Deformation Characteristics and Delamination Strength of Adhesively Bonded Aluminium Alloy Sheet under Plastic Bending*

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Press-formed sheet metal parts are usually adhesively bonded together at the final stage of assembly. Instead of such a conventional process, a new technique of press-forming of adhesively bonded sheet metals was investigated. In this process, first flat sheets are adhesively bonded, and then press-formed into final shapes. From V-bending experiments on adhesively bonded aluminium alloy sheets, it was found that large shear deformation occurred in the adhesive layer during the bending, which in some cases lead to the delamination. Both from the experimental observations and numerical simulation, it is concluded that the large shear deformation of the adhesive layers can be suppressed when performing air-bending of enough long span, rather than die-contact V-bending.

Key Words: Plastic Working, Bending, Adhesive Joints, Aluminium Alloy Sheet, Experimental Strain Analysis, Numerical Analysis, Adhesive Strength

1. Introduction

Recently, the strength and reliability of structural adhesives have become much higher than before, consequently, adhesive bonding is being used increasingly in many industrial fields for assembling structural elements. Adhesive bonding has several advantages over the other joining techniques such as welding and diffusion bonding, e.g., any dissimilar metals are easily bonded together, there is no need to care about the thermal strain which is often induced by welding, the adhesive layer can play the role of vibration damping, and moreover, it makes possible to produce easily light-weight and high-precision mechanical parts and constructions.

In the sheet metal industries, press-formed sheet elements are usually adhesive-bonded together at the

final stage of assembly. Instead of such a conventional process, if it could be possible to make the process sequence inverse in such a way that first flat sheets are adhesive-bonded together and then press-formed into the final products, it would be an excellent technique from the viewpoint of high productivity. As for other related subjects, there are some papers⁽¹⁾⁻⁽⁴⁾ which dealt with press-forming of metal-resin composite sheets, such as vibration damping steel sheets. However, these papers mainly discussed the geometrical imperfections of press-formed composite sheets, such as *gull-wing bend* which is induced by the transverse shear deformation of the sandwiched resin layer, but did not pay much attention to the failure (or reduction of strength) of the resin layer during bending. In the press-forming of adhesively bonded sheet metals, the lap length may affect the deformation behaviour and the delamination, however, so far it has never been investigated.

In the present work, a new technique of press-forming of adhesively bonded sheet metals was investigated using a special adhesive with high strength and high ductility. The mechanical properties in terms of strength and ductility of the adhesive were determined by tension tests of single-lap joint. The transverse shear deformation of the adhesive layer in adhesively bonded aluminium alloy sheets under V-bending were

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examined, and furthermore, the effect of the bending-induced shear pre-strain on the adhesive strength was investigated. Based on the plasticity analysis, the mechanism of shear deformation of the adhesive layer in the course of bending, as well as the bending conditions for suppressing the large shear deformation of adhesive layer, are discussed.

2. Shear Deformation and Strength of Adhesive Layer in Tensile Lap Shear Tests

2.1 Adhesive and lap-joint specimen

The adhesive employed in the present work was an acrylic adhesive *M-372-20 Hardrock* (Denki Kagaku Kogyo, Co., Ltd.). This adhesive has high ductility, as well as high strength of the same level as conventional epoxy adhesives. An aluminium alloy sheet (A5083P-O) of 1.0 mm thick was used as adherend. Figure 1 shows the shape and dimension of the single-lap joint specimen (hereafter, SLJ, as abbreviation) used for tensile lap shear test. In order to reduce the effect of bending deformation of the adherend during stretch-shear experiments, another type of single-lap specimen, as shown in Fig. 1(b), where each aluminium alloy sheet was reinforced by a steel plate (SS400) of 2.6 mm thick (adhesively bonded together), was also prepared. The lap length was chosen as 8 mm long so that the adherend sheet would not yield before the fracture of the adhesive.

