Effect of Joint Reformation on Adhesive Strength of 6061 Aluminum Alloy to Polycarbonate Lap Structures

D. W. Seo, H. J. Kim, and J. K. Lim

Abstract

Adhesive-bonded joints are widely used in the industry. Recently, applications of adhesive bonding joints have been increased extensively in automobile and aircraft industry. The strength of adhesive joints is influenced by the surface roughness, adhesive shape, stress distribution, and etc. However, the magnitude of the influence has not yet been clarified because of the complexity of the phenomena. In this study, as the fundamental research of adhesive bonding joints, the effects of adhesive shape and loading speed on bonding strength properties and durability of aluminum to polycarbonate single-lap joints were studied. To evaluate the effect of adhesive shape, several modified shapes were used, and loading speeds were varied from 0.05 to 5mm/min. As a result, the load distribution showed a brittle fracture tendency. The trigonal edged single lap and bevelled lap joints showed the higher strength than the plain single lap, trigonal single lap, joggle lap and double lap joints in same adhesive area. The fractures of trigonal single lap and trigonal edged single lap joints that had the higher strength level were shown as the mixture type of the cohesive and interfacial-failure, mostly joggle lap joints that had the lower strength level were shown as the adhesive-failure.

Key Words : Adhesive joint, Adhesive strength, Lap joint, Reformation, Loading speed, Surface treatment.

1. Introduction

Adhesive bonding method has been widely applied in the aerospace industries, automobile and construction industries, it is technology to be applicable on a wide scale in many fields of manufacturing.[1~5] Adhesive bonding is fractionated by structural adhesives and nonstructural adhesives according to adherend materials bonded by surface adhesive.[6] In the structural adhesives, adhesives must be endured yield strength of material and main load of structure.[6] Recently, adhesive are used for sealing insulation and vibration damping properties.[7] But application of structural adhesive bonding method is less used than welding or other mechanical joining methods. Adhesive bonding is joining method to be distributed stress than another mechanical joints or welding.[4] It shows complex strength distribution in all part of material. The light structures can be easily produced using adhesive methods. Adhesive bonding is used to require for simpler, cheaper and more environmentally friendly process.[3] The design of adhesive joint is considered to choice adhesives, surface treatment, adhesive shape and curing. Adhesives are chosen by a manufacturing process, and curing method is decided according to

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adhesives.[8] Therefore, the design of adhesive joint after selecting adhesives is a conclusion in adhesive shape, size and surface treatment. Usually, most adhesive bonding methods are single-lap joint, double-lap joint and butt joint. Single lap joint is generally used. The design of single lap joint must be decided to lap length, adhesive thickness and surface treatment of joint, it is important for adhesive design to evaluate relationship of strength and influences in these elements.[9] The joining mechanism of adhesive structures acts under mechanical and chemical reaction. After surface treatment, structure, shape and chemical change effect adhesive capacity.[9] Therefore, it is important to evaluate relationship between joint shape and strength of adhesive joint in structural elements of adhesive bonding study.[9,10]

In this study, it is showed that reformation of joint shape affects adhesive strength and durability of aluminum to polycarbonate lap joints, and loading speed affects tensile shear strength of adhesive joints.

2. Theoretical background

2.1 Theory of adhesive joints

Although much is known about particular aspects of adhesion, widely divergent views exist with respect to others. No single mechanism or theory can satisfactorily explain all of joining mechanism taken place in an adhesively bonded joint. Regardless of the specific mechanism or mechanisms responsible for adhesion in adhesive bonding, a substantial proportion of the attractive forces between adhesives and adherends arise from chemical bonding. Two principal secondary bonding interactions that contribute to adhesion are Van der Waals bonds and permanent dipole bonds. Van der Waals secondary bonding arises from the fluctuating-dipole nature of an atom with filled electron shells, while permanent dipole bonding arise when two polar molecules with asymmetrically distributed charge attract one another's oppositely charged ends to produce a combination with a lower net energy. Also, according to the mechanical theory of bonding, for an adhesive to function properly, it must penetrate the microscopic asperities on the surface of the substrates and displace any trapped air at the interface. Adhesion is thus believed to be the result of mechanical interlocking or anchoring, with no need for any secondary bonding. A secondary theory of adhesion attributes the adhesive force to the molecular contact that occurs between two materials and the resulting surface forces. The process of establishing intimate contact between the adhesive and the adherend is called wetting. Wetting is the process in which a liquid spontaneously adheres to and spreads on a solid surface and is controlled by the surface energy of the liquid-solid interface versus the liquid-vapor and the solid-vapor interfaces.

