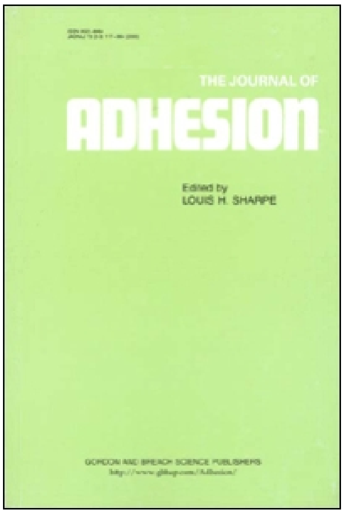

The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

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To cite this Article Ikegami, Kozo , Kajiyama, Masaaki , Kamiko, Satoshi and Shiratori, Eiryo(1979) 'Experimental Studies of the Strength of an Adhesive Joint in a State of Combined Stress', The Journal of Adhesion, 10: 1, 25 — 38
To link to this Article: DOI: 10.1080/00218467908544609
URL: http://dx.doi.org/10.1080/00218467908544609

J. Adhesion, 1979, Vol. 10, 25–38

Experimental Studies of the Strength of an Adhesive Joint in a State of Combined Stress

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(*Received January 4, 1978; in final form June 26, 1978*)

The adhesive strength of a butt-type specimen of two cylinders is experimentally studied. Combined stresses are applied on the adhesive layer by subjecting the specimen to combined axial load, torsion and internal pressure. The effects of the surface roughness, the thickness of adhesive layers and the combined stresses on the adhesive strength are examined for the specimens of various metals bonded with epoxy resin. The adhesive failure locus under the combined stress state are represented by a polynominal equation of stress tensors.

1. INTRODUCTION

Adhesive structures have many advantages compared with such mechanical bonding as bolts, nuts and rivets. However, they are not so reliable as regards their strength. This is caused by the fact that adhesive structures are designed often on empirical knowledge, because the characteristic values of the adhesive strength for the design are not established. To make a rational strength design of adhesive structures, at least the following two characteristic values of adhesive strength are necessary:

1) The adhesive strength under uniform stress.

2) The adhesive strength in a state of combined stress (hereafter called the adhesive strength law).

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The adhesive strength law is indispensable not only to the design of adhesive structures, but also the investigation of the fracture of composite materials in which the bond strength between matrix and fiber has a significant effect.

Though many studies[1] are to be found on actual adhesive structures, there are few investigations on the adhesive strength in a complex stress state such as combined normal and shear stresses.

As to the testing method of adhesive strength, butt joints of rods or blocks are mainly used to measure the tensile strength, while the lap joints are widely used for determining the shear strength.[2] By these methods, it is difficult to subject the adhesive layer to uniform stress of tension or shear. The values of strength measured by these methods are influenced by the dimensions of specimens. Moreover, it is impossible to obtain the strength under a known state of combined stress by these methods.

A specimen consisting of two thin-walled cylinders bonded to each other at their ends has the advantage that it can be used of to subject the adhesive layer to both states of unform stress and combined stresses. In this paper, the adhesive strength under a state of combined stress is experimentally investigated by using the butt type specimen of two cylinders. The effects of the surface roughness and the thickness of the adhesive layer are examined. The laws of adhesive strength are proposed on the basis of the experimental results of various metal specimens.

2. EXPERIMENTAL PROCEDURES

2.1 Specimens

Two types of cylindrical specimens shown in Figure 1 are used. The adhered surfaces of the specimens are the edges of the cylinder indicated by the arrow A. The specimens of the type I and II are used to investigate the effects of the surface roughness and the thickness of the adhesive layer, respectively. The thickness of the adhesive layer in the type II specimen can be settled to a given value by using the thickness gauge inserted between the circular regions indicated by the arrow B of the two cylinders which will be bonded to each other. The surface roughness of the specimen is varied by abrading through various abrasive papers. Then the specimens are washed in a solution of methyl alcohol and a chlorofluorocarbon agitated ultrasonically.

