Estimation of viscoelastic resistance and subduction profile of acrylic based pressure sensitive adhesive sheet subjected to wedge indentation

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Abstract
This paper aims to estimate the indentation resistance and deformation shape of a 0.5mm thickness acrylic Pressure Sensitive Adhesive (PSA) sheet subjected to a wedge indentation. As for the effect of apex angle of a wedge blade on the cutting characteristics of the PSA sheet, a 60° wedge blade was mainly investigated through experiments and numerical simulations, while the wedge angles of 42, 16° were discussed with respect to the subduction profile of wedge surface. For the sake of development of PSA deformation model, the Prony series based viscoelastic properties were determined by the shear stress relaxation test. Also, the equivalent Young’s modulus was estimated by comparing with an out-of-plane compressive experiment and a Finite Element Method (FEM) based compressive simulation. Through the experimental wedge indentation using the 60° wedge blade, three stages of cutting load response were detected: (1) an exponential response, (2) an extremely increasing response based on the saturated inclined angle of subduction zone, and (3) a saturated gradient for the final stage. Furthermore, it was clarified that the proposed FEM model of viscoelastic-deformable sheet subjected to the 60° wedge indentation was applicable for simulating the cutting deformation for the early stage less than 60% of the thickness. The simulated inclined angle of subduction zone tended to be linearly increased with the indentation depth up to a certain extent, whereas the experimental inclined angle saturated to a constant for the indentation depth larger than 70% of the thickness. One of the reasons why the experimental cutting force was higher than the simulated result was explained as the wetting spreading effect due to the yield flow of PSA sheet. In the latter stage of indentation, the correlation between the mismatching of cutting line force and the mismatching of inclined angle of subduction zone was revealed.

Keywords: Wedge indentation, Compressive characteristic, Adhesive, Viscoelastic, Material processing

1. Introduction

A wedge cutting method with a center bevel blade into a sheet material on a counter plate is widely used for cutting off into a complicated formed pattern from resin based composite sheets such as printed labels, optical-transparent clear adhesive films and multi-functional adhesive films for electronic equipment (Kirwan, 2013). The wedge cutting method has some merits such as a moderate accuracy and high productivity for stripping various complicated patterns, and a high maintainability. The processed sheet material has usually a laminated structure containing a Pressure Sensitive Adhesive (PSA) layer in the intermediate layer. Namely, the PSA layer is put between a substrate film for printing or coating and a release film for protecting PSA layer.

The PSA are used for many applications. They are used for tapes, labels, and many other products, including their use for the lamination of flexible webs and for product assembly applications. The PSA provide a convenient and easy means to bond a flexible material to another surface. It is a substance that adheres to an adherend by applying a light pressure at room temperature. The PSA is a kind of polymeric material which has viscoelastic properties (Istvan, 2004). Due to the viscoelastic properties, the deformation behavior of the PSA is strongly affected by the strain rate and the
temperature of the substrate. The PSA can be classified from the aspects of the physical and chemical composition, i.e. the main elastomer used in the adhesive formulation is such as acrylic, styrenic block copolymers, natural rubber and silicone. The acrylic based PSA is acrylic esters that is yield soft and tacky polymers having the low glass transition temperature. Generalized acrylic PSAs are composed of 50−98 % main monomer, 10−40 % modifying monomer, and 0.5−20 % monomer with functional groups (Satas, 1999). They have many applications spread in various fields, from a specific to common usage. They are applied to self-adhesive labels, protective films, sign and marking films.

When the wedge cutting is applied to a laminated sheet which has a PSA in the intermediate layer, various troubles sometimes occur. As for real jamming, there are several reasons by being wet on the blade, detaching/peeling of the end of sheared section and flowing out from the sheared section. The jamming phenomena are not revealed sufficiently, while many actual troubles are empirically taken by the hand operation of experts. In order to predict wedge cutting characteristics of the PSA sandwiched sheet in the intermediate layer and to choose the mechanical conditions of cutting off the sheet successfully, the effect of wedge indentation on the time-dependent deformation of the PSA sheet should be clarified. Before discussing the PSA sandwiched sheet cutting, it is necessary to reveal the deformation characteristics of a single bulk PSA sheet which is subjected to a wedge indentation. As for the solid sheet materials, there are several papers on the cutting behavior of laminated structure (Chaijit et al., 2008), resin material (Mitsomwang et al., 2012, Nagasawa et al., 2010a, 2010b) and viscoelastic material (Boisly et al., 2016, McCarth et al., 2010). In addition, several numerical studies had been reported to predict the time-dependent deformation characteristics of viscoelastic materials (Kucuk et al., 2013, Okazawa et al., 2007).