2.2 Adhesive joints failure

While there seem to be many mechanisms that can operate singularly or in various combinations to produce adhesive bond strength, there are also different mechanisms by which an adhesively bonded joint can fail. The two predominant mechanisms of failure in adhesively bonded joints are adhesive failure or cohesive failure.[1] Adhesive failure is interfacial failure between the adhesive and one of the adherends and tends to be indicative of a weak-boundary layer, often due to improper preparation. Cohesive failures when fracture results in a layer of adhesive remaining on either adherend surfaces or, more rarely, when the adherend fails before the adhesive, with fracture totally contained in the adherend. This latter mechanism is known as cohesive failure of the substrate. Premature failure of adhesively bonded joints, as well as any joint, is always a serious concern. The precise cause of premature failures in adhesively bonded joints is difficult to determine[1] ; much more difficult than for joints produced by other processes. For example, if the adhesive fails to wet the surface of the adherend completely during adhesive application, the bond is certain to be unsuitable. Internal stress arising from adhesive shrinkage during setting, or stresses from different coefficients of thermal expansion can cause premature failures. The types of stress acting on the completed bonds, their orientation to the adhesive, and the rate of application are also important factors influencing

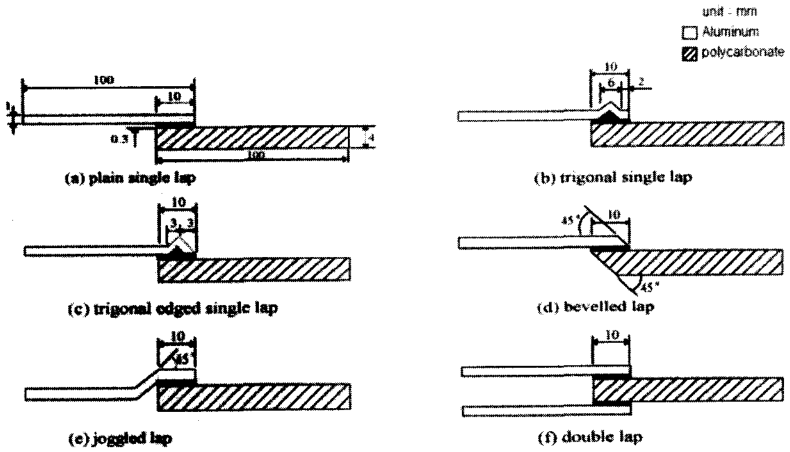


Fig. 1 Schematic diagram of various lap joint specimens

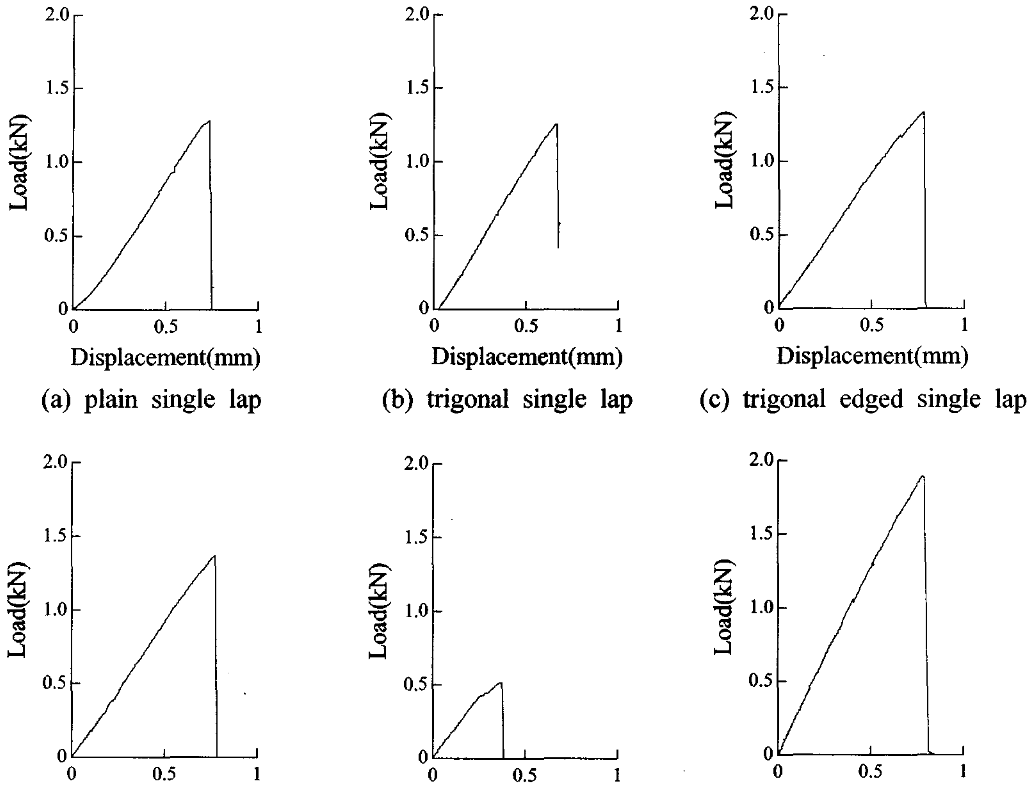
on the failure.

3. Material and experimental procedure

Specimens were prepared according to ASTM D3163.[11] The substrates, i.e. adherends were AA6061-T8 aluminum alloy and polycarbonate sheet. The dimension of aluminum sheet used to make the join was : length 100mm, width 25mm and thickness 1mm. For polycarbonate, length is 100mm, width 25mm and thickness 4mm. The joint overlap length was 10mm resulting in a pre-cured 250mm^2 effective bond area. The geometry and dimensions of the tensile-shear specimens are shown in Fig. 1. Joint shapes of adherend