2.2 Adhering process

The adhesive is epoxy resin (R-820 of Showa Kobunshi Co., Ltd.). The specimens are bonded under the weight of 15 kg for 2 hours at room temperature, cured for 2 hours at 70°C, and cooled to room temperature at the rate of 5°C/hr. After these processes, the specimens are left at room temperature for 14 hours and then tested.

2.3. Testing methods

A specially designed attachment with two spherical seats was used for tensile and compressive loading to reduce the effect of misalignment of the axial

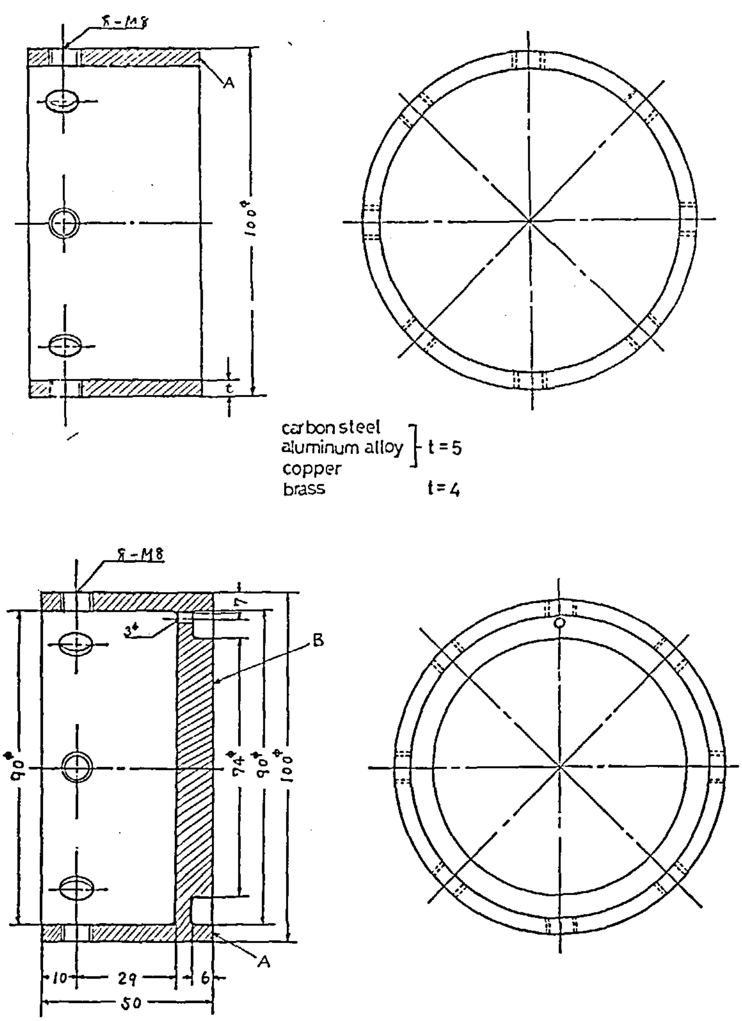

FIGURE 1 Dimensions of cylindrical specimen. (A) Type I, (B) Type II.

lines between the specimen and the testing machine. Figure 2 shows the assembly of the specimen and the attachment. The experiments are conducted by subjecting this set to combined axial load, torsion and internal pressure with the combined testing machine.[3] The combined loads are applied along the path of constant load ratio (proportional loading path). The loads at

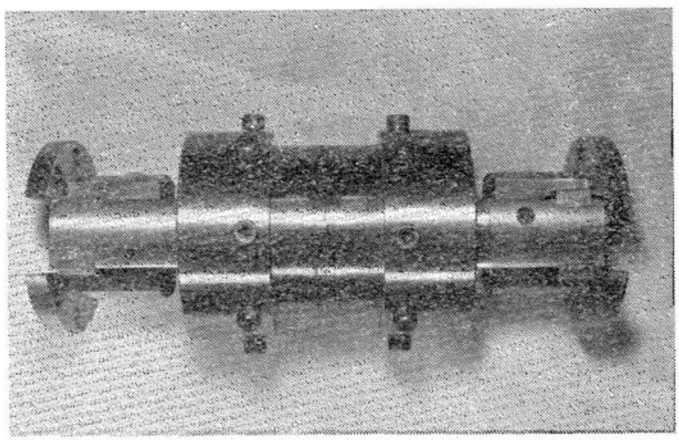

FIGURE 2 Specimens and attachments.

