EXPERIMENTAL STUDY ON PROBABILITY OF STRENGTH FOR EPOXY ADHESIVE-BONDED METALS

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ABSTRACT

Adhesive bonding is becoming one of the popular joining techniques in metal industries, since it has some advantages over other techniques such as welding and diffusion bonding, e.g., any dissimilar metals are easily adhesive-bonded together. In this study, the experiments were carried out in order to provide the statistical data with strength evaluation methods: tension, shear and four-point bending tests for thermoplastic epoxy resin based adhesive-bonded metal joints. We should certificate on the probability of the adhesive strength that has the tendency of brittle fracture, the adhesive bonding strength between metals with thermoplastic adhesive has the best probability at four-point bending test. The strength testing method that has higher probability is four-point bending test, shear test and tensile test in order.

KEYWORDS

Adhesive, Probability, Epoxy, Testing method, Adhesive strength

1. Introduction

Recently, several types of high strength adhesives have become available for assembling structural elements, consequently, adhesive bonding is being used increasingly in many fields of industry. Adhesive bonding has several advantages over other joining techniques such as welding and diffusion bonding, e.g., any dissimilar metals are easily bonded together, and there is no need to care about the thermal strain which is often induced by welding, and moreover, the adhesive layer can play the role of vibration damping [1].

In the case of brittle behaviors, we cannot help obtaining the result that strengths are expressed with statistical distribution, even though the specimens are made from the same materials [2]. Because the each specimen of brittle fracture material has a different size of defect from others, the size of defect depends on the level of severity of defect, and is not uniform but expressed with distribution. This situation is not for the ductile fracture material like almost of metals. Because the plastic deformation by the movement of dislocation relieves the density of severity of it under the stress, even though metals have the defect with distribution. Therefore the same metal specimens have the almost same strengths; the strength of Al_2O_3 has the range of distribution from 360 MPa to 440 MPa. Hence the lowest strength by the severest defect is to be the strength of brittle fracture material, if the specimen has the same stress distribution when tensile testing. So, the statistical data from a large number of specimens, the strength distribution can be treated as the extreme value statistics. This research consists of statistical analysis of brittle fracture and probability analysis based on statistics.

In this study, the epoxy-based adhesive metal-joints were used to evaluate the strength and probability. The thermoplastic epoxy-based adhesives have a tendency of brittle fracture such as ceramic material. The conventional test methods such as tensile, shear and four-point bending test were conducted to evaluate the probability of adhesive strength. And the effect of the adhesive sectional area on the adhesive strength was evaluated.

2. Experimental procedures

A commercial ANSI 304L stainless steel was used for this study as the specimens for tensile test, four-point bending test and shear test. The adhesive sectional areas were varied as 2×3, 3×4, 4×5 and 5×6 mm^2 to evaluate the effect of it on strength. Namely, the thickness of the specimen was changed as 2, 3, 4 and 5 mm. And 20 specimens were tested for the each condition. Each specimen is shown in Fig. 1. The section of contact surface is uniformly polished with #400 SiC sand paper. The commercial Technicoll 8266/8267, thermoplastic epoxy-based adhesive, was used as the adhesive. Technicoll 8266 component A is epoxy resin and Technicoll 8267 component B is amine-setting agent (thixotropic, pasty). 8266 and 8267 were mixed by 100:100 Vol.%, reference ratio, and bonded in the electric furnace of 125°C during 30 min. Added pressure on the adhesive bonding was 1.0 g/mm^2, as the same pressure on every specimen. Table 1 shows the properties of adhesive and the reaction product.

Tensile, shear and four-point bending test were conducted with a hydraulic material testing machine, Instron 8516, and the load cell of 500 kg was used. Crosshead speed maintained constant 3 mm/min to make the same condition for three kinds of tests. The data were obtained with 50 Hz. The equipment of shear test was specially designed for small specimens such as ceramic or metal adhesive joints. There was attached micrometer for better accuracy.

