Evaluating Strength of Adhesive Interface between Metal and Resin in Resin-Molded Structures*

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Abstract
For the stabilization of insulation performance in resin-molded insulators, strong adhesion between the resin and metal is required. In this paper, the influence of surface roughness on the interfacial strength between the resin and metal was investigated. Test pieces were made by covering Cu and SUS cylinders, which had varying for surface roughness, with epoxy resin. The interfacial strength was evaluated with shearing tests on these test pieces. The effective adhesive surfaces of those cylinders were evaluated from surface observation with a laser microscope. The interfacial strength increased with surface roughness. The adhesion-strength index ($\mu+\delta$), which was proposed in our previous paper, was calculated with the effective adhesive surface and the interfacial strength. The adhesion-strength index gave a constant value with various surface roughnesses for each metal.

Key words: Resin-Molded Structure, Bonded Interface, Debonded Interface, Surface Roughness, Adhesive

1. Introduction
Insulators such as insulating vessels are widely used in electrically powered devices(1) (2). These insulators are fabricated from molding resins used with insert materials such as metals and ceramics. Depending on the combination of insert materials and resins, cracks and interface debonding may occur at the edge of their interface, where stress is concentrated because of the difference in the thermal contraction between the insert material and resin. The metal-resin interface influences the stress concentration caused by the hardening shrinkage during molding less than it does for the ceramic-resin interface, because the difference in thermal expansion is small.

However, the metal-resin interface may debond under lower external load than the ceramic-resin interface, because the former has higher contact pressure, which is caused by residual stress of molding, than the latter has. Due to these phenomena, a cavity is formed, and the insulation performance of the resin-molded insulators decreases because air and moisture that permeate the resin and the residual substance through the hardening reaction fill the cavity. Thus, to ensure stable insulation performance, cracks in the internal interface between the resin and the insert material must be prevented, as well as debonding.

Through adhesion tests, transmission electron microscopy, and other techniques, micro- and nano-scale evaluation and fracture mechanics have been performed recently to achieve an increase in the interface adhesion strength (3)-(9).

In our previous paper (10)-(12), methods were reported that improve the interface adhesion strength of resin in order to prevent stress concentration at the interface between...
resins and ceramics with a large heat contraction difference. A molecular dynamics simulation was used to thermochemically model including the orientation and bonding of the interface. The interface reforming was modeled with a coupling agent, which improved the interface adhesive strength by changing the functional groups of the interface processing agent according to the chemical structure of the resin. The interfacial fracture energy obtained from the simulation was consistent with the adhesive strength index, (μ + B), obtained from the interface adhesion test, where μ is the coefficient of friction and B is the adhesion coefficient. Thus, it was proposed that this method could be used to predict the strength of the adhesive bonding of the metal/resin interface qualitatively.

Additionally, for the metal-resin interface of the resin-molded structure, it is necessary to improve the strength of the adhesive bonding of the interface in order to prevent interface debonding. However, the interface strength also depends on the surface roughness; increasing the roughness of the metal surfaces is known qualitatively to improve the interface strength. However, it is important to evaluate the relationship between the surface roughness and the interface strength quantitatively in order to use this method commercially. The effect of the surface roughness on the strength of the metal-resin interface could be estimated by using the interface strength prediction technique for resin-molded structures proposed in our previous paper (5).

In this report, we have quantitatively determined the effective surface area by changing the surface roughness of the metal in a resin-molded structure. The effect of the surface roughness on the interface shear strength was also investigated by using an adhesion test (3)-(5). Furthermore, the adhesive strength index was used to separate the effect of the metal surface roughness and the characteristics of the interface, to evaluate the influence of surface roughness on the interface strength, and to clarify the relationship between the interface strength and the surface roughness.

2. Shape of test pieces

The test piece and the stress field after molding used in this study on the strength of the interface between a metal surface and a resin is shown in Fig. 1. To manufacture this test piece, a metal pillar (diameter: 37 mm, height: 30 mm) was first inserted in a pillar-type metallic mold. Afterward, liquefied epoxy resin was poured into the metallic mold [Fig. 1(a)]. This metallic mold could be used to fabricate a resin-molded 10-mm thick test piece. Then, air was removed from the resin by using a vacuum.