fracture of the specimens are measured. The nominal values of axial, circumferential and shear stresses at fracture are calculated on the basis of the original dimensions of the specimen by using the following equations:

$$\text{the axial stress:} \quad \sigma_x = \frac{W}{\pi d_m t} + \frac{p_i d_i^2}{4 d_m t}$$

$$\text{the circumferential stress:} \quad \sigma_y = \frac{p_i d_i}{2t}$$

$$\text{the shear stress:} \quad \tau_{xy} = \frac{2T}{\pi d_m^2 t}$$

where W axial load
P_i internal pressure
T torque
d_i internal diameter of cylinder
t thickness of cylinder
d_m d_i+t

The tests are conducted at room temperature and with a stress rate of 0.05 kg/mm$^2\cdot$sec in normal stress and of 0.03 kg/mm$^2\cdot$sec in shear stress.

3. EXPERIMENTAL RESULTS

3.1 The effect of the surface roughness of adherend and the thickness of adhesive layer on the tensile adhesive strength

Figure 3 shows the relation between the tensile adhesive strength and the surface roughness which is indicated by the value of the center line average (R_a). This result was obtained by the specimens of type I which was made by carbon steel. The thickness of the adhesive layer (l) is 12 μ in this case. There is optimal surface roughness which maximizes the tensile adhesive strength.

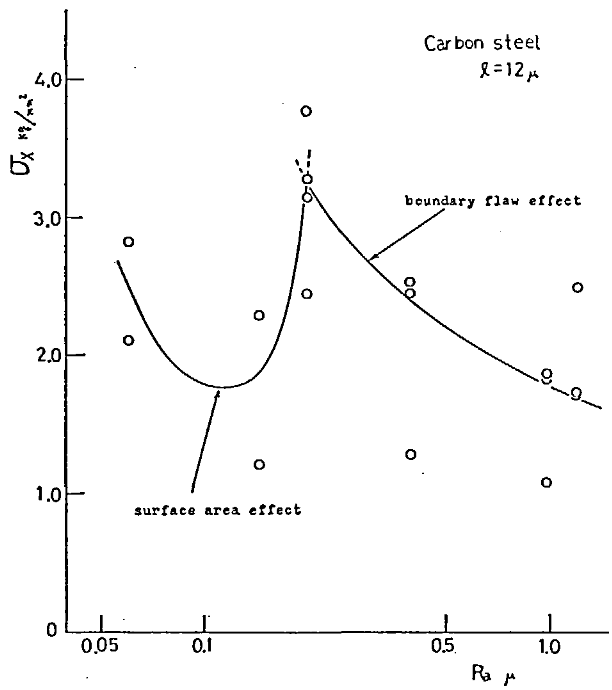

FIGURE 3 Effect of the surface roughness on tensile adhesive strength for carbon steel specimens.

The surface roughness can have both positive and negative effects. The positive effect is to increase the surface bonding area. The negative effect is that flaws can be formed at the interface by residual abrasive particles and by voids due to poor wetting by the adhesive. It is considered that these two effects are balanced at the optimal surface roughness.