were modified as 6 kinds of joint shape from the standard of single lap joint. Surfaces of adherends were treated by sand blasting of #42. The roughness of adherends measured after surface treatments are shown in Table 1. Epoxy adhesive was prepared in accordance with manufacturer's instruction, mixing Techicoll 8266 component A (resin) and 8267 component B (hardener) in equal volumes using a 10ml syringe. Prior to curing, the join was prepared to a constant adhesive thickness (0.3mm) by inserting thin wires of 0.3mm diameter on joining region. For all specimens, a constant pressure (23.52kPa) was applied perpendicular to overlap area. The curing temperature was 125℃ in air and holding time was 30 min. The adhesive strength was conducted after aging of 120 hrs at room temperature. The tensile-shear strength was tested using an Instron hydraulic machine, model 8516. To evaluate the effect of loading speed on adhesive strength at room temperature, test were carried out at various loading speed, i.e. CHS (crosshead speed) = 0.05, 0.5 and 5.0 mm/min.

Table 1 Properties of adhesive bond

Product data		
Description	Technicoll 8266 comp. A	Technicoll 8267 comp. B
Density	1.30±0.05g/㎤	1.10±0.05g/㎤
Viscosity	496±160Pas (25℃)	496±96Pas (25℃)
Properties of the reaction product		
Hardness	70±5 Shore D (set 30 min at 120℃)	
Weight/ Volume	1.20±0.05g/㎤	
Peeling strength	ca. 4.5N/㎟ (setting 1d/RT and 2h/100℃)	
Bonding strength	ca. 20-20N/㎟ after 7d/22℃ ca. 30-32N/㎟ after 30min/125℃	



(a) plain single lap (b) trigonal single lap (c) trigonal edged single lap

(d) bevelled lap (e) joggle lap (f) double lap

Fig. 2 Load-displacement curves at CHS = 0.5mm/min

4. Results and discussion

4.1 Load-displacement curves

Typical relations between load and displacements of aluminum/polycarbonate joints at CHS=0.5mm/min according to various adhesive shape are shown in Fig. 2. All these curves show the tendency of brittle fracture. In the case of PSL, TSL, TESL, BL, maximum load are distribute 1.2-1.4kN, load are shown 0.5kN in the JL and 1.7-2.5kN in the DL. The reason of showing maximum load in case of DL specimen is due to the same adhesive type of Al ; because adhesive area was wider than another specimens.