The epoxy resin was joined to the metal pillar by a hardening reaction caused by an increase in temperature, and the resin was separated from the mold. The mold was kept in a furnace at the primary curing temperature (85°C) for 7 h and then at the secondary hardening temperature (130°C) for 24 h. After that, the mold, still in the furnace, was cooled to room temperature at 7°C/h. The maximum temperature change during the molding process was 110°C, and the highest temperature attained was 130°C. The glass transition temperature of the epoxy resin was 140°C; therefore, the viscosity of the resin was unlikely to have affected the experiment. The strain caused by the primary and secondary hardening reaction was counteracted by the creep strain generated during the secondary hardening. The strain, which remained as residual stress, was heat strain generated during cooling.

Metal pillars made of C1011 oxygen-free high conductivity copper (Cu) and SUS304 stainless steel (SUS) with arithmetic mean surface roughnesses, Ra (JIS B 0601-1994), of 0.2 a, 5.0 a, or 12.5 a were used as substrates. An engine lathe operating at the same rotation speed with a working tool with a changing feed speed was used to process the metal surface for the three surface roughnesses.

The internal interface between the resin and the metal surface is shown in Fig.1(c).
In a thermally hardened resin-molded structure, the residual stress $\sigma_{pm}$ induced by volume change due to the resin hardening and by the difference in thermal expansion between the resin and metal surface was applied to the metal-resin interface as pressure [Fig. 1 (c)]. In the debonding experiments on the interface, the ram of the testing machine pushed out the metal center. The shearing force $f_s$ and displacement $x$ were then measured at that time; these values were evaluated as the interfacial strength.

3. Roughness measurements and the effective surface area of the metal

The roughness of the metal surface was measured with a laser beam microscope (VK-9510, Keyence) and used to determine the effective surface area of the metal. The laser beam microscope measured the unevenness of the path direction on the pillar surface at intervals of 1 $\mu$m around the circumference and along the shaft.

The surface profiles around the circumference (c), along the shaft (z), and along the path (r) are shown in Fig. 2. The path direction coordinates (r) indicate the height of the surface roughness. Figure 2 shows a 1380 $\times$ 1380 $\mu$m area on the surface of the Cu with a surface roughness of 12.5 a. Figure 3 shows the axial cross section of the surface shown in Fig. 2 for the SUS and Cu with a surface roughness of 12.5 a. The arithmetic mean surface roughness of 12.5 a is shown as a broken line, and the average value is shown as a dashed line; the measured value fell mainly within the range defined by the broken line.

To determine the effective surface area from the surface roughness of the metal cylinder shown in Fig. 2, the surface area of the complicated curved surface must be determined. The surface was modeled with polygons. Each area created by two polygons (Fig. 4) was calculated by using Heron’s formula with the coordinates of the four corners that were measured at equal intervals in the circumferential and axial direction. The total surface area of the polyhedron was determined by summing these values. The side length of the two triangles (side b1 - side b5) can be calculated by using Eqs. 1 to 5 with the measured coordinates of four corners, where $z(i, j)$, $r(i, j)$ and $c(i, j)$ are the coordinates of the axial, radial and circumferential directions, respectively.

\[
b_1(i, j) = \sqrt{[(c(i, j) - c(i + 1, j))^2 + (r(i, j) - r(i + 1, j))^2]}
\]

(1)

\[
b_2(i, j) = \sqrt{[(z(i, j) - z(i, j + 1))^2 + (r(i, j) - r(i, j + 1))^2]}
\]

(2)

\[
b_3(i, j) = \sqrt{[(c(i, j + 1) - c(i + 1, j))^2 + (z(i, j + 1) - z(i, j))^2 + (r(i, j + 1) - r(i + 1, j))^2]}
\]

(3)

\[
b_4(i, j) = \sqrt{[(c(i, j + 1) - c(i + 1, j))^2 + (z(i, j + 1) - z(i + 1, j))^2 + (r(i, j + 1) - r(i + 1, j))^2]}
\]

(4)

\[
b_5(i, j) = \sqrt{[(z(i + 1, j) - z(i + 1, j))^2 + (r(i + 1, j) - r(i + 1, j))^2]}
\]

(5)

The areas, $A_{e1}$ and $A_{e2}$, can be calculated with Eqs. 6 and 7 by using Heron’s
formula. Therefore, the usable area, $A_e$, of the measured range can be determined with Eq. 8 by summing the areas in the direction of the circumference and the shaft.