The surface of the metal sheets were polished using sandpapers (grade No. 150), and after that, it was washed and cleaned with acetone. When the surface of the sheets were completely dried, they were bonded together and cured at a temperature of $25 \pm 2^\circ\text{C}$ with a humidity of $60 \pm 10\%$. On the lateral side of the specimen, 1-mm pitch lines were scribed for the measurement of the relative displacement between two face sheets of the specimen (i.e., the transverse

Fig. 1 Two types of single-lap joint specimens

shear deformation of the adhesive layer). The images of the displacement during the tensile lap shear test were observed by a fifty-power microscope and recorded on a video.

Figure 2 illustrates the stress-strain (σ - ϵ) curve of the aluminium alloy sheet (A5083P-O) under uniaxial tension with a cross-head speed of 0.1 mm/min, where open circles are experimental data and the solid line is the curve calculated by the following equation:

$$\sigma = c\epsilon^n \quad (c=643, n=0.316). \quad (1)$$

The above constitutive equation is used for the stress analysis which will be mentioned in section 4.

2.2 Tensile lap shear tests

It is well known that the adhesive strength is strongly influenced by the condition of adhesion, such as the thickness of adhesive layer and curing time⁽⁵⁾, therefore, in preliminary experiments, the curing time of adhesive bonding and the appropriate thickness of adhesive layer were determined. It was found that, at room temperature, at least one full day is necessary for bonding, and after that the adhesive strength gradually increases with curing time and saturated within a week. Concerning the thickness of the layer, the highest strength of the adhesive layer was measured when it was around 0.1 mm thick. Therefore, in our experiments, the specimens of 0.1-mm adhesive thickness were prepared with a week curing. The tensile lap shear tests were conducted with two different speeds of 0.1 and 0.01 mm/min (quasi-static speed).

Figure 3 illustrates the shear stress-strain curves of the adhesive obtained from the tensile lap shear tests. It shows that this adhesive has high ductility and also strong rate-sensitivity in flow stress. It should be noted that there is a considerable difference in the experimental results between SLJ and SLJ+steel specimens. For SLJ specimen, the effect of peeling stress (the normal stress acting on the adhe-

Fig. 2 Stress-strain curve of aluminium (A5083) sheet

Fig. 3 Shear stress-strain curves of adhesive

sive) is not negligible in the tensile lap shear test since the bending of the sheets is more likely to occur, compared to SLJ+steel specimen. This is the main reason why adhesive strength determined for SLJ+steel specimen is apparently higher than that of SLJ specimen. For the stress analysis of V-bending (in section 4), therefore, the determination of the constitutive equation for the adhesive, we should use the experimental data of SLJ+steel specimen rather than SLJ specimen. It was found that the following constitutive equation is a good choice for the adhesive:

$$\tau_a = C_a \gamma_a^{n_a} \quad (C_a = 11.56, n_a = 0.234), \quad (2)$$

where the material constants C_a and n_a were determined from the experimental data of the tensile lap shear test, using SLJ+steel specimen, conducted at quasi-static condition ($V = 0.01$ mm/min). The calculated shear stress-strain curve by Eq.(2) is shown with thick solid line in Fig. 3.

As a measure of forming limit of adhesively bonded sheet metals under bending, it is important to know the critical shear strain of the adhesive only below which the adhesive layer keeps enough strength. From the experimental data of tensile lap shear tests, it was found that its value lies between 2.1 (found for SLJ+steel specimen) and 2.6 (for SLJ specimen).

From the observation of the fracture surfaces of the specimens, it was found that, in any cases, the fracture mostly occurred at the inside of the adhesive layer, but not at the interface between the adhesive and the sheet metals.