Figure 4 shows the relation, obtained by carbon steel specimens of type II,

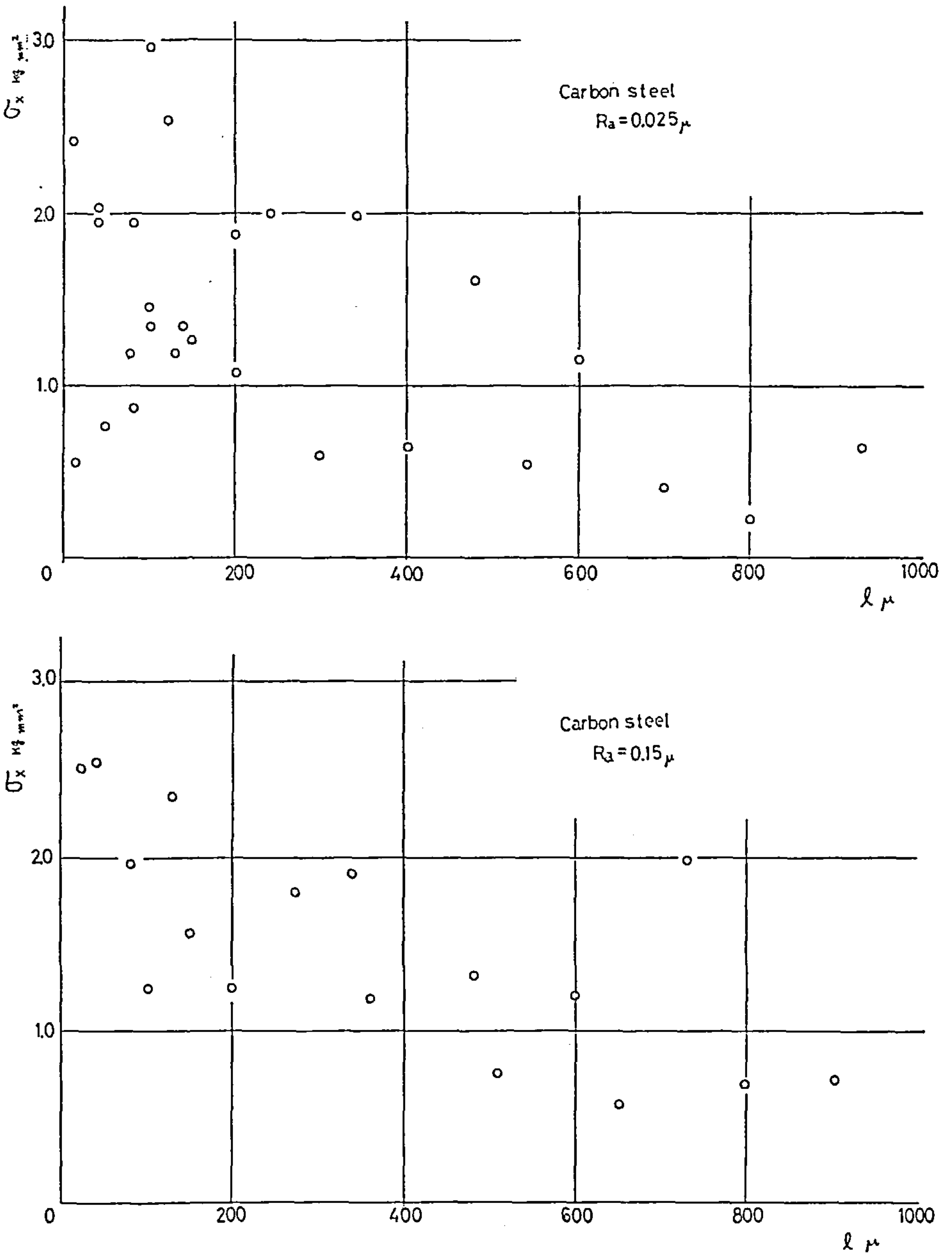

FIGURE 4 Effect of the thickness of adhesive layers on tensile adhesive strength for carbon steel specimens. (A) Surface roughness $R_a = 0.025\ \mu$; (B) Surface roughness $R_a = 0.15\ \mu$.

between the tensile adhesive strength and the thickness of adhesive layers for the case of two different surface roughnesses. The tensile adhesive strength is found to increase as the thickness of the adhesive layer decreases. This tendency is not so much affected by the surface roughness. The results shown in Figure 4 support the rule "the thinner the film the stronger the joints".[5]