$$A_e(i, j) = \sqrt{s_1(i, j)(s_1(i, j) - b_1(i, j))(s_1(i, j) - b_2(i, j))(s_1(i, j) - b_3(i, j))}$$

$$s_1(i, j) = (b_1(i, j) + b_2(i, j) + b_3(i, j))/2$$

(6)

$$A_e(i, j) = \sqrt{s_2(i, j)(s_2(i, j) - b_1(i, j))(s_2(i, j) - b_2(i, j))(s_2(i, j) - b_3(i, j))}$$

$$s_2(i, j) = (b_1(i, j) + b_2(i, j) + b_3(i, j))/2$$

$$A_e(i, j) = \sum \sum (A_{i1}(i, j) + A_{i2}(i, j))$$

(7)

Because the measured region is a tiny proportion of the total surface of the cylinder, the surface area (not taking into consideration the surface roughness) is assumed to be $A_0 = C \times Z$, where $C$ is the die length in the direction of the circumference and $Z$ is the die length along the shaft. The ratio of $A_e$ to the upper surface area $A_0$ is defined as the magnification, $e$, of the usable area. Figure 5 shows the relationship between the surface roughness and calculated magnification, $e = A_e/A_0$. The magnification, $e$, of the usable area was different for the SUS and Cu for the same surface roughness. This was because the shape of the cutting trace was altered by the hardness of the metal; the convex portion of the cutting trace contained extra undulations in the SUS (Fig. 3), which contributed to the increase in the effective surface area.
4. Debonding test for resin-molded structure (13)-(16)

The debonding test for the resin-molded test piece is shown in Fig. 1 (c). The metal/resin interface, which is subjected to the compression pressure of molding, was debonded by by pushing the central metal cylinder in the test piece out at 0.01 mm/s by using displacement control.

The shearing force, $f_{s-ra}$, and the displacement, $x$, were measured. The relation between $f_{s-ra}$ and $x$ is shown in Figs. 6 (a) - (f) for the Cu and SU with surface roughnesses of 0.2 a, 5 a, and 12.5 a. For both the Cu and SUS, 0.2 a and 5 a showed a peak that decreased rapidly after $f_{s-ra}$ increased rapidly when $x$ was small. When $x$ was small for 12.5 a, a peak was visible, which decreased rapidly after $f_{s-ra}$ increased rapidly. However, it repeatedly decreased and increased as $x$ gradually increased. The peak magnitudes at the beginning of the experiment indicated the maximum shearing force $f_{smax-ra}$ and thus the adhesion interface. Subsequently, debonding produced a peak magnitude generated all over the interface, and the adhesive strength was released. The adhesion interface became a contact interface between the metal and the resin, and the frictional force, $f_{f-ra}$, took over.

For the surface roughness of 0.2 a in Fig. 6 (a), $f_{s-ra}$ decreased gently as $x$ increased after the peak. This is because the contact surface area decreased and $f_{s-ra}$ between the metal and the resin decreased as the metal cylinder was pushed out. For the surface roughness of 12.5 a shown in Figs. 6 (c) and (f), the $f_{s-ra}$ repeatedly increased and decreased, although its overall magnitude decreased. The adhesive strength was released after debonding, which created a contact interface. The sliding surfaces caused cohesion failure because the peaks on the metal surface removed the peaks on the resin surface and increased the frictional force. The shearing force may repeatedly decrease and increase gradually in order for the contact surface area to decrease to allow the cohesion failure to be repeated. The appearance of the test piece after an adhesion test can indicate whether this occurs.

Photographs of the 0.2-a and 12.5-a SUS test pieces after an debonding/shear test are shown in Figs. 7 (a) and (b), respectively. When the inner circumference of the resin cylinder of both 0.2 a and 12.5 a was measured after debonding, the 12.5-a test piece had been shaved off the resin by the cohesion fracture of the resin [Fig. 7 (b)].

![Fig. 6 Relationship between shearing forces and displacement](image-url)
5. Quantitative evaluation of the strength of the internal adhesion interface by surface roughness

The strength of the internal adhesion interface was quantitatively evaluated by the change in surface roughness. The relationship between the maximum shearing force and the surface roughness for the adhesion interface was determined. The experimental results were analyzed by using the relationship between the contact pressure force and the shearing force. The interface and the surface roughness and their effect on the shearing force were clarified. The relationship between the surface roughness and the maximum frictional force generated at the contact interface after debonding was clarified, and the effect of the surface roughness on the strength of the adhesive bonding was considered.