3. V-bending of Adhesively Bonded Sheet Metals

3.1 Deformation behaviour of adhesively bonded sheet metals during V-bending

Among several types of bending processes, the present paper exclusively deals with V-bending. Figure 4(a) shows the shape and dimension of the specimen, and Fig. 4(b) illustrates the experimental

Fig. 4 Specimen and experimental set-up for V-bending test

Table 1 Experimental conditions of V-bending

Punch radius R_p (mm)	Lap length l_p (mm)	Die span L (mm)
0.5, 5.0	30	20
	40	27
	50	34
	70	48

set-up for V-bending experiment. Table 1 indicates experimental conditions of V-bending. It had been found in preliminary experiments that the *gull-wing bend* is likely to occur when the lap length, l_p , is much longer than the die-span, L . Therefore, in order to examine the effect of l_p and L , several combinations of l_p and L were chosen (see Table 1). In this experiment, L was determined for a given l_p such that the overhang of the lapped part is about 25 mm long when V-bending have finished. It should be noted, in the following discussion on the effect of l_p , it includes the l_p -dependent change of L . The punch speed, V , in the V-bending experiment was 1 mm/min, where the shear deformation rate in the adhesive layer was less than 0.01 mm/min, which is regarded as an quasi-static deformation.

Figure 5 shows a schematic illustration of deformation behaviour of adhesively bonded sheet metals during V-bending. Figure 5(a) illustrates a state of three-point bending (hereafter, which is called 'air-bending⁽⁶⁾') where the sheet is supported by die edges. As a punch goes down from Figs. 5(b) to (c), the die-contact point of the sheet moves down along the die-slope. When moving the punch further, a certain area of the sheet surface is transversely compressed between the punch and the die-slope (see Figs. 5(d))

Fig. 5 Schematic illustration of deformation behaviour of adhesively bonded sheet metals during V-bending process

Fig. 6 Adhesively bonded specimen after V-bending ($l_p=50$ mm, $L=34$ mm, $R_p=0.5$ mm, $P_{\max}=11.8$ kN)

and (e)). The process shown in Figs. 5(b) - (e) is called 'die-bending'⁽⁶⁾. In our experiments, the punch was stopped at a state of (c) just before (d). The largest punch load $P_{\max}$ was set as large as 11.8 kN. We have chosen such a bending condition so as to avoid the unbending of the sheet which may occur in the states of (d) and (e).

Figure 6 shows an example of adhesively bonded specimen ($l_p=50$ mm, $L=34$ mm, $R_p=0.5$ mm) after V-bending, where slip between upper and lower sheets (large transverse shear deformation in the adhesive layer) occurs. Figure 7 illustrates the shear strain distribution of adhesive layer for the case of punch-tip radius of 0.5 mm ($R_p=0.5$ mm). Almost the same distribution was observed for the case of $R_p=5$ mm. In this figure, the shear strain sharply increases from the punch-loading point and its peak appears at a point of short distance away from the loading point, and then it decreases along the sheet. This result of the shear strain distribution is quite similar to that found in vibration damping sheets⁽¹⁾. In the case of R_p

Fig. 7 Distribution of shear strain of adhesive layer after V-bending ($R_p=0.5$ mm)

$=0.5$ mm, compared to the result of $R_p=5$ mm, larger shear strain peak $\gamma_{a(\max)}$, and the steeper decrease of shear strain along the sheet, was found. In sum, the amount of shear deformation is strongly dependent on the condition of bending in terms of the punch-tip radius, R_p , die span, L , and the punch load, P . In the case of $l_p=30$ mm, large transverse shear deformation occurs all over the lap, while for longer lap the shear strain decreases more rapidly along the sheet. Even so, the maximum value of the shear strain $\gamma_{a(\max)}$ does not differ so much with l_p . This result shows that, as far as die-bending is concerned, longer laps cannot help us to reduce the shear deformation. Although, the critical shear strain measured from the tensile lap shear test was 2.1~2.6 (refer to subsection 2.2), the delamination did not occur in most of bent sheets, even when the amounts of shear strain of their adhesive layers exceeded 2.6 (the delamination was found only in a case of $l_p=30$ mm, where the shear strain reached a value of 3.2). This is because in bending the shear strain at the end of lap is not so large, compared to the tensile lap shear test where the delamination begins at the end of lap because of the high stress concentration.