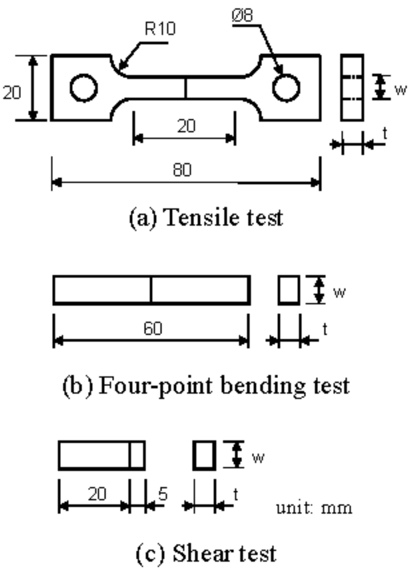


Fig. 1 Specimen configurations

Table 1 Properties of adhesive

Product data

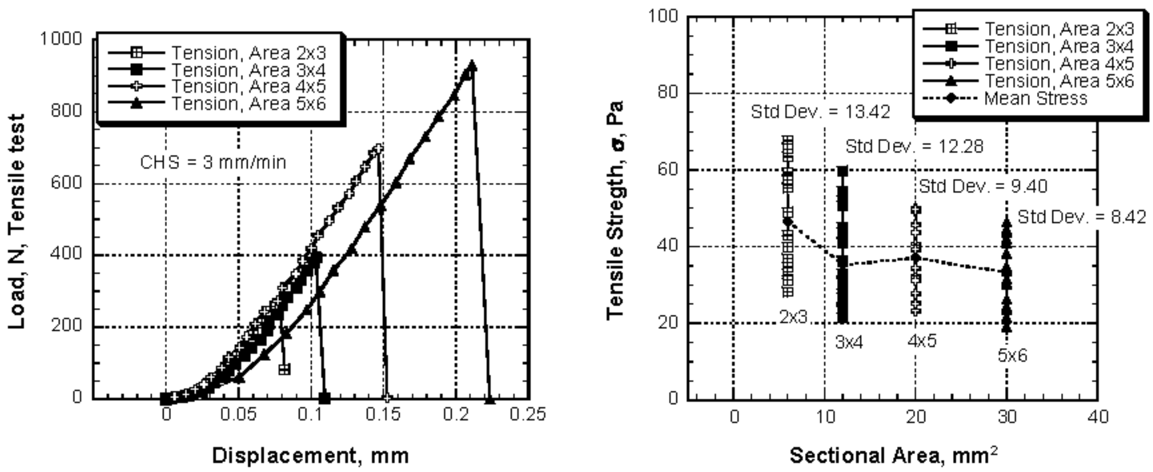
Technicoll	8266 comp. A	8267 comp. B
Component	Epoxy resin	Amine setting agent
Mixing ratio (v/v)	100	100
Density	1.30 g/cm^3	1.10 g/cm^3
Viscosity(25℃)	496±160 Pas	400±96 Pas

Reaction product

Hardness(set 30min/120℃)	70±5 Shore D
Weight/Volume	1.20±0.05 g/cm^3
Peeling strength(set 2h/100℃)	ca. 4.5 N/mm
Bonding strength(after 7d/22℃)	240hr at RT

3. Results and discussions

Fig. 2 shows fracture behaviors of tensile test with various sectional areas. As the figure, we can use the statistical analysis of Weibull, because the fracture behaviors of the specimens follow brittle fracture. Even though thermoplastic epoxy adhesive has rather ductile fracture behavior, it has brittle fracture behavior caused by layer adhesive bonding between two stainless steel surfaces. From Fig. 2 (b), the specimen of 5×6 mm^2 has the smallest standard deviation, in other words the larger sectional area gets, the less stress the specimen has. Because the defect, directly effected on fracture strength, namely the part of incomplete adhesive structure may has relatively uniform distribution as sectional area under the stress increases.



(a) Load vs. displacement (b) Strength vs. sectional area

Fig. 2 Fracture behavior of tensile test with various sectional area

3.1 Effect of sectional area

Fig. 3 shows the diagram of the tensile test results according to sectional area by Weibull theory. The *m* means Weibull modulus, and the degree of incline obtained, using the least square method one data under the one condition. The *m* value of 5×6 mm^2 was the biggest, 4.049, in the case of tensile test. Higher *m* means higher probability comparing with another specimens. The result of Fig. 2 (b) on the standard deviation is the same tendency with Fig. 3. Because the distribution of the defects becomes uniform in the specimen as the adhesive sectional area increases. However, Weibull modulus has little difference, that is, the effect of sectional area is not high on the probability.

The Weibull plot of four-point bending test is shown in Fig. 4. Relatively small specimens, 2×3 and 3×4 mm^2, have bigger *m*, and specimen of 3×4 mm^2 had the biggest probability. There is tensile stress between outer supporters and compressive stress between inner supporters, because of the geometrical characteristics of four-point bending test. The inner compressive stress makes the crack growth stop instantly due to structural reason. In other words, it causes the increase of strength. Fracture behavior like these is observed when the sectional area is larger, and it is the main reason to make the probability of the adhesive worse. Namely the specimen with small sectional area has big deflection, and the restraint of structural crack decreases.

