Effect of Forming Speed on Plastic Bending of Adhesively Bonded Sheet Metals*

Michihiro TAKIGUCHI** and Fusahito YOSHIDA***

Using highly ductile acrylic adhesive, the present authors proposed a new technique of plastic bending of adhesively bonded sheet metals. In this process, the suppression of large transverse shear deformation occurring in the adhesive layer, which in some cases would induce the geometrical imperfection (so-called '*gull-wing bend*') and the delamination of the sheet, is one of the most important technical issues. In the present work, the effect of forming speed on bending deformation was investigated. From experimental observations in V-bending experiments of adhesively bonded aluminium sheets, as well as the corresponding numerical simulations which consider the viscoplasticity nature of the adhesive resin, it was found that the large shear deformation and '*gull-wing bend*' are successfully suppressed by high-speed forming since the deformation resistance of the adhesive resin becomes higher at a high strain rate.

Key Words: Plastic Working, Bending, Adhesive Joints, Rate-dependent Shear Strength, Experimental Strain Analysis, Numerical Analysis, Constitutive Equation

1. Introduction

The present authors have recently proposed a new technique of plastic bending of adhesive-bonded sheet metals using highly ductile acrylic adhesive^{(1),(2)}. In this technique, suppression of large shear deformation occurring in the adhesive layer during bending is of vital importance, since it would cause the geometrical imperfection of bent sheets (so-called '*gull-wing bend*'⁽³⁾), and in an extreme case, delamination. In our previous work⁽¹⁾ on plastic bending of adhesive-bonded aluminium sheets, it was found that

—the adhesive strength remains sufficiently high

even after bending, if the shear deformation is within an acceptable limit,

- under a certain condition of bending, namely air-bending with longer lap and longer die span, *gull-wing bend* can be suppressed, and
- the shear deformation becomes smaller with increasing strength of the adhesive.

As for the flow stress of the adhesive resin, we observed in tensile-lap shear tests⁽⁴⁾ that this adhesive has a high rate sensitivity, namely, the higher the shear strain rate, the higher the flow stress. These facts suggest that high speed forming would be effective for suppressing the large shear deformation of the adhesive layer.

In the present paper, the effect of forming speed on the plastic bending behaviour of adhesive-bonded sheet metals, especially on the shear deformation of the adhesive layer and the *gull-wing bend*, is discussed based on the numerical simulation and the experimental observations of V-bending. For that purpose, a new analytical method for V-bending of adhesive-bonded sheet metals, taking account of the viscoplasticity behaviour of the adhesive, is presented, which is an extension of our previously reported method of

* Received 9th June, 2003 (No. 02-0006). Japanese Original: Trans. Jpn. Soc. Mech. Eng., Vol. 68, No. 672, A (2002), pp. 1236-1242 (Received 4th January, 2002)

** Department of Maritime Technology, Hiroshima National College of Maritime Technology, 4272-1 Higashino, Osakikamijima-cho, Toyota-gun, Hiroshima 725-0231, Japan. E-mail: taki@hiroshima-cmt.ac.jp

*** Department of Mechanical Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan

rate-independent plasticity^{(1),(2)}. In this analysis, for the adhesive, a constitutive model of viscoplasticity which we have recently proposed⁽⁴⁾ is used.

It should be emphasized that the effect of forming speed on the plastic bending behaviour of polymer sandwiched sheets has never been reported before, while rate-independent deformation characteristics, such as the effects of core/skin strength differential, bending conditions of span and counter-punch pressure have been reported^{(3),(5)–(10)}.

2. Experimental Work and Numerical Analysis

2.1 Mechanical properties of adhesive and sheet metal

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. Figure 1 shows the shear stress-strain curves of the adhesive determined from tensile lap shear experiments⁽⁴⁾, where the shear-strain rate $\dot{\gamma}$ was determined as $\dot{\gamma} = V/t_a$ (V : cross-head speed of the testing machine; t_a : thickness of the adhesive layer). In this figure, strong rate sensitivity in flow stress is observed. To describe such rate-dependent stress/strain responses, we have proposed the following constitutive equation⁽⁴⁾:

$$\tau = C\dot{\gamma}^n + D(1 + k\dot{\gamma}^a)(1 - e^{-b\dot{\gamma}^m}), \quad (1)$$

where γ and $\dot{\gamma}$ stand for the shear strain and its rate of the adhesive, respectively. In Fig. 1, the solid lines show the stress-strain curves calculated by this model, where the material parameters are listed in Table 1. This model can well capture the rate-dependent behaviour of the adhesive.

An aluminium alloy sheet (A5083P-O) of 1.0 mm thickness was used as adherend. Figure 2 illustrates the stress-strain curve of the sheet under uniaxial tension, where open circles are experimental data and the solid line is the result calculated by the following equation:

$$\sigma = C_{al}\epsilon^{n_{al}} \quad (C_{al}=643, n_{al}=0.316). \quad (2)$$

By this equation, the yield plateau, which appears in the actual stress-strain curve, cannot be described, however, it would not cause a serious calculation error since the yield-plateau strain is very small (approximately 0.02) compared to the bending strain (0.1~0.2 at the surface).

The surfaces of the metal sheets were polished using sandpaper (grade No. 150), then, they were washed and cleaned with acetone. When the surfaces 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 $60 \pm 10\%$.

Table 1 Material parameters of acrylic adhesive resin (*M-372-20 Hardrock*, Denki Kagaku Kogyo, Co., Ltd.)

C (MPa)	n	D (MPa)	k	a	b	m
7.7	0.222	3.02	5.65	0.183	2.39	0.352

Fig. 1 Shear stress-strain curves of adhesive

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

2.2 V-bending

V-bending under air-bending condition was investigated since it has an advantage over die-contact bending in reducing the shear deformation of the core adhesive^{(1),(2)}. Figure 3(a) shows the shape and dimension of the specimen, and Fig. 3(b) illustrates the experimental setup for the V-bending experiment. In these figures, P , l_p , L and x represent punch load, lap length, die-span and distance from the bending center, respectively. 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, λ_a , (i.e., the transverse shear deformation of the adhesive layer). By measuring the shear deformation of the adhesive layer λ_a using a scanner (EPSON GT-7600U), the shear strain of

Table 2 Experimental conditions of V-bending

Lap length l_p (mm)	Die span L (mm)	Punch speed V (mm/min)
50	20	1
		20
		500

(a) Specimen

(b) V-bending

Fig. 3 Specimen and experimental setup for V-bending test

adhesive layer, γ_a , was determined as $\gamma_a = \lambda_a / t_a$. The error in measurement of λ_a was approximately $\pm 5 \mu\text{m}$. The thickness of the adhesive layer, t_a , was controlled so as to have a value of 0.1 mm, however it had scattered values between 0.106 and 0.121 mm.

Table 2 shows the experimental conditions for V-bending. To examine the effect of forming speed on the deformation characteristics of the sheet, particularly in terms of *gull-wing bend*, a span of 20 mm, which is significantly shorter than the lap of 50 mm, was chosen because in this condition the *gull-wing bend* is likely to occur. The V-bending experiment was conducted at room temperature, where the punch travel was 8 mm for all the testings.

2.3 Numerical analysis

A schematic for air-bending is shown in Fig. 4. After obtaining all of the statical and kinematical quantities (stresses/strains of face metals and the adhesive, as well as sheet geometry) at time $t=t$, let us discuss the analytical scheme for the determination of the solution after the next time step Δt , at $t=t+\Delta t$.

The idealized model of deformation of each layer of a bonded sheet is illustrated in Figs. 5(a) and 5(b). For the deformation of face sheet metals, the

Fig. 4 Schematic of deformation of an adhesively bonded sheet in a time step Δt under three-point bending

(a) Adhesive layer

(b) Sheet metals

Fig. 5 Deformation of adhesively bonded sheet metal

classical thin plate theory based on the Kirchhoff-Love hypothesis, which states that '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 of the Mindlin type⁽¹¹⁾, as shown in Fig. 5(a), is assumed. In these figures, γ_a , τ_a , t_a and t_f represent shear strain of the adhesive layer, and shear stress and thicknesses of the adhesive layer and each face sheet metal, respectively. Figure 6 shows a schematic of the stress resultant, N_x , and the bending moment, M_x , acting on each face sheet metal.

Let the $x-y$ coordinates be fixed in the specimen, where the x -axis lies on the mid-surface of the adhesive layer, and the y coordinate denotes the distance from the mid-surface to a material point. The normal strain in the adhesive layer, ϵ_a , induced by bending, is

Fig. 6 Stress resultants and bending moments acting on each layer

expressed as a function of the curvature of the middle surface, κ_0 , and the shear strain gradient, $d\gamma_a/dx$, as follows (refer to Yoshida⁽⁷⁾):

$$\varepsilon_a = [\kappa_0 - (d\gamma_a/dx)]y. \quad (3)$$

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

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

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. 5(b)):

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

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

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

The force equilibrium condition for the face metals is expressed by

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

It should be noted that shear stress τ_a is a function of shear strain γ_a and its rate $\dot{\gamma}_a$, as represented in Eq. (1). If the bending moment acting on the adhesive layer is negligibly small compared to that of the face metals, then the moment equilibrium for the overall adhesive-bonded sheet is given by

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

In the present analysis of air-bending (three-point bending), bending moment $M(x)$ acting on an overall cross-section of the bonded sheet is explicitly determined for a given punch load $P^{(1),(2)}$. Since the stress

of the face metals, σ_f , is given by the constitutive equation (Eq. (2)), where the strains are a function of κ_0 and a (Eq. (7)), the stress resultant N_f and the bending moment M_f are calculated as implicit functions of κ_0 and a , as follows.

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

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

For air-bending (three-point bending with two supports at distance L), as illustrated in Fig. 4, the boundary conditions are,

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

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

The scheme of the present numerical calculation is the following:

(i) A punch load P at a time $t=t+\Delta t$ 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 Eqs. (6) and (8) with respect to x , and also $M_f(x)$ from Eq. (9). From Eqs. (10) and (11), $\kappa_0(x)$ and $a(x)$ are determined. It should be noted that, in Eq. (8), τ_a is a function of not only shear strain γ_a but also its rate $\dot{\gamma}_a$ (refer to Eq. (1)). Since the shear strain rate at a fixed material point, under a constant punch speed, will not be changed significantly during a time step Δt , we assumed:

$$\dot{\gamma}_a(x, t+\Delta t) \approx [\gamma_a(x, t) - \gamma_a(x, t-\Delta t)]/\Delta t. \quad (14)$$

(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 ($x=L/2$). This is also accepted as a solution for this problem.

(v) The process (i)~(iv) is continued until the punch travel $\eta(0)$ (or bent load P) reaches its target value.

This analysis is basically a load-controlled type where a punch-load increment ΔP in a time-step Δt is prescribed, although in our experiments punch speed V was kept constant, i.e., a displacement-controlled condition. Therefore, in the calculation, every time increment Δt should be determined as $\Delta t = \Delta u_{\text{punch}}/V$, where Δu_{punch} is the calculated punch travel for a punch-load increment ΔP , as shown in Fig. 4.

3. Results and Discussions

3.1 Shear deformation of the adhesive layer

Figure 7 illustrates the comparison between the numerical and experimental results for the shear strain distributions of the adhesive layer after V-

bending conducted at various punch speeds. The calculated results are in good agreement with the corresponding experimental data. This figure shows that the shear strain is highly rate-dependent: the larger the punch speed, the lower the shear strain. This is because the flow stress of the adhesive layer will increase with increasing strain rate (forming speed), and as a result, the shear deformation is

Fig. 7 Effect of the punch speed on shear strain in the adhesive layers by V-bending ($l_p=50$ mm, $L=20$ mm)

(a) $V=1$ mm/min

(b) $V=20$ mm/min

(c) $V=500$ mm/min

Fig. 8 Effect of the punch speed on the sheet geometries in V-bending ($l_p=50$ mm, $L=20$ mm, experimental results)

unlikely to occur.

3.2 Geometrical imperfection of adhesive

Figures 8(a), 8(b) and 8(c) are experimental observations of sheet geometries after V-bending conducted at three different punch speeds of 1, 20, and 500 mm/min, respectively. It is clearly seen in these figures that the *gull-wing bend* is disappearing with increasing punch speed. Figures 9(a), 9(b) and 9(c) are the corresponding results of numerical simulation, which are in good agreement with the experimental observations.

The *gull-wing bend* appearing at the overhang of the sheet is caused by the bending moment, acting on each face metal, which is induced by the shear stresses acting on the adhesive/face-metal interfaces. As already discussed, the shear deformation decreases with increasing forming speed, and consequently, the shear stress becomes lower.

3.3 Stress distribution of adherend

The effect of forming speed is seen in the stress distribution. Figures 10(a) - (c) show the calculated distributions of bending stress in the face metals, at the final stage of V-bending (punch travel $\eta(0)=8$ mm), at four different material points (A: loading

(a) $V=1$ mm/min

(b) $V=20$ mm/min

(c) $V=500$ mm/min

Fig. 9 Numerical simulation of V-bending corresponding to the experimental results shown in Fig. 8

point; B and C: points in the span, particularly point C is the place of inflection; D: at the support). Comparing the stress distributions for various punch speeds (compare Figs. 10(a) – (c)) at point D where the *gull-wing bend* occurs significantly, we can determine that the bending stress is apparently reduced with increasing punching speed, which would lead to the decrease of the *gull-wing bend*.

It should be emphasized, from the viewpoint of industrial applications, that the above-mentioned deformation characteristics are excellent, because undesirable shear deformation of core adhesive and the *gull-wing bend* will be successfully suppressed by high-speed forming.

4. Concluding Remarks

The effect of forming speed on the deformation characteristics of V-bending for an adhesively bonded aluminium sheet was investigated both experimentally and analytically. The present findings are summarized as follows:

(1) The large shear deformation and '*gull-wing bend*' are successfully suppressed by high-speed forming, since the deformation resistance of the adhesive resin becomes higher at high strain rate.

(2) The accuracy of the newly developed code of numerical simulation of air-bending, which considers the viscoplasticity of adhesive, has been confirmed by comparing the results of numerical simulation and the

(a) $V=1$ mm/min ($p=40.1$ N/mm, $\kappa_0(0)=0.2726$ mm⁻¹)

(b) $V=20$ mm/min ($p=42.1$ N/mm, $\kappa_0(0)=0.26603$ mm⁻¹)

(c) $V=500$ mm/min ($p=44.0$ N/mm, $\kappa_0(0)=0.265957$ mm⁻¹)

Fig. 10 Effect of the punch speed on stress distribution of adherend in V-bending ($lp=50$ mm, $L=20$ mm, $\eta(0)=8$ mm)

corresponding experimental results.

In summary, high-speed forming is recommended for V-bending of adhesive-bonded sheet metals.

Acknowledgments

The adhesive employed in this study was offered by Mr. Koichi Taguchi of Denki Kagaku Kogyo, Co. Ltd. Throughout this work, the authors had valuable discussions with many members of the Japan Institute of Light Metals. Mr. Hidenori Hirota, a technician of Hiroshima University, and Mr. Yoshihiro Morishita, a technician of Hiroshima National College of Maritime Technology, have devoted much time and made an effort for preparing specimens and the experimental apparatus. The authors would like to express their sincere gratitude to all of them.

References

- (1) Takiguchi, M. and Yoshida, F., Deformation Characteristics and Delamination Strength of Adhesively Bonded Aluminium Alloy Sheet under Plastic Bending, *JSME, Int. J., Ser. A*, Vol. 46, No. 1 (2003), pp. 68-75.
- (2) Takiguchi, M. and Yoshida, F., Plastic Bending of Adhesive-Bonded Sheet Metals, *J. Materials Processing Technology*, Vol. 113 (2001), pp. 743-748.
- (3) Yoshida, M., Press Formability of Vibration-Damping Sheets, *J. Jpn. Soc. Technol. Plastic.*, (in Japanese), Vol. 26, No. 291 (1985), pp. 394-399.
- (4) Takiguchi, M., Izumi, S. and Yoshida, F., Rate-Dependent Shear Deformation of Ductile Acrylic Adhesive and Its Constitutive Modeling, *Key Eng. Materials*, Vol. 233-236 (2003), pp. 175-180.
- (5) Makinouchi, A., Yoshida, S. and Ogawa, H., Finite Element Simulation of Bending Process of Steel-Plastic Laminate Sheets, *J. Jpn. Soc. Technol. Plastic.*, (in Japanese), Vol. 29, No. 330 (1988), pp. 755-760.
- (6) Ito, K., Sagawa, T. and Terada, M., Simple Analysis of Double-Bent in V-Type Bending of Steel/Resin/Steel Laminates Vibration Damping Sheet, *J. Jpn. Soc. Technol. Plastic.*, (in Japanese), Vol. 30, No. 346 (1989), pp. 1490-1496.
- (7) Yoshida, F., Elastic-Plastic Analysis for Bending of Metal/Polymer/Metal Sandwich Plate, in: *Proceedings of the Third International Conference on Technology of Plasticity (ICTP-3)*, Vol. 3 (1990), pp. 1513-1518.
- (8) Hirose, Y., Kojima, M., Hayashi, Y. and Sudo, C., Bending Performance of Steel-Plastic-Steel Laminated Sheet, in: *Proceedings of the Third International Conference on Technology of Plasticity (ICTP-3)*, Vol. 3 (1990), pp. 1519-1524.
- (9) Kim, J.-K. and Yu, T.-X., Forming and Failure Behaviour of Coated, Laminated and Sandwiched Sheet Metals: A Review, *J. Mat. Process. Technol.*, Vol. 63 (1977), pp. 33-42.
- (10) Yoshida, F., Deformation and Fracture of Sheet Metal Laminates in Plastic Forming, in: *Proceedings of the Fourth International Conference on Composite Engineering (ICCE-4)*, (1997), pp. 61-64.
- (11) Mindlin, R.D., Influence of Rotatory Inertia and Shear on Flexural Motions of Isotropic, Elastic Plates, *J. Appl. Mech.*, Vol. 18 (1951), pp. 31-38.