Figure 8 indicates the deformation behaviour of adhesive layer ($l_p=50$ mm, $L=34$ mm, $R_p=0.5$ mm) in V-bending process. A typical example of the load vs. punch travel in V-bending is illustrated in Fig. 8(a), and the shear strain distributions of the adhesive layer for punch travel A~F, shown in Fig. 8(a), are depicted in Fig. 8(b). From this illustration it can be seen that the shear strain of the adhesive layer does not increase so much during air-bending process (O → A → B), and they grow rapidly from the early stage of die-bending (points, C → F). Therefore, for preventing a large shear deformation in the adhesive layer,

(a) Load vs. displacement curve

(b) Distribution of shear strain of adhesive layer

Fig. 8 Deformation behaviour of adhesive layer in V-bending process ($l_p=50$ mm, $L=34$ mm, $R_p=0.5$ mm)

air-bending process is more suitable than die-bending.

3.2 Adhesive strength after V-bending process

In order to examine the adhesive strength of the sheet after V-bending, a tensile shear test was performed using small specimens cut from several parts of the V-bent sheet, as shown in Fig. 9. In this test, a specimen was set in a pair of jigs, and sheared at a speed of 0.1 mm/min. During the test, the jigs was laterally compressed lightly by rigid plates so as not to be inclined. To reduce the friction, teflon sheets and also petroleum jelly were put between the jigs and the plates. The adhesive strength was determined by subtracting the friction force from the obtained maximum shear force.

Figure 10 shows the result of the adhesive shear strength of the specimens after V-bending. A broken line in this illustration denotes the adhesive strength obtained from the specimen before V-bending, which is regarded as the strength of non-prestrained adhesive. The amounts of pre-strain induced by bending are indicated for each data point. It is found from these results that the adhesive strength τ_a obviously

Fig. 9 Shearing test for strength evaluation of adhesive layer

Fig. 10 Shear strength of adhesively bonded sheet which had been subjected to V-bending ($R_p=0.5$ mm)

decreases when the shear strains are as high as $\gamma_a=2.4\sim3.0$, but small pre-strains ($\gamma_a\leq 1.7$) do not affect so much the adhesive strength. Consequently, it has been confirmed that press-forming of adhesively bonded sheet metals is possible unless the shear deformation of the adhesive is not too large.

4. Discussion on Appropriate Process Conditions Based on Numerical Analysis of Bending

From the experimental results reported in section

3, it is obvious that air bending is more suitable for V-bending for adhesively bonded sheet metals than die-bending. In this section, appropriate process conditions for bending for adhesively bonded sheet metals are discussed based on the numerical analysis of air-bending (i.e. three-point bending).

4.1 Numerical analysis

The idealized model of deformation of each layer of a bonded sheet is illustrated in Figs. 11(a) and (b). For the deformation of face sheet metals, the classical thin plate theory based on the Kirchhoff-Love hypothesis, 'the transverse section, originally normal to the middle surface, remains plane and normal to the surface' was used. On the other hand, for the adhesive layer, the transverse shear deformation is allowed, as shown in Fig. 11(a), although the transverse section is assumed to be kept plane (refer to Yoshida *et al.*'s⁽³⁾ analysis of V-bending of a vibration damping sheet). In these figures, γ_a , τ_a , t_a and t_f represent shear strain of adhesive layer, shear stress and thicknesses of the adhesive layer and each face sheet metal, respectively. Figure 12 shows a schematic illustration of the stress resultant, N_f , and the bending moment, M_f , acting on each face sheet metal.