However, there are not almost research papers on the cutting characteristics and compressive flow behavior of the PSA sheet. Therefore, this work aims to reveal the wedge indentation characteristics of the acrylic PSA sheet through the experiment and the Finite Element Method (FEM) based numerical simulation which considers the viscoelastic properties with respect to the indentation velocity at a constant temperature. This temperature condition covers many factory’s environment, even though the deformation characteristics of the PSA sheet seem to depend on the temperature and the strain rate.

The indentation resistance by the wedge blade of 60° was mainly investigated using the 0.5 mm thickness acrylic PSA sheet through experiments and numerical simulations. In order to determine the material properties of PSA sheet, the equivalent Young’s modulus was estimated from the preliminary analysis adapted to the out-of-plane compressive test, and the viscoelastic properties were identified by the shear stress relaxation test. In order to verify the validity of the proposed FEM model, the simulated cutting line force and deformed shape were compared with the experimental results. As the additional, the wedge indentation of the acrylic PSA sheet was experimentally and numerically verified when changing the apex angle of the wedge blade.

2. Experimental condition
2.1 Identification of material properties

To simulate the deformation of the acrylic PSA sheet, the general purpose Finite Element Code Abaqus/Explicit version 6.14-1 was used. As for the time-dependent material properties of the PSA sheet, an isotropic linear viscoelasticity was assumed. When considering the relationship between a shear strain $\gamma(t)$ and a shear stress $\tau(t)$, the constitutive equation was defined by Eq. (1). Here the time varying rate of shear strain $\dot{\gamma}(t)$ which varies at time $t$, the shear stress denoted as $\tau(t)$, and $G_R(t)$ is the shear relaxation modulus that characterizes the response of the material. The variable $s$ is an arbitrary dummy time before time $t$. Considering a generalized Maxwell model which is approximated with a prony series (Abaqus Analysis User’s Manual, 6.14) for the shear relaxation modulus, $G_R(t)$ is assumed to be Eq. (2). Here, $G_0 = G_R(0)$ is the instantaneous shear modulus, and $\tau$ is the relaxation time for the i-th term ($i = 1,2,\ldots,n$), $G_i$ is the i-th shear modulus coefficient.

$$\tau(t) = \frac{d}{dt} \int_0^t G_R(t-s)\gamma(s)ds = \int_0^t G_R(t-s)\dot{\gamma}(s)ds$$  \hspace{1cm} (1)

$$G_R(t) = G_0 \sum_{i=1}^{n} G_i \left(1 - \exp\left(-\frac{t}{\tau_i}\right)\right)$$  \hspace{1cm} (2)
The shear stress can be illustrated by considering a relaxation test in which a shear strain is suddenly applied to a specimen and it is held in constant for a long time. Assuming that the shear strain $\gamma(t)$ is suddenly applied at the start time $t = 0$ of the relaxation response, since $\dot{\gamma}(0)=0$ for $t > 0$, Eq. (3) is obtained.

$$
\tau(t) = G_R(t)\gamma_0 = G_0 g_R(t)\gamma_0
$$

Here, the normalized shear relaxation modulus $g_R(t)$ is defined as $G_R(t)/G_0$, and $\gamma_0$ is a specified constant shear strain. The shear stress $\tau(t)$ is replaced to Eq. (4) using $g_R(t)$.

$$
\tau(t) = G_0 \int_0^t g_R(t-s)\dot{\gamma}(s)ds
$$

Within the periods of the shear stress relaxation response, the normalized shear relaxation modulus $g_R(t)$ is expressed as Eq. (5). Here, the coefficients $g_i$ and $\tau_i$ are the normalized amplitude of relaxation modulus and the relaxation time for the i-th term ($i = 1,2,\ldots,n$). Provided that $n$ is a necessary order’s index number.

$$
\frac{\gamma_0}{G_0\tau_0} = g_R(t) = 1 - \sum_{i=1}^{n} g_i \left(1 - \exp\left(-\frac{t}{\tau_i}\right)\right)
$$

The coefficients $g_i$ and $\tau_i$ of Eq. (5) are approximately obtained from the measurement results of the shear stress relaxation test using the least square method.