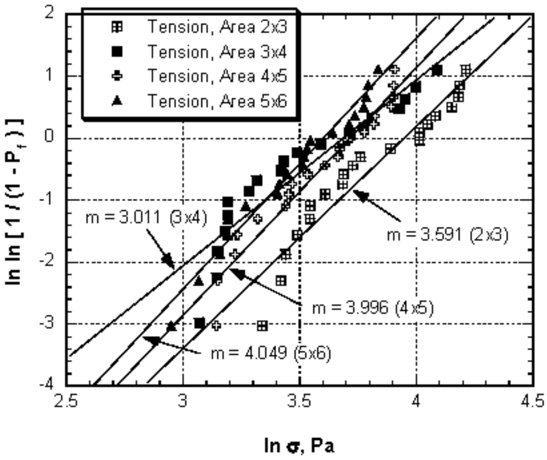


Fig. 3 Weibull plot of tensile test with various sectional area

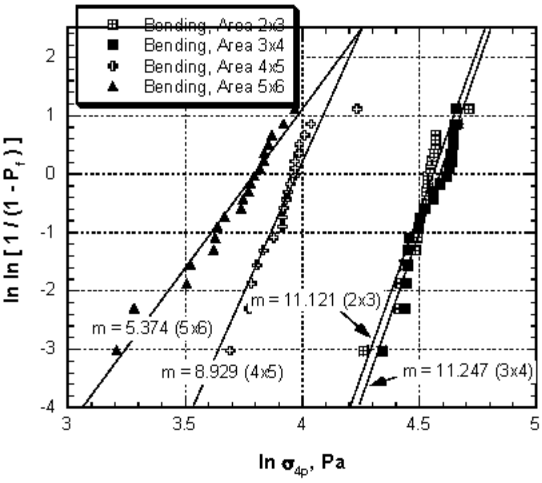


Fig. 4 Weibull plot of four-point bending test with various sectional area

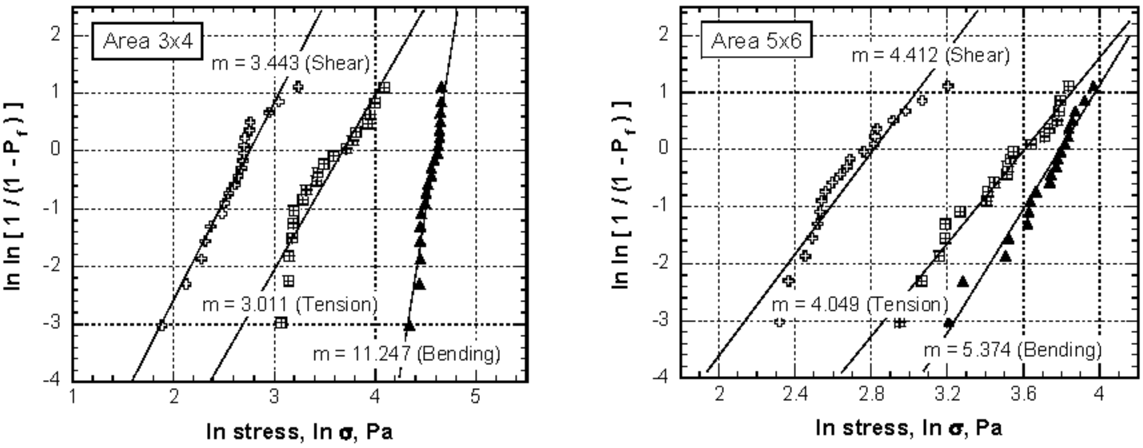
3.2 Effect of test method

Fig. 5 shows the change of Weibull modulus according to various tests with same sectional area. Fig. 5 (a) shows four-point bending test has the highest probability with the area of 3×4 mm^2. And tensile and shear tests have the almost same value of Weibull modulus. Fig. 5 (b) shows that Weibull modulus of four-point bending test is also the biggest value. For tensile and shear tests, m value were almost same. In general, tensile test has the best probability, however four-point bending test has the best one because there is no effect of eccentricity and the test equipment is relatively simple. Adhesive bonding and derailment of the applied line of load cause the eccentricity. And the fracture behavior by the structural characteristics of four-point bending test increases the probability. From Fig. 5, the shear testing with the small area has the almost same level of probability as tensile testing or has higher.

Table 2 shows the results of tests. The mean strengths cannot be compared with those of other test methods because their equations are different. Probability increases according to the increase of sectional area, because the possibility to become relatively uniform distribution of the defect within the layer of adhesive bonding as Weibull moduli of tensile and shear test show the value of probability. However the case of four-point bending test doesn't show the best probability for the biggest specimen because the defect distribution of adhesive bonding layer and the action of inner compressive stress make an effect on fracture behavior. From the results of four-point bending test, 3×4 mm^2 specimen has the highest probability. The shear test has the distribution of the least strength, however, has the least standard deviation among three kinds of test. That is, shear test is less affected by sectional area comparing with others. And we can confirm that each sectional area has relatively uniform deviation and probability.