But the stress shows similar value of PSL. Displacement shows within 0.6-1.0mm, but in the case of JL specimen, 0.4-0.5mm. It started to spread out bending shape, due to applied stress in adhesive joined region. Like this, a tendency of load-displacement curve was showed similar tendency in all crosshead speed. According to increasing of loading speeds, CHS =0.05, 0.5, 5mm/min, load increased about 0.3kN. In the case of CHS=5mm/min, maximum load was shown in the TSL and the TESL specimens, it is due to developing the twice crack in the inside of triangle bends part. Most specimens was fractured at interface between PC and adhesives, but TSL and TESL specimens discovered adhesive interfacial-failure, because of elongation extended about 0.2mm compared with another specimens.

4.2 Effect of adhesive shapes

In the case of JL joint, maximum load is 0.4kN and displacement is 0.35mm as shown in Fig. 2, and this load is lowest value among other specimens. It is considered that this is due to stress concentration of adhesive bending part. Maximum loads of the specimens of another condition (e.g. PSL, TSL, TESL joint) are 0.9-1.0kN and displacements are 0.62-0.75 mm, these specimens shows a similar tendency. But the maximum load of BL specimen is 1.3kN and displacement is 0.78mm. It is considered to increasing chemical reaction and displacement that is due to structural property of upper part of adhesive joints. In the case of DL specimen, maximum load is 1.8kN and displacement 0.86mm, and this DL specimen shows the highest maximum load and displacement than another specimens. It is due to increase of adhesive area, but stress shows the same value as PSL joint which is the same adhesive type. Fig. 3 shows an average strength according to adhesive type with various crosshead speeds (CHS=0.05, 0.5, 5 mm/min). As Fig. 2, the strength of JL specimen shows the lowest strength. Adhesive type shown maximum strength is the TESL specimen, value is 4.8MPa. Also, the strength of BL specimen was 4.75MPa, it is similar with TESL specimen. DL specimen strength is bigger, but it is due that adhesive area is twice, it is similar with PSL strength (3.62MPa). Distribution of strength according to adhesive type increased in the order of JL, PSL, DL, TSL, BL and TESL joint.

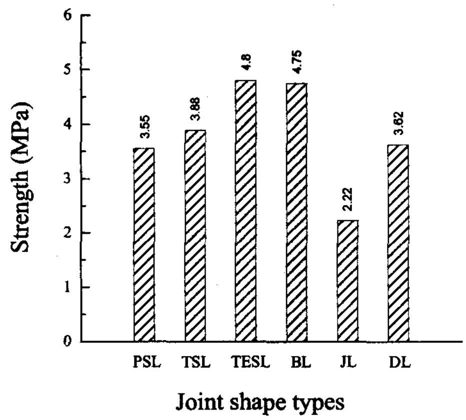


Fig. 3 Strength distributions according to joint shape types

4.3 Effect of loading speeds

Fig. 4 shows strength distributions according to the adhesive joint shapes and loading speeds. The brittle fracture tendency was shown. Generally the strengths increase according to increasing the loading speeds, but it shows the similar tendency with the case of PSL, TSL, TESL and BL joint. But, in the case of JL and DL joint, strength increased particularly at the condition of CHS=5 mm/min. Strength and displacement increased about over 30% than others.