3.2 Adhesive strength under combined normal and shear stresses

Figures 5 to 8 show the failure loci under combined axial and torsion of the specimens of type I, which are made of brass, copper carbon steel and aluminum alloy, respectively. The thickness of adhesive layer and the surface

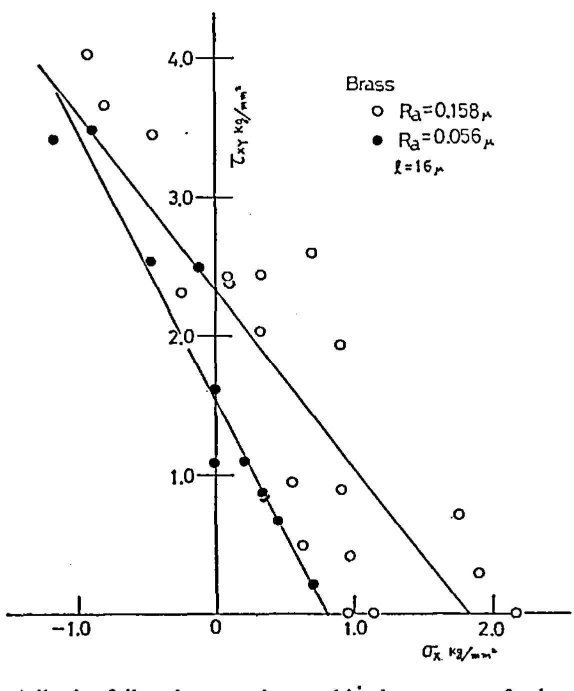

FIGURE 5 Adhesive failure locus under combined stress state for brass specimens.

roughness of adherends are indicated in the figures. The combined stress effect on the adhesive strength is remarkable. The tensile strength is decreased by the existence of the shear stress. Conversely, the shear strength is increased by the existence of the compressive stress, while it is decreased by the tensile stress.

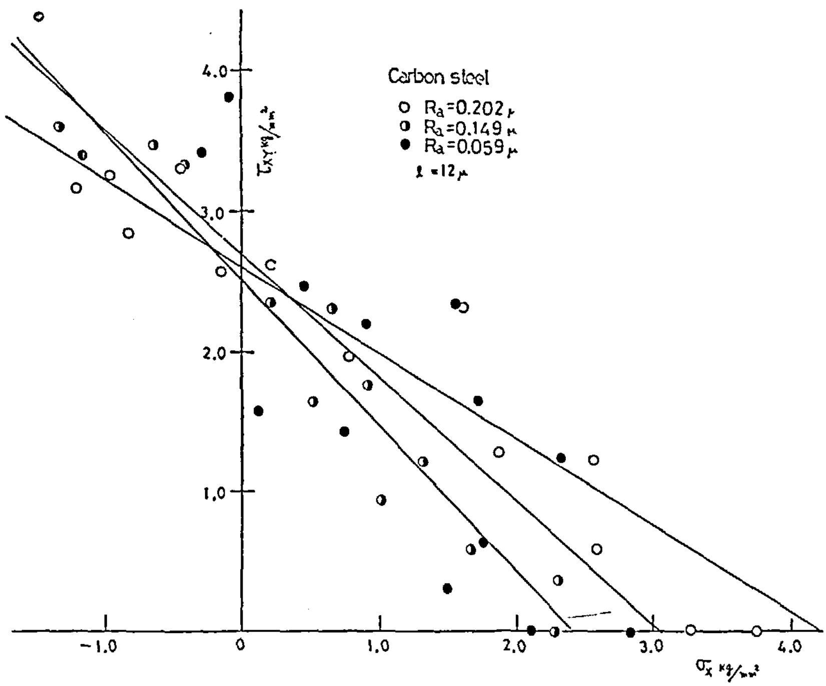

FIGURE 6 Adhesive failure locus under combined stress state for carbon steel specimens.