Let the x - y coordinate be fixed in the specimen, where the x -axis lies on the mid-surface of the adhesive layer, and the y denotes the distance from the mid-surface to a material point. The normal strain in the adhesive layer, ε_a , induced by bending, is expressed as a function of the curvature of the middle surface, κ_0 , and the shear strain gradient, $d\gamma_a/dx$, as follows:

(a) Adhesive layer

(b) Sheet metals

Fig. 11 Deformation of adhesively bonded sheet metal

$$\varepsilon_a = \{\kappa_0 - (d\gamma_a/dx)\}y. \quad (3)^*$$

The strains in the face sheet metals, ① and ②, are given by the equations:

$$\left. \begin{aligned} \varepsilon_1 &= -\frac{1}{2}t_a\left(\frac{d\gamma_a}{dx}\right) + \kappa_0 y \\ \varepsilon_2 &= \frac{1}{2}t_a\left(\frac{d\gamma_a}{dx}\right) + \kappa_0 y \end{aligned} \right\}. \quad (4)$$

Since the distance, y_n , from the mid-surface of the adhesive layer ($y=0$) to the neutral surface is derived by substituting $\varepsilon_1=0$ into Eq.(4), as

$$y = y_n = \frac{t_a}{2\kappa_0}\left(\frac{d\gamma_a}{dx}\right), \quad (5)$$

the distance between the neutral surface and the mid-surface for each face sheet metal, denoted by a , is given by the equation (refer to Fig. 11):

$$a = \frac{1}{2}(t_a + t_f) - y_n = \frac{1}{2}(t_a + t_f) - \frac{t_a}{2\kappa_0}\left(\frac{d\gamma_a}{dx}\right). \quad (6)$$

When using a new measure, $\tilde{y}$, indicating the distance from the mid-surface of each face sheet metal to a material point, ① and ②, the above equations can be rewritten as

$$\left. \begin{aligned} \varepsilon_1 &= \kappa_0(\tilde{y} + a) \\ \varepsilon_2 &= \kappa_0(\tilde{y} - a) \end{aligned} \right\}. \quad (7)$$

The force equilibrium condition for the face metals is expressed by the equation:

$$dN_f/dx = -\tau_a. \quad (8)$$

The bending moment acting on the adhesive layer is negligibly small compared to that of the face metals, then, the moment equilibrium for overall adhesive-bonded sheet is given by the equation:

$$2M_f + (t_a + t_f)N_f = M. \quad (9)$$

Since the stress of the face metals, σ_f , is given by the constitutive equation (Eq.(1)), where the strains are a function of κ_0 and a (Eq.(6)), the stress resultant and the bending moment, N_f and M_f , are calculated as implicit functions of κ_0 and a , as follows.

Fig. 12 Stress resultants and bending moments acting on each layer

* The shear strain of the adhesive layer, γ_a , is defined as $\gamma_a = -\gamma_{xy}$. Also, the shear stress acting on the adhesive/face-metal interface, τ_a , is defined as $\tau_a = -\tau_{xy}$.

$$N_f = \int_{-t_f/2}^{t_f/2} \sigma_f d\tilde{y} = N_f(\kappa_0, a). \quad (10)$$

$$M_f = \int_{-t_f/2}^{t_f/2} \sigma_f \tilde{y} d\tilde{y} = M_f(\kappa_0, a). \quad (11)$$

For air-bending (three-point bending with two supports of which distance is L), as schematically illustrated in Fig. 13, the boundary conditions are:

$$\text{at } x=0, \gamma_a=0, \quad (12)$$

$$\text{at } x=l_p/2, \kappa_0=0. \quad (13)$$

The bending moment M acting on an overall cross-section of the bonded sheet, at a point $A(\xi, \eta)$, is given by the equation:

$$M = P(\xi \tan \theta_d + \eta)/2. \quad (14)$$

Since the coordinate of point A in the current configuration (at a time $t=t$) is not prescribed, instead, for the present numerical simulation, we employ the coordinate obtained at one time-step before (at $t=t-\Delta t$).

The scheme of the present numerical calculation is the following:

(i) A punch load P at a time t is prescribed.

(ii) Assuming κ_0 and η at $x=0$ as initial guesses, $a(0)$, $N_f(0)$ and $M_f(0)$ are determined from Eqs. (7) and (9)~(11).

(iii) $\gamma_a(x)$ and $N_f(x)$ are calculated by integrating the differential equations (6) and (8) with respect to x , and also $M_f(x)$ from Eq. (9). It should be noted that, in Eq. (8), τ_a is a function of γ_a (see Eq. (2)). From Eqs. (10) and (11), $\kappa_0(x)$ and $a(x)$ are determined.

(iv) Initial guesses of $\kappa_0(0)$ and $\eta(0)$ are revised iteratively until the boundary conditions of Eq. (13) are satisfied. In some cases, the curvature becomes zero ($\kappa_0=0$) at a point between the support and the end of the lap ($x=l_p/2$). This is also accepted as a solution for this problem.

(v) The process (i)~(iv) is continued until the bent angle θ_d (or bent load P) reaches its target value.

Fig. 13 Three-point bending

4.2 Discussion on appropriate bending conditions based on the numerical simulation

Figure 14 illustrates the comparisons between calculated and experimental results for bending-induced shear deformation of adhesive layer when $\theta_d=45^\circ$. The calculated results are in good agreement with the corresponding experimental data, consequently, the validity of this analytical method has been confirmed. In this figure, it is found that for air-bending the longer die span, L , leads to the smaller shear deformation of the adhesive layer, while for die-bending large shear deformation always occurs independently of L and l_p (see Fig. 7). The shear strain is mainly dependent on die span, L , but not on lap length, l_p . However, it would be better not to use the larger lap length for a given die span, because it will cause the *gull-wing bend* (refer to subsection 3.1). Details of discussions on the *gull-wing bend* based on the numerical simulation has been reported recently by the present authors⁽⁷⁾.

Figure 15 demonstrates the effects of strength of the adhesive layer on its shear deformation by inputting the virtual data of the strength, which are 1.5 and 2.0 times larger than the actual one, into the numerical simulation for the case of $l_p=30$ mm, $L=20$ mm, $\theta_d=45^\circ$. From these results, it is clear that the stronger adhesive layer leads to smaller shear deformation. This fact suggests that, when employing an adhesive with strong rate-sensitivity, high-speed forming would be quite effective to suppress the shear deformation of the adhesive layer.

5. Concluding Remarks

In the present paper, a new technique of press-forming of adhesively bonded sheet metals has been

Fig. 14 Comparisons between calculated and experimental results for bending-induced shear deformation of adhesive layer ($\theta_d=45^\circ$)

Fig. 15 Influence of strength properties of adhesive on shear strain

proposed. In order to confirm its possibility, V-bending experiments, as well as its numerical simulation, were performed. The main conclusions are summarized as follows:

(1) In V-bending of adhesively bonded sheet, the large displacement between the two face sheets of a specimen (shear deformation of adhesive layer) was found. However it would not cause the decrease of adhesive strength unless the shear strain exceeds a certain value (1.7, in this experiment). Hence, it would be concluded that press-forming of adhesively bonded sheet metals is practicable.

(2) The amount of shear deformation of adhesive layer in V-bending process increases rapidly at the early stages of die-bending process, but it will not become so large during air-bending process. The shear deformation after die-bending is considerably large independently of the lap length and die span. Air-bending process, therefore, would be recommended for V-bending operation for adhesively bonded sheet metals.

(3) For a given die span, the longer lap should not be used, because it will cause larger *gull-wing bend*. In air-bending, the longer lap, and also the longer die span, lead to smaller shear deformation of the adhesive layer.

(4) Numerical simulation of air-bending (three-point bending) was performed. The calculated results are in good agreement with the corresponding experimental data, especially in terms of bending-induced shear deformation of adhesive layer, and thus, the validity of this analytical method has been confirmed. The computer code which has been developed in the present work will be a powerful tool for determining

an appropriate process condition for V-bending (air-bending) of adhesively bonded sheet metals.

(5) The adhesive employed in this experiment has strong rate-sensitivity in flow stress, as well as high ductility. For such an adhesive with strong rate-sensitivity, high-speed bending would be quite effective to suppress the shear deformation of the adhesive layer, since the numerical experiments have clearly shown that the stronger adhesive layer leads to smaller shear deformation.

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