The viscoelastic properties of the acrylic PSA sheet were experimentally measured by the shear stress relaxation test described below. The shear stress relaxation test was carried out at a room temperature 296 K ±1 K for over 24 h before the relaxation test using a parallel plate measurement system MCR 302 Anton-Paar rheometer. The specimens of PSA sheet had a thickness of 0.5 mm and a diameter of 8 mm. The initial state of the shear strain $\gamma_0$ was prepared in about 0.05 s. Here, the shear strain was chosen as $\gamma_0 = 5, 10, 20,$ and 40 %.

The specimens were kept in a constant shear strain during the shear stress relaxation test. The time-dependent response of $\tau(t)$ was measured with the intervals of time 0.05 s.

Figure 1 shows the relaxation curves. Seeing the measurement results and the approximated curves with three terms of $n = 3$ by Eq. (5), they indicated a similar tendency for all the shear strain $\gamma_0$ for the measuring duration $t < 100$ s. This shear stress relaxation test revealed that the acrylic PSA sheet behaved a linear viscoelastic response (as the generalized Maxwell model with three terms) for the range of shear strain $\gamma_0$ from 5 to 40 % in the limited duration of $t = 99$ s. Table 1 shows the normalized amplitude of relaxation modulus $g_i$ and the relaxation time $\tau_i$ for $i = 1-3$ at the shear strain $\gamma_0 = 40\%$.

![Fig.1 Relaxation curves of the acrylic PSA sheet. The measurement results and the fitted curves with Eq. (5) showed the similar tendency for $\gamma_0 = 5 \sim 40 \%$. The shear stress relaxation test revealed that the PSA sheet behaved a linear viscoelastic response.](image)

| $n$ | $g_i$ / MPa | $\tau_i$ / s |
|-----|-------------|-------------|
| 1   | 0.327       | 0.118       |
| 2   | 0.279       | 1.398       |
| 3   | 0.223       | 22.06       |

The relaxation properties shown in Table 1 were taken into account with the FEM model in the out-of-plane compressive test and the wedge indentation test. From Eq. (3), (5), $G_R(t)$ is obtained by multiplying the instantaneous shear modulus $G_0$ to $g_R(t)$ when assuming the isotropic linear viscoelastic material. It is expressed as Eq. (6)
\[
G_R(t) = G_0 \left(1 - \sum_{i=1}^{3} g_i \left(1 - \exp \left(-\frac{t}{\eta_i}\right)\right)\right)
\]  

(6)

As for the 0-th order term, \(G_0\) is determined by using Eq. (7). Namely, it is estimated from the instantaneous elastic modulus \(E_0\) and the Poisson’s ratio \(\nu\).

\[
G_0 = \frac{E_0}{2(1+\nu)}
\]  

(7)

In order to determine the instantaneous elastic modulus \(E_0\) of the acrylic PSA sheet, a tensile test or compressive test is necessary. However, it was difficult to measure the stress and strain in the uni-axial tensile test. Because there was a sort of slip on the fixed part between the fixture and a PSA sheet, and then a certain difference (mismatching) of strain rate between the inside and outside (surface zone) was occurred. In the case of the out-of-plane compressive test, the frictional boundary condition must be considered against the pressing tool. Therefore, \(E_0\) was here identified from an out-of-plane compressive simulation and out-of-plane compressive experiment described below.

In the experimental out-of-plane compressive test, the downward velocity of the movable punched head was chosen as \(V_C = 0.05, 0.17\) and \(0.42\) mm \(s^{-1}\), in order to compare the influence of compressive velocity \(V_C\). Each specimen of the acrylic PSA sheets was prepared as a square plate which had a thickness of \(t_w = 0.5\) mm and a side length of \(L_c = 2\) mm. The compressive test was carried out with 8 times for each velocity \(V_C\).