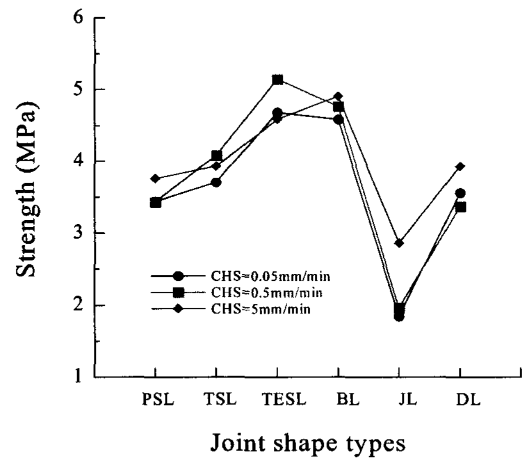


Fig. 4 Strength distributions according to joint shape types with various loading speeds

4.4 Effect of surface roughness

Fig. 5 shows the distribution of strength according to surface roughness. Surface roughness is the value at the interfacial surfaces to be broken, that is, this value is the roughness of polycarbonate because most specimens were fractured at interface between PC and adhesives. As shown in Fig. 5, the distribution of surface roughness is within 13-23μmin all specimens ; effect of surface roughness on strength was not shown. The condition of adhesive shape showed an influence on strength than surface roughness. The specimens classify 3 types according to strength distribution. The specimens types shown the higher strength were BL and TESL joint, the middle strength type was PSL, TSL and DL joint, the lowest strength type was JL joint.

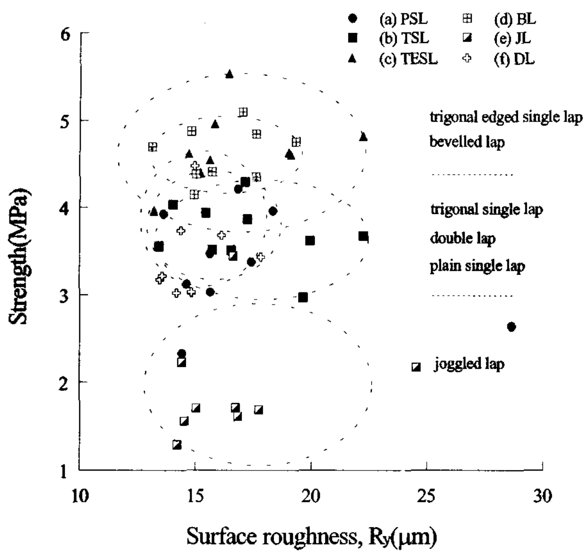


Fig. 5 Strength distributions according to surface roughness with joint shape types

Table 2 Average values of surface roughness

Bonding shape type	Average surface roughness $R_V(\mu m)$		No. of specimen
	AL	PC	
Plain Single Lap (PSL)	21.56	17.21	10
Trigonal Single Lap (TSL)	21.33	16.79	10
Trigonal Edged Single Lap (TESL)	21.00	16.80	10
Bevelled Lap (BL)	19.74	16.11	10
Joggle Lap (JL)	19.70	15.29	10
Double Lap (DL)	22.21	14.88	10
Average value	20.90	16.18	60

4.5 Failure classification

Fig. 6 shows failure modes of adhesive joints in this study. Mode-A shows the cohesive and adhesive failure at the same time. Mode-A is the mixture of cohesive failure and interfacial failure which is occurred by stress concentration between adhesives and adherend. Therefore, Mode-A has cohesive failure part which is located in the overlap and its width is more than 20% per overlap length. Mode-B is also occurred cohesive and adhesive failure at the same time. Mode-A shows similar failure process. But Mode-B has poor cohesive failure part than Mode-A. Its width is less than 20% of overlap length. Mode-C has only adhesive failure. It is because of interfacial failure in the entire overlap of adhesive joint. Fig. 7 shows failure mechanisms after the tests according to adhesive type. The PSL specimen showed Mode-A in all specimens. The TSL and TESL specimens showed Mode-B in 90% of specimens, and Mode-C was also observed in a part. BL specimens showed Mode-A about 70% and Mode-C was also observed in a part of specimens. The JL specimen showed Mode-A and Mode-C in half area. DL specimens showed Mode-A in 90% specimens, was observed Mode-C in a part. In this study, the highest strength was observed in Mode-B mode of TSL and TESL specimens, JL specimens which observed Mode-C was shown in the lowest strength.