5.1 Relationship between surface roughness and maximum shearing force

The shearing force, $f_{s-ra}$, for each surface roughness is shown in Fig. 6 (f) from the surface roughness in Fig. 6 (a). The relationship between the displacement $x$ and the surface roughnesses for the Cu and SUS and the relationship between the maximum shearing force $f_{max-ra}$ are shown in Fig. 8. The maximum shearing force increased with the surface roughness for both materials. However, Fig. 5 shows the relationship between the surface roughness for the Cu and SUS and the effective surface area. The increase in the effective surface area, which accompanied the increase in the surface roughness for the surface roughness of 12.5 a, was 2.1-fold greater for the SUS than for the Cu. The increase in the maximum shearing force accompanying the increase in the surface roughness was 1.5-fold greater for the SUS than for the Cu, as shown Fig. 8. The effect of the surface roughness on the maximum shearing force suggests that it exerts an effect that adds to the increase in the effective surface area.

The effect of the surface roughness on the maximum shearing force for the metal/resin interface was determined by examining the force required to break the interface. It was previously proposed that the shearing force, $f_s$, required to break the interface is described by the adhesion coefficient, $B$, and the coefficient of friction, $\mu$.

This is expressed as $f_s \cong (\mu + B)\sigma_{pm}A_e^{(10)}$. However, if the surface roughness is taken into consideration, the direction in which the shearing force that breaks the metal/resin interface is applied to the concavo-convex interface surface must be taken into consideration. Scanning electron microscopy (SEM) was used to determine the surface morphology of the resin/metal interface. The SUS interface with a surface roughness of 12.5 a is shown in Fig. 9 (a), and Fig. 9 (b) shows an enlargement of the photograph. Resin filled in the unevenness of the cutting trace in the surface.

The load of the shear in the $z$ direction should cause interface debonding where the periodic unevenness was formed at the interface, [Fig. 9 (a)]. A simulation that modeled these cutting traces by using FEM analysis showed that the tensile stress occurred around peaks in the cutting trace and at the internal interface in both the resin and the SUS in the previous paper $^{(13)}$. This could explain the tensile stress in the cutting trace and the fracture mode-I progression of the debonding. Persson and coworkers are investigating the progression of debonding $^{(17)}$.

Thus, we propose that the fracture mode-I dissociation of...
bonding occurs macroscopically and then causes the interface debonding of the resin-molded structure, which arises from the surface roughness of the interface.

If the perpendicular force at a concavo-convex interface is the maximum shearing force, then \( f_{\text{max-ra}} = f \cos \theta \) at the slanted face of the concavo-convex interface and the angle \( \theta \) is the inclination on the surface from the unevenness [Fig. 7 (a)]. Therefore, \( f_{\text{max-ra}} \) for roughness surfaces can be expressed by using Eq. 9.

\[
f_{\text{max-ra}} = (\mu + B)(\sigma_{\text{pm}} A_e \cos \theta)
\]  

(9)

Moreover, the contact pressure force, \( \sigma_{\text{pm}} A_e \cos \theta \), on the right-hand side of Eq. 9 was larger for the SUS than for the Cu for every surface roughness (as shown in Table 1) because the values of \( \sigma_{\text{pm}} \) and \( A_e \) were larger.

However, the \( f_{\text{max-ra}} \) for Cu below a surface roughness of 5a was larger than for the SUS; the Cu with a contact pressure force smaller than the SUS exhibited better adhesion at the interface. Therefore, when surface roughness is small, the influence of the adhesion coefficient, B, on the interface strength is greater than that of the effective surface area \( A_e \).

The relationship between the contact pressure force, \( \sigma_{\text{par}} A_e \cos \theta \), and the maximum shearing force, \( f_{\text{max-ra}} \), is proportional, and thus, Eq. 9 applies to the conditions under which the contact pressure force was applied (Fig. 10). Figure 10 also confirms that each material possesses a unique adhesive strength index (\( \mu + B \)). Although the coefficient of friction, \( \mu \), is affected by the surface roughness, it should not significantly affect the index because the adhesion coefficient, B, is unique for each material.