To simulate the out-of-plane compression of the acrylic PSA sheet, the general purpose FEM code Abaqus was used. The subdivided element model of three dimensional compressive test was shown in Fig. 2. Here, a quarter symmetric model was considered. The \(z\)-axis was chosen as the thickness direction. The \(x-z\) plane and \(z-y\) plane were symmetric planes. The acrylic PSA sheet (deformable body) and the upper/lower plates (rigid bodies) were connected with each other, using rough friction model of Abaqus. The eight-node hexahedron element type with approximately 25500 elements was used for modelling the PSA sheet. The upper plate moved downward with the compressive velocity of \(V_C = 0.05, 0.17\) and \(0.42\) mm \(s^{-1}\) against the fixed lower plate. The normalized amplitude of relaxation modulus \(g_i\) and the relaxation time \(\tau_i\) of the viscoelastic model were specified by using Eq. (5) and Table 1. As for the static elastic modulus, the instantaneous elastic modulus \(E_0\) was iteratively investigated using the FEM simulation by varying the value of \(E_0\) in the out-of-plane compressive deformation test with the intervals of \(\Delta E_0 = 0.1\) MPa. Here, the Poisson’s ratio was assumed to be \(\nu = 0.49\) due to the empirical fact that the PSA sheet seemed to be a non-compressed material and for the sake of stable convergence.

Figure 3 shows the compressive stress–strain curves in the out-of-plane compressive test. Seeing Fig. 3, the stress increased with the compressive velocity \(V_C\). It seemed that their relationships were exponentially increased. When the instantaneous elastic modulus of the acrylic PSA sheet was assumed to be \(E_0 = 0.7\) MPa, which was a smallest error in the strain range of \(\varepsilon < 0.3\) from the experimental result, the simulated result well matched the experimental result in the
strain range of \( \varepsilon < 0.3 \), whereas the mismatching of curves for the strain of \( \varepsilon > 0.3 \) was appeared to be caused by any nonlinear elastic behavior at a large strain state.

2.2 Experimental apparatus and the method of wedge indentation

In the wedge indentation test, the specimens of the acrylic PSA sheet were a rectangle shape which had a thickness of \( t_w = 0.5 \) mm, a length \( L \) of 40 mm and a width \( W \) of 20 mm. These specimens were kept in a room with a temperature of 296K ±1 K and a humidity of 50 \% ±1 % RH for over 24 h before the test.

Figure 4 shows a schematic view of the wedge indentation apparatus. Measurements were carried out 10 times for each case. On the wedge indentation apparatus, the upper crosshead had the wedge cutting blade mounted on a load cell with the maximum load 10 kN. Attitude of the cutting blade was vertical to the specimen. Each specimen was stacked on the underlay of a 0.5 mm(=\( t_o \)) thickness polycarbonate (PC) sheet and then it was placed onto a steel counter plate fixed on the lower crosshead. The mechanical properties of PC with horizontal direction for the underlay were shown in Table 2. The underlay had an extremely high stiffness compared to the specimen.

The wedge cutting blade, made with Cemented Carbide (W-C-Co, FM10K), had the width of \( w = 30 \) mm, the thickness of \( t_b = 0.9 \) mm, and the tip thickness of \( w = 2 \) \( \mu \)m. The apex angle of the cutting blade was mainly chosen as \( \alpha = 60^\circ \). The height of the cutting blade was estimated as \( h = t_b/(2\times\tan(\alpha/2)) = 0.9/(2\times\tan(30^\circ)) = 0.78 \) mm in this case. The cutting blade was indented to the surface of the acrylic PSA sheet until the PSA sheet was cut off sufficiently.

In order to investigate the influence of the indentation velocity \( V \), the upper crosshead moved downward with \( V = 0.05, 0.17 \) and 0.42 mm\( \cdot \)s\( ^{-1} \). The cutting force \( F \) N was measured by the load cell during the wedge indentation and the cutting line force \( f = F/W \) N\( \cdot \)mm\( ^{-1} \) was recorded. The indentation depth \( d \) mm of the wedge cutting blade into the specimen was measured by the displacement meter of the upper crosshead. In addition, a CCD camera was also installed for investigating the side-view deformation of the subduction zone on the upper surface of the acrylic PSA sheet.