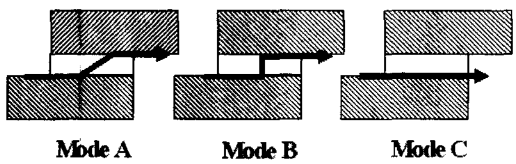
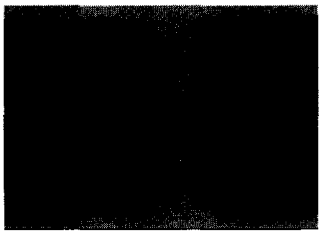


Fig. 6 Failure modes of adhesive joint

5. Conclusion

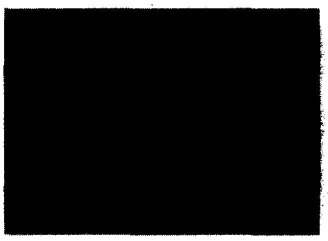
In this study, adhesive lap joints were evaluated mechanical properties to improve adhesive strength between polycarbonate and aluminum with modified joint shapes, and effect of loading speed on adhesive

(a) plain single lap



(b) trigonal single lap

(c) trigonal edged single lap



(d) bevelled lap

(e) joggle lap

(f) double lap

Fig. 7 Photographs of failure surface of Al/PC specimens with various joint shape types

strength was studied with various loading speeds. The results were obtained as follows.

1. Load-displacement curves showed brittle fracture, TESL and BL joint showed the highest strength in the same adhesive area.

2. Effect of loading speed on adhesive strength is not remarkable in all modified joint shapes of lap joint.

3. Adhesive strength was easily affected by adhesive shapes than surface roughness.

4. The fracture type of TSL and TESL which showed the highest strength showed Mode-B mode, mostly joggle lap joints which showed the lowest strength showed Mode-C mode (interfacial failure).

References

1. A. Pirondi and G. Nicoletto : Mixed mode Ⅰ/Ⅱ fracture toughness of bonded joints, *International Journal of Adhesion & Adhesives*, Vol. 22, No. 2 (2002), pp. 109-117
2. A. Higgins : Adhesive bonding of aircraft structures : The effect of moisture on the dimensional stability of adhesively bonded joints, *International Journal of Adhesion & Adhesives*, Vol. 20, No. 5 (2002), pp. 367-376
3. O. Lunder, B. Olsen, and K. Nisancioglu : Pre-treatment of AA6060 aluminum alloy for adhesive bonding, *International Journal of Adhesion & Adhesives*, Vol. 22, No. 3 (2002), pp.143-150
4. A. Roy, C. Mabru, and J. L. Gacougnolle : Damage mechanisms in composite/composite bonded joints under static tensile loading, *Applied Composite Materials*, Vol. 4, (1997), pp. 95-119
5. L. Tong, A. Sheppard, and D. Kelly : Relationship between surface displacement and adhesive peel stress in bonded double lap joints, *International Journal of Adhesion & Adhesives*, Vol. 15, No. 1 (1995), pp. 43-48
6. R. W. Messler : Joining of advanced materials, *Butterworth-Heinemann*, (1993), pp. 108-180
7. S. Bistac : Durability of steel/polymer adhesion in an aqueous environment, *International Journal of Adhesion & Adhesives*, Vol. 18, No. 5 (1998), pp. 365-369
8. W. Wylde : Measurement of adhesive joint fracture properties as a function of environmental degradation, *International Journal of Adhesion & Adhesives*, Vol. 18, No. 4 (1998), pp. 237-246
9. G. Belingardi, L. Goglio, and A. Tarditi : Investigating the effect of spew and camber size on the stresses in metal/plastics adhesive joints, *International Journal of Adhesion & Adhesives*,

Vol. 22, No. 4 (2002), pp. 273-282

10. D. W. Seo, H. C. Yoon, S. C. Yoo, J. K. Lim, and L. Dorn : Effect of surface treatment on adhesive strength properties of Al/PC adhesive joints, *Transactions of the KSME*, Vol. 27, No. 5 (2003), pp. 840-847
11. ASTM D3163-96, *ASTM*, Pennsylvania, (1998)