Fig. 8 Relationship between shearing forces and surface roughness

(a) Interface observed by microscope enlarged 500 times

(b) Picture of Part A

Table 1 Comparison of maximum shearing force and surface pressure

<table>
<thead>
<tr>
<th>Surface roughness (μm)</th>
<th>( f_{\text{max-ra}} ) (kN)</th>
<th>( \sigma_{\text{pm}} ) (MPa)</th>
<th>( \frac{A_e}{A_0 \times e} )</th>
<th>( \cos \theta )</th>
<th>( \sigma_{\text{pm}} \cos \theta A_e ) (kN)</th>
<th>( \frac{A_e}{A_0 \times e} )</th>
<th>( \cos \theta )</th>
<th>( \sigma_{\text{pm}} \cos \theta A_e ) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>20.0</td>
<td>3.78</td>
<td>( 3487 \times 2.78 )</td>
<td>( \cos(3.9°) )</td>
<td>( 36.54 )</td>
<td>13.0</td>
<td>( 3487 \times 2.78 )</td>
<td>( \cos(3.9°) )</td>
</tr>
<tr>
<td>5.0</td>
<td>32.8</td>
<td>3.78</td>
<td>( 3487 \times 4.53 )</td>
<td>( \cos(4.9°) )</td>
<td>( 59.58 )</td>
<td>30.0</td>
<td>( 3487 \times 5.75 )</td>
<td>( \cos(4.9°) )</td>
</tr>
<tr>
<td>12.5</td>
<td>47.0</td>
<td>3.78</td>
<td>( 3487 \times 6.15 )</td>
<td>( \cos(7.5°) )</td>
<td>( 80.90 )</td>
<td>51.0</td>
<td>( 3487 \times 9.80 )</td>
<td>( \cos(7.5°) )</td>
</tr>
</tbody>
</table>
Therefore, the increase in the maximum shearing force with the surface roughness was 2.1-fold greater for the SUS than it was for the Cu, and the increase in the effective surface area with the surface roughness was 1.5-fold greater for the SUS than it was for the Cu (Figs. 5 and 6). This may be because the increase in the adhesion coefficient has a greater effect than does the effect that the increase in the effective surface area, caused by the surface roughness, has on the maximum shearing force.

5.2 Relationship between surface roughness and maximum frictional force

If the force applied to the interface reaches the maximum shearing force, interface debonding occurs, the adhesion coefficient B falls to zero, and the interface becomes a contact surface between the metal and the resin. Subsequently, the surfaces slide according to the frictional force, with the coefficient of friction, $\mu$, and a reduced contact surface product. Furthermore, if the surface roughness is large and the angle $\theta$ of the peaks in the contact surface become large, a cohesive fracture occurs, which slips if peaks in the metal surface destroy the peaks in the resin surface. In this case, the shearing strength, $\tau$, is required for a cohesive fracture at the maximum frictional force; the maximum frictional force is expressed in Eq. 10.

$$f_{\text{max-ra}} = \mu(\sigma_{\text{pm}} A_c \cos \theta) + \tau A_c \tag{10}$$

Here, $A_c$ is the area of the shear direction produced by the cohesive fracture of the resin, which varies with the angle $\theta$ of the peaks.

For surface roughnesses of 0.2 a and 5 a, $A_c = 0$ because there is no cohesive fracture. For the Cu and SUS test piece with a surface roughness of 12.5 a, which contained cohesive fractures, the area of the shear direction, which the cohesive fracture produced from the interface, was difficult to measure accurately after sliding [Fig. 7 (b)]. Therefore, $A_c$ was estimated immediately after debonding from the SEM image in Figs. 11 (a) and (b). The contact surface of the resin was shaved, the cohesive fracture of resin occurred and the resin slipped on the copper surface, when the length of copper plug becomes 1/2 or more of the length of resin at the same radius as shown with broken line of part C in Fig. 11(b), because the shear strength of copper is twice as large as that of the resin. Therefore, the die length of the w-r area shown in Fig. 11 (b) increased to twice the die length of the w-c area next to the Cu; this is the die length of the shear direction of the resin area of the side faces, from which the cohesive fracture arises. This Cu area is in contact with only resin. For the cohesive fracture in the Cu, the area of the shear direction of the resin was about 22% of $A_0$, and for the SUS, it was 17% of $A_0$. 