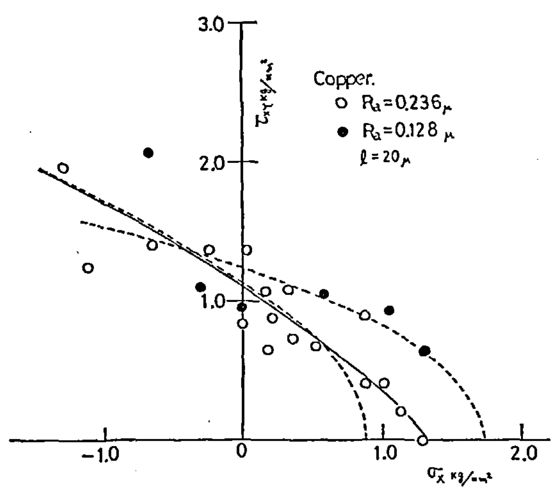

FIGURE 7 Adhesive failure locus under combined stress state for copper specimens.

The tensile adhesive strength is affected more remarkably by the surface roughness than is the shear adhesive strength. In the case of brass, the adhesive failure locus for large surface roughness is located above that for small roughness as shown in Figure 5. A similar result is observed for carbon steel in Figure 6 except in the case of the surface roughness of $R_a = 0.059\ \mu$. In these cases, the surface roughness has a positive effect except for the very fine surface roughness range. For such surface roughness as $R_a = 0.059\ \mu$, the adhesive strength increases slightly as shown in Figure 3. Therefore, in

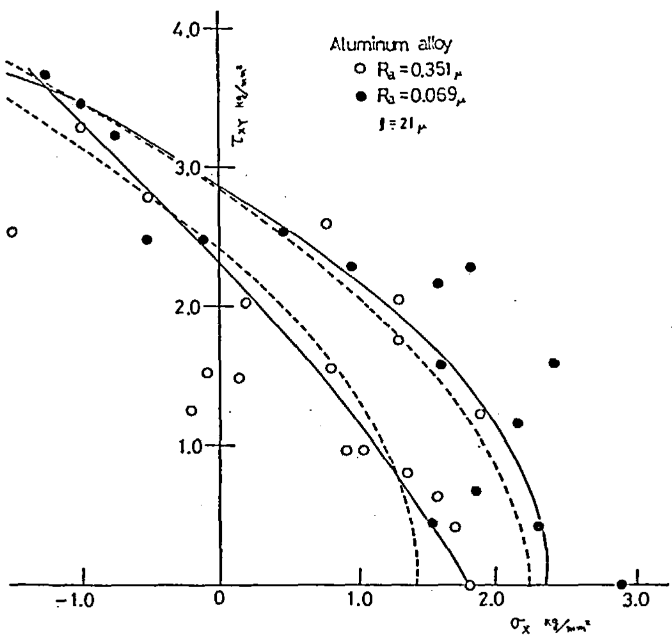

FIGURE 8 Adhesive failure locus under combined stress state for aluminum alloy specimens.

Figure 6, the failure locus for $R_a = 0.059\ \mu$ is located above that for $R_a = 0.149\ \mu$. For the copper specimen of Figure 7 and the aluminum alloy specimen of Figure 8, the adhesive failure loci for large surface roughness are located below those for small roughness. The surface roughness has a negative effect for these adherends.

3.3 Adhesive strength under biaxial tension

Figure 9 shows the failure loci for carbon steel and aluminum alloy under combined axial load and internal pressure which are obtained by using the