3.3 Classification of fracture surface

After failure, the fracture shape of adhesive surface had different features according to the strength distribution. Fig. 6 shows the fracture surfaces of specimens with ×50 magnification and they are classified according to the range of the applied strength and sectional area. The bright field is the surface of metal, and dark field is the adhesive left, not torn out. We can observe that there is large part of adhesive torn out from metal surface when it failed in the relatively lower strength to all test methods. And the adhesive left on metal surface has irregular shape. Comparatively the crack grew along the inside of epoxy adhesive in the case of higher strength, and the fracture surface has the condition of relatively uniform surface roughness. In the case of the mean strength, the conditions of maximum strength and minimum strength are mixed. There is less adhesive torn from metal surface comparing with the case of minimum strength, and the surface is more rough than one of the case of maximum strength. However, the shape of facture surface is not changed according to sectional area. And bright field is observed where the stress concentrate for four-point bending test and shear test.

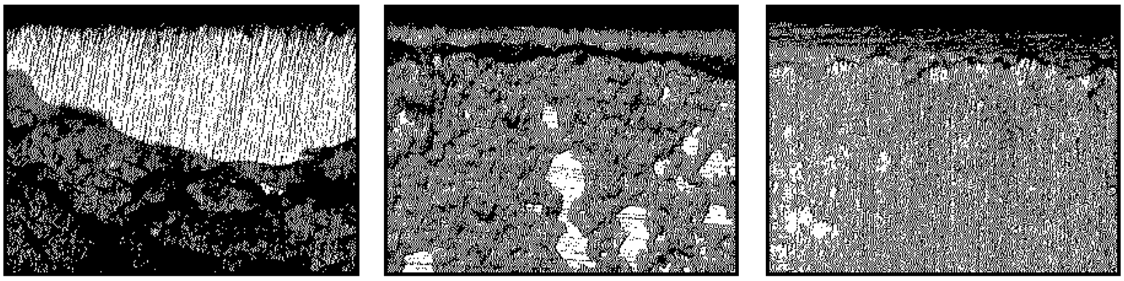


(a) Area 3×4 mm^2 (b) Area 5×6 mm^2

Fig. 5 Weibull plot of various test methods in same area

Table 2 Weibull data of tensile, bending and shear strength

Test method	Area (mm^2)	Mean strength (Pa)	Max. strength (Pa)	Min. strength (Pa)	Std. deviation (Pa)	Weibull modulus	No. of spec.
Tensile	2×3	46.59	67.62	28.21	13.42	3.59	20
	3×4	35.36	59.74	21.50	12.28	3.01	19
	4×5	37.12	49.78	23.17	9.40	4.00	20
	5×6	33.33	46.41	19.10	8.42	4.05	20
4-Point bending	2×3	91.92	111.1	70.95	8.39	11.12	20
	3×4	94.66	105.3	76.68	8.71	11.25	20
	4×5	50.97	68.97	40.16	6.02	8.93	20
	5×6	41.18	52.91	24.70	7.41	5.37	20
Shear	2×3	10.35	17.55	5.30	3.07	3.49	19
	3×4	14.07	25.46	6.60	4.32	3.44	20
	4×5	16.74	32.24	10.86	4.76	3.97	19
	5×6	15.12	24.62	10.17	3.75	4.41	20



(a) Min. strength (b) Mean strength (b) Max. strength

Fig. 6 Fracture surfaces with strength fields

4. Conclusions

In this study, the epoxy-based adhesive metal-joints were used to evaluate the strength and probability. The thermoplastic epoxy-based adhesives have a tendency of brittle fracture such as ceramic material. The conventional test methods such as tensile, shear and four-point bending test were conducted to evaluate the probability of adhesive strength. And the effect of the adhesive sectional area on the adhesive strength was evaluated. The following conclusions were obtained from this study.

(1) Specially designed equipment test of shear test especially has the equivalent probability to conventional tensile test.

(2) The adhesive joint between metals with thermoplastic epoxy resin based adhesive has the best probability in four-point bending test. Probability of the general strength tests is like the following; four-point bending test > shear test ≥ tensile test.

(3) The specimen of sectional area 5×6 mm^2 has the best probability for tensile and shear tests, 3×4 mm^2 specimen has the best one for four-point bending test. And the shear test is less affected by sectional area comparing with others.

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