![Fig. 10 Relationship between maximum shearing forces and pressure forces](image-url)
If the maximum shearing force shown in Fig. 6 and the debonding/shear test in Eq. 9 are equal, then the adhesive strength index can be expressed as \((\mu + B) = f_{\text{max-ra}}(\sigma_{\text{pm}A_c \cos \theta})\). In addition, if the maximum frictional force \(f_{\text{fr max-ra}}\) in Eq. 10 is the same as the \(f_{\text{fr max-ra}}\) shown in Fig. 6, the coefficient of friction, \(\mu\), can be expressed as \((f_{\text{fr max-ra}} - \tau A_c)/(\sigma_{\text{pm}A_c \cos \theta})\) (Table 2). The adhesive strength index in Table 2 lists the characteristics of the interface for each material without the effect of the contact pressure force. The coefficient of friction, \(\mu\), increases with the surface roughness of the Cu and SUS. However, the adhesion coefficient, \(B\), is not affected by the surface roughness. The adhesion coefficient \(B\) of the Cu is larger than that of SUS. Therefore, to improve the adhesion interface strength in resin-molded structures, the effective surface area could be increased by increasing the surface roughness, and material combinations with suitable adhesion characteristics could increase the adhesion coefficients.

Therefore, the adhesion coefficient, \(B\), describes the specific adhesion characteristics between materials, even when the surface roughness is changed. It has been reported that the mismatch in the molecular structure is related to the strength of an interface. The relationship between the interfacial failure energy calculated by molecular dynamics and the interatomic distance of the molecular structure may help explain our observations. The interatomic distance of Cu is 0.256 nm, and the interatomic distance of the resin is 0.250 nm. The mismatch between Cu lattices is only about 2%, whereas for Fe, it is 14%. The interfacial failure energy of the resin and Cu is larger than for other metals, such as Fe and Al.

It may be expressed that the adhesion coefficient, \(B\), obtained from the debonding test and the observation at the micro-scale shown in this report is related to the specific adhesion characteristics between materials like the interfacial fracture energy obtained from the molecular dynamics simulation at the nano-scale. We hope to use the interfacial failure energy to investigate the dissociation of interface bonding at a molecular level in future research.

<table>
<thead>
<tr>
<th>Surface roughness (μm)</th>
<th>Experimental value</th>
<th>Theoretical value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cu</td>
<td>SUS</td>
</tr>
<tr>
<td>(f_{\text{fr max-ra}}) (kN)</td>
<td>(f_{\text{fr max-ra}}) (kN)</td>
<td>(f_{\text{fr max-ra}}) (kN)</td>
</tr>
<tr>
<td>(\sigma_{\text{act}}) (kN)</td>
<td>(\tau A_c) (μB)</td>
<td>(\mu)</td>
</tr>
<tr>
<td>0.2</td>
<td>20.0</td>
<td>6.3</td>
</tr>
<tr>
<td>5.0</td>
<td>32.8</td>
<td>10.5</td>
</tr>
<tr>
<td>12.5</td>
<td>47.0</td>
<td>46.9</td>
</tr>
</tbody>
</table>

(a) Interface observed by microscope  (b) Picture of B part enlarged 150 times

Fig. 11 Interface observed by microscope (Debonding state)
6. Summary

Resin-molded structure test pieces with different metal surface roughnesses were used to quantitatively determine the effective surface area. The effect of the effective surface area on the interface shearing strength was investigated by using an adhesion test. Moreover, the relationship between the surface roughness and the adhesive strength index, and thus the interface strength, was clarified. The following conclusions were drawn from the effective surface area, the contact pressure force, and the shear strength.

(1) The magnification of the usable areas of SUS and Cu were different, even for the same surface roughness. This is because the shape of the cutting trace was affected by the hardness of the material and was thus different for the Cu and for SUS. The shape of the cutting trace contributed to the increase in the effective surface area. The interface adhesion coefficient, $B$, obtained from the relationship between the maximum shearing force and the contact pressure force did not depend on the surface roughness and was a constant value for each metal. This suggests that $B$ represents the unique adhesion characteristics of the interface.

(2) Although the interface strength of the resin-molded structure increased with the effective surface area, the effect on the interface strength of the adhesion coefficient was greater than that of the effective surface area. The adhesion interface strength between the metal and the resin could be improved by increasing the effective surface area by increasing the surface roughness and choosing suitable material combinations to increase the adhesion coefficients.

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