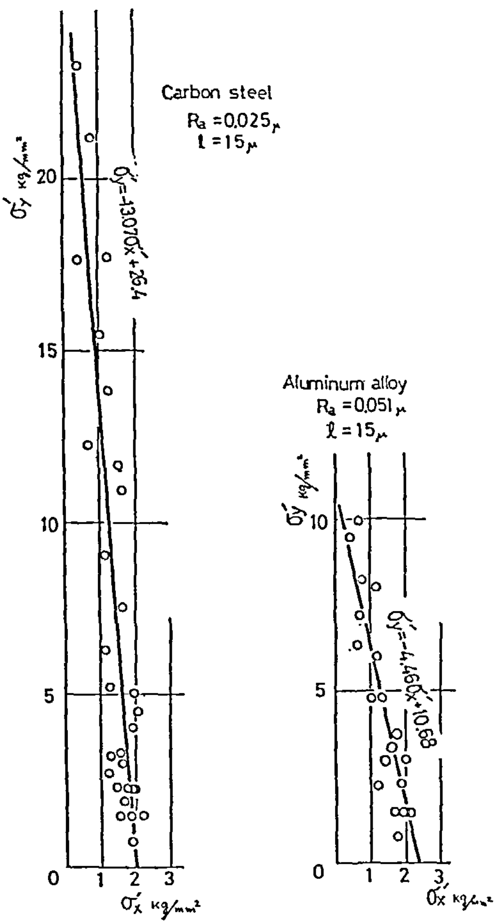

FIGURE 9 Stress values at fracture of specimens under biaxial tension.

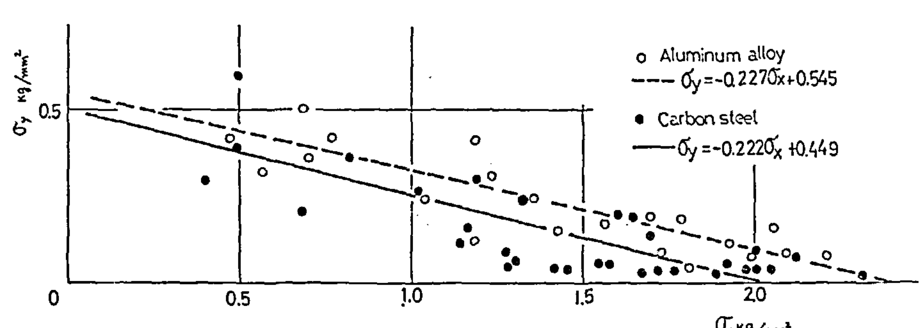

FIGURE 10 Adhesive failure locus under biaxial tension.

specimens of type I. The thickness of adhesive layers and the surface roughness of adherends are indicated in the figure. The values of the circumferential stress at failure of the specimens are much larger than those of the axial stress. This is due to the fact that the adherend has a large elastic modulus compared with the adhesive resin, and hence the circumferential deformation of the adhesive layer is restricted to almost the same order as that of the adherend. The values of the circumferential stress given in Figure 10 are determined from the assumption that the strains in the adhesive layer are the same as those in the adherends. The tensile adhesive strength is affected significantly by the lateral stress.

4. FORMULATION OF THE ADHESIVE FAILURE LOCUS UNDER COMBINED STRESSES

Although many failure theories are proposed,[6] the failure criterion for adhesive strength has not yet been established.[7] The failure loci under combined stresses of brass specimens in Figure 5 and carbon steel specimens in Figure 6 show a similar tendency to that predicted by Coulomb–Mohr's fracture criterion. According to the Coulomb–Mohr's criterion, the failure is assumed to occur at the time when the shear stress reaches the critical value which is given as the sum of a "cohesive strength" C and a frictional stress,

$$|\tau| = C+\mu\sigma, \tag{1}$$

where μ is a material constant called the coefficient of friction, and σ is the normal stress. The generalized form of Eq. (1) is expressed as

$$\tau = F(\sigma) \quad \text{or} \quad \sigma = G(\tau). \tag{2}$$

Expansion of Eq. (2) into a polynominal of τ, gives

$$\sigma_x = b_0+b_1\tau_{xy}+b_2\tau_{xy}^2+\ldots, \tag{3}$$

where the subscripts x and y mean the axial and circumferential directions, respectively. The results of Figures 5 and 6 can be approximated by the equation,

$$\sigma_x = h_0+h_1\tau_{xy}, \tag{4}$$

which is applicable to the case when the surface roughness acts as the positive effect. The results of Figures 7 and 8 for the case when the surface roughness has a negative effect can be expressed by the equation,

$$\sigma_x = k_0+k_1\tau_{xy}+k_2\tau_{xy}^2, \tag{5}$$

or more approximately by the equation,

$$\sigma_x = k_0'+k_1'\tau_{xy}^2. \tag{6}$$

The coefficients of Eqs. (4) to (6) are given in Tables I and II for the adherends tested.

The failure locus under combined axial load and internal pressure can be represented by the linear relation between the axial stress and the circumferential stress as shown in Figure 10.

TABLE I

Coefficients for the adhesive failure locus for the positive effect of surface roughness

	Carbon steel			Brass	
$R_{x\mu}$	0.202	0.149	0.059	0.158	0.056
h_0	4.25	2.41	3.06	1.78	0.814
h_1	−1.65	−0.971	−1.14	−0.763	−0.518

Figure 11 shows the formulated failure surface under combined axial load, internal pressure and torsion in the case of the specimen of carbon steel. In this figure, the fractured surfaces of the specimens are also shown schematically. The black-colored parts indicate the remaining adhesive layers on the surface of adherends. When the specimen is fractured by the axial load, almost all of the adhesive layer remains on the surface of one of the adherends. In the case of the specimen fractured by the shear load, the fragments of the adhesive layer remain almost equally on both surfaces of the adherends. The adhesive layer makes spots on the surface of the adherends when it fractures under the large internal pressure.

TABLE II

Coefficients for the adhesive failure locus for the negative effect of surface roughness

	Copper		Aluminum alloy	
$R_{a\mu}$	0.236	0.128	0.351	0.069
k_0	1.35		1.80	2.38
k_1	−1.11		−0.630	3.22×10^{-4}
k_2	−0.144		−0.0634	−0.288
k'_0	0.869	1.73	1.38	2.25
k'_1	−0 643	−1.21	−0.240	−0.273

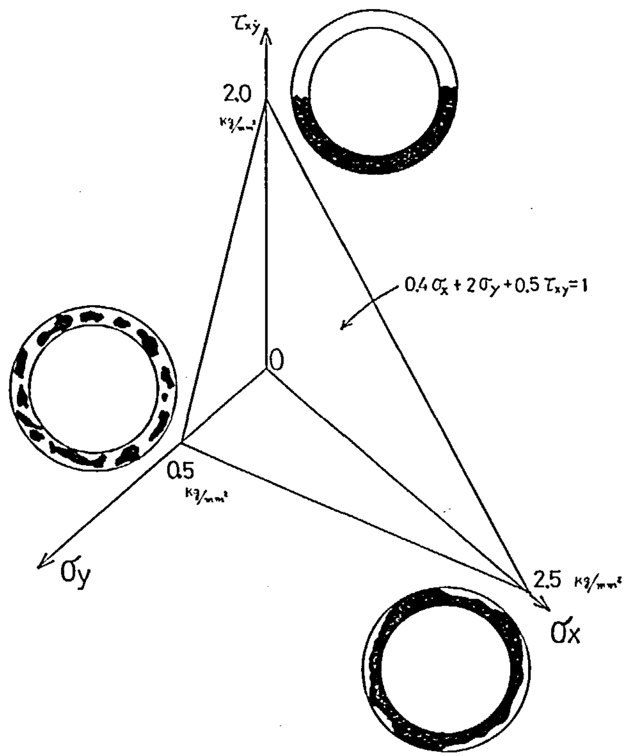

FIGURE 11 Adhesive failure surface and schematic diagram of the fractured surface of specimens.

5. CONCLUSIONS

The adhesive strength is experimentally studied by using the butt-type specimen of two cylinders. The combined stresses are applied on the adhesive layer by subjecting the specimen to combined axial load, torsion and internal pressure. The effect of the surface roughness of the adherend, the thickness of the adhesive layer and the combined stresses on the adhesive strength are examined for the various metal specimens bonded with epoxy resin. The following results are obtained:

1) There is an optimal surface roughness which makes the tensile adhesive strength maximum.

2) The tensile adhesive strength is affected more remarkably by the surface roughness than the shear adhesive strength.

3) The tensile adhesive strength increases as the thickness of the adhesive layer decreases.

4) The adhesive failure loci under a combined stress state are represented by a polynominal equation of stress tensors.

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