3. Experimental results and discussion

3.1 Cutting load characteristics

Figure 5 shows the experimental relationship between the cutting line force \( f \) and the indentation depth \( d \) under the indentation velocity \( V = 0.05, 0.17 \) and 0.42 mm\( \cdot \)s\( ^{-1} \). Here, all the measurement results were plotted. The depth \( d \) was defined to be zero when upper surface of the acrylic PSA sheet was contacted with the tip of the wedge cutting blade.

From this figure, the following features were found: (i) The load response between \( f \) and \( d \) seemed to be exponentially increased. Namely, it was a monotonically increased without any peak maximum. The gradient of \( f \) by \( d \) was extremely increased for \( \text{d}l/t_w > 0.8 \). (ii) The load response of \( f \) increased with the velocity \( V \), as well as \( d \). (iii) The inflection point of load increasing occurred at around \( d = 0.40 \sim 0.45 \) mm. When \( d \) reached at 0.52 mm, the response of \( f \) behaved as the infinitive gradient, owing that the wedge cutting blade completely cut off the acrylic PSA sheet and contacted the underlay.

In order to characterize the cutting line force \( f \) with the indentation depth \( d \) and velocity \( V \), it was assumed to be a
function of $d$ and $V$, as shown in Eq. (8).

$$f = f(d, V)$$

(8)

In order to confirm the effects of the indentation velocity $V$ on the cutting line force $f$ and/or the increasing rate of $f$, the cutting line force gradient $\Delta f/\Delta d$ was calculated from Eq. 5 for each velocity $V$. This gradient was calculated with a constant intervals $\Delta d = 0.01 \text{ mm}$. Figure 6 shows the relationship between the gradient $\Delta f/\Delta d$ and the indentation depth $d$ for each velocity $V$. Seeing Fig. 6, the gradient was exponentially increased for $d < 0.44 \text{ mm}$, whereas the gradient was almost in constant for $d \geq 0.44 \text{ mm}$. Since the gradient was extremely changed at $d = 0.38 - 0.44 \text{ mm}$, the load response seemed to be classified in three stages: (1) exponential, (2) extreme increasing and (3) saturated gradient.

![Fig.5 Relationship between the cutting line force $f$ and the indentation depth $d$ for indentation velocity $V = 0.05$, $0.17$ and $0.42 \text{ mm}^{-1}$. The line force $f$ increased with $d$ and $V$.](image1)

![Fig.6 Relationship between the cutting line force gradient $\Delta f/\Delta d$ and the indentation depth $d$ for indentation velocity $V = 0.05$, $0.17$ and $0.42 \text{ mm}^{-1}$. The gradient $\Delta f/\Delta d$ increased exponentially for $d < 0.44 \text{ mm}$ while it was saturated for $d \geq 0.44 \text{ mm}$.](image2)

Table 3 The coefficients $\kappa_1$ and $\kappa_0$ in Eq. (9) at the indentation depth $d = 0.15$, $0.35$, $0.40$ and $0.44 \text{ mm}$.  

| $d$ (mm) | $\kappa_1$ | $\kappa_0$ |
|---------|------------|------------|
| 0.15    | 0.17       | 0.86       |
| 0.35    | 0.79       | 4.01       |
| 0.40    | 1.92       | 9.45       |
| 0.44    | 4.41       | 26.9       |

Table 3 shows the coefficients $\kappa_1$ and $\kappa_0$ for $d = 0.15$, $0.35$, $0.40$ and $0.44 \text{ mm}$. The error bars of the measurement results were sufficiently small in Fig. 7.

$$\frac{\Delta f}{\Delta d} = \frac{\partial f}{\partial d} = \kappa_1 \ln(V) + \kappa_0$$

(9)

Seeing Fig. 7 and Table 3, it was found that the coefficients $\kappa_1$ and $\kappa_0$ depended on the indentation depth $d$ in Eq. (9). Therefore, the cutting line force gradient $\partial f/\partial d$ was related to $\ln(V)$ and also a function of $d$. This means that $\kappa_0$
and \( \kappa_1 \) are described as a function of \( d \).

Figure 8 shows the relationship between the coefficient \( \kappa_0 \) and the indentation depth \( d \). The coefficient \( \kappa_0 \) was approximated by an exponential function of Eq. (10) in the range of \( 0 < d < 0.38 \) mm. It increased exponentially with the depth \( d \). In the range of \( 0.38 \leq d < 0.44 \) mm, \( \kappa_0 \) linearly increased with \( d \) as shown by Eq. (11). In addition, it behaved mostly in constant for \( d \geq 0.44 \) mm.

Figure 9 shows the relationship between the coefficients \( \kappa_1 \) and \( \kappa_0 \) for \( d < 0.5 \) mm. It was found that the correlation between the coefficients \( \kappa_1 \) and \( \kappa_0 \) are linearity related for \( 0 < d < 0.44 \) mm.

\[
\kappa_0 = 0.21 \exp(d/0.125) \quad \text{for } 0 < d < 0.38 \tag{10}
\]

\[
\kappa_0 = 331.3 \ d - 122.0 \quad \text{for } 0.38 \leq d < 0.44 \tag{11}
\]

\[
\kappa_1 = 0.205 \ \kappa_0 \quad \text{for } 0 < d < 0.44 \tag{12}
\]

\[
\frac{\partial \kappa}{\partial d} = \kappa_0 \left( 1 + 0.205 \ln(V) \right) \quad \text{for } 0 < d < 0.44 \tag{13}
\]

Eq. (14.1) and (14.2) were obtained by integrating the partial derivative of Eq. (13) with respect to the indentation depth \( d \). Here, two expressions Eq. (10) and (11) were used for the corresponding range of \( d \).

\[
f(d, V) = \begin{cases} 0.0261 \left( \exp(d/0.125) - 1 \right) \left( 1 + 0.205 \ln(V) \right) & \text{for } 0 < d < 0.38 \tag{14.1} \\ \left( 165.7 \ d^2 - 122.0 \ d + C_0 \right) \left( 1 + 0.205 \ln(V) \right) & \text{for } 0.38 \leq d < 0.44 \tag{14.2} \end{cases}
\]

Here, since \( f(0, V) = 0 \) N-mm\(^{-1} \) for an arbitrary velocity \( V > 0 \), the constant of integration was determined for \( 0 < d < 0.38 \) and Eq. (14.1) was derived. Since Eq. (14.2) coincides with Eq. (14.1) when \( d = 0.38 \) mm, the constant of integration \( C_0 \) is estimated as \( C_0 = 22.96 \) N-mm\(^2 \) for the arbitrary velocity \( V > 0 \).

The cutting line force \( f \) calculated by the approximation formula of Eq. (14.1), (14.2) was compared with the experiment. From the comparison result, it was confirmed that the correlation coefficient was \( R > 0.99 \), which roughly agrees with the experiment for \( 0 < dtw < 0.88 \).

From the experimental investigation, it was found that the indentation resistance of the acrylic PSA sheet were affected by the indentation velocity \( V \) of the wedge cutting blade as shown in Eq. (14.1), (14.2).

Regarding the load response pattern, three stages were detected: (1) exponential for \( 0 < dtw < 0.76 \), (2) extreme increasing for \( 0.76 \leq dtw < 0.88 \) and (3) saturated gradient for \( 0.88 \leq dtw < 1.0 \). The first stage (1) an exponential response is similar to the early stage of the out-of-plane compressive response, whereas the second and third stages (2) an extreme increasing response and (3) a saturated gradient response are non-linear behavior. This kind of behavior is discussed in the next section from the aspect of subduction flow characteristics.
3.2 Subduction profile

Figure 10 shows the side-view photographs of wedged zone of the acrylic PSA sheet when the 60° wedge cutting blade was indented to the PSA sheet with the indentation velocity \( V = 0.05, 0.17 \) and \( 0.42 \text{ mm·s}^{-1} \). Observing the subduction zone on the upper surface of the PSA sheet, the inclined angle of subduction zone appeared to be increased with the indentation depth \( d < 0.30 \text{ mm} \). When the bottom zone of the PSA sheet was observed, any necking and warpage were not detected there, because the PSA sheet adhered to the cutting edge and the underlay.

\[
\begin{align*}
&\text{Fig. 10 Side views of wedged zone of 0.5 mm thickness acrylic PSA sheet with respect to indentation depth } d \\
&\text{for the indentation velocity of } V = 0.05, 0.17 \text{ and } 0.42 \text{ mm·s}^{-1} . \text{ Subduction zones on the upper surface were observed. The inclined angle of subduction zone appeared to be increased with the depth } d .
\end{align*}
\]

Figure 11 shows the side-view photograph and schematic of wedged zone of the acrylic PSA sheet when choosing \( d = 0.40 \text{ mm} \) and \( V = 0.17 \text{ mm·s}^{-1} \). Seeing Fig. 11(a), the photograph of the bottom zone of the PSA sheet was out of focus due to being flown out in the lateral direction (perpendicular to the side view). In order to investigate the deformation state of wedged zone for the range of depth \( 0.10 < d < 0.50 \text{ mm} \), the inclined angle \( \theta \) of the subduction zone on the upper surface which was measured against the horizontal direction as shown in Fig. 11(b).

Figure 12 shows the relationship between the inclined angle \( \theta \) and the indentation depth \( d \). From this figure, it was found that the angle \( \theta \) was linearly increased with the depth \( d \) for \( d < 0.35 \text{ mm} \), whereas it behaved as a constant inclined angle \( \theta_s \approx 28^\circ \) for \( d \geq 0.35 \text{ mm} \) when choosing the velocity \( V = 0.05, 0.17 \) and \( 0.42 \text{ mm·s}^{-1} \). For an example, in the case of \( V = 0.17 \text{ mm·s}^{-1} \), the gradient of inclined angle with indentation depth \( \beta (=\Delta \theta/\Delta d) \) was linearly approximated as \( \beta = 63.7 \text{ deg·mm}^{-1} \) for \( 0.10 < d < 0.30 \text{ mm} \).

From this result, it was revealed that a linearly increasing of the inclined angle \( \theta \) was caused by the wedge indentation on the upper surface of the acrylic PSA sheet for \( 0 < dl_{tw} < 0.7 \), whereas the angle \( \theta \) behaved as saturated value for \( 0.7 \leq dl_{tw} < 1.0 \). The latter saturation seemed to be caused by the yield flow resistance of the upper surface area. Comparing the angle \( \theta \) of the subduction zone and the gradient \( d\theta/dd \), the extreme increasing of \( d\theta/dd \) \((0.76 \leq dl_{tw} < 0.88)\) seemed to be caused by three dimensional flow (in the lateral direction) for wetting on the side edge of blade and the variation of the surface tension or the yield resistance limit of the PSA sheet. Because, the saturation of \( \theta \) (for \( dl_{tw} \geq 0.7 \)) increases the wetted (contact) area between the blade surface and the sheared section of the PSA sheet. The final saturation of \( d\theta/dd \) \((0.88 \leq dl_{tw} < 1.0)\) seemed to be caused by a sort of necking phenomena, although there
were not any lift and detachment of lower surface against the underlay.

In order to compare the deformation state and the internal stress states during indentation process, they are analyzed using the FEM simulation in the following section.

### 4. Finite element analysis

#### 4.1 Modelling condition

To simulate a wedged deformation of the acrylic PSA sheet, the general purpose FEM code ABAQUS was used. The two dimensional plane strain and a half symmetric FEM model was considered as shown in Fig. 13. The X-axis and Y-axis were chosen as the horizontal direction and the thickness direction, respectively. The acrylic PSA (deformable body) sheet had a thickness of \( t_w = 0.5 \text{ mm} \) and a length of \( L_a = 1.5 \text{ mm} \) which was three times of the thickness. A 60° wedge cutting blade was moved downward with the indentation velocity \( V = 0.17 \text{ mm} \text{ s}^{-1} \). The inclination angle \( \theta \) of the subduction zone was measured against the horizontal direction.

The four-node quadrilateral plain strain element type with 4060 elements and 4366 nodes was used for modelling the deformable body. The indentation zone which had length \( L_d = 0.1 \text{ mm} \) was modelled using fine-divided elements. The lateral-side length of the fine-divided minimum elements was chosen as 0.5 \( \mu \text{ m} \), while the divided length in the horizontal direction was totally designed as a geometric diving with the common ratio of 1.04. The height-side length was divided as 10-20 \( \mu \text{ m} \).

Fig. 12 Relationship between the inclined angle \( \theta \) and the indