence of electric properties of the oxide film which occurs at temperatures around 375°C. These facts indicate that the reaction or the change in the temperature dependence of electric properties of the oxide film initiates the increase in the metal-to-metal contact and the bonded region in stage 3. The variation of the contact parameter shown in Fig. 12 is considered to be related to these changes in the contact state observed with SEM.

Thus in the early bonding process of aluminum, titanium and copper, the area and/or number of metal-to-metal contact spots are increased as the faying surface becomes roughened. As described in §3.1, this means that the disruption of the oxide film is promoted by the deformation of micro-asperities as the faying surface becomes roughened. This result can be explained as follows: As the faying surface becomes roughened, the number of contact spots becomes smaller since the number of micro-asperities per a unit length decreases as shown in Table 1. Consequently, the pressure exerted on each contact spot at a given welding pressure is increased as the faying surface becomes roughened. This increase in the pressure exerted on a contact spot increases the degree of the deformation of micro-asperities at the contact spot and promotes the disruption of the oxide film.

Thus the deformation of micro-asperities results in the increase in the metal-to-metal contact. On the other hand, the micro-asperity on the faying surface causes the formation of voids at the bonding interface and so the void increases in size as the faying surface becomes roughened. Therefore the roughness of the faying surface should be selected after consideration of these two effects of the micro-asperity on the bonding process.

## 4. Summary

The effect of the faying surface roughness on the early process of diffusion welding has been investigated with the measurement of electric resistance across the bonding interface; a couple of base metals which were brought into contact at a given welding pressure were heated from room temperature at a constant rate and the electric resistance across the bonding interface was measured in the heating process. The base metals used were aluminum, titanium and copper, and their faying surfaces were finished with emery paper of various grades. The electric resistance across the bonding interface was analysed using the contact parameter $W$ derived on the basis of the constriction resistance theory ($W$ increases with increase in the area or number of metal-to-metal contact spots per a unit area). The results obtained are summarized as follows:

(1) In the bonding process of aluminum, titanium and copper, the contact parameter at room temperature and in the heating process increased as the faying surface became roughened. Particularly, in the bonding process of aluminum, a large increase in the contact parameter was observed in the temperature range from room temperature to 220°C(stage 1) where the contact parameter hardly increased when the fine faying surface was used.

(2) The results described in (1) indicate that the disruption of the oxide film and the formation of the metal-to-metal contact in the early bonding process are promoted as the faying surface becomes roughened; the degree of the deformation of micro-asperities which results in the disruption of the oxide film increases with roughening the faying surface. The oxide film of aluminum is so tenacious that its disruption requires much more amount of the deformation of micro-asperities compared with those of titanium and copper.

(3) In the bonding process of titanium, the electric resistance of contact spots where the contact occurs between the oxide film has more effect on the electric resistance across the bonding interface than in the bonding process of aluminum and copper.

(4) As described in (2), the disruption of the oxide film is promoted with roughening the faying surface, while micro-asperities on the faying surface cause the formation of voids at the bonding interface. Therefore the roughness of the faying surface should be selected after consideration of these two effects of the micro-asperity on the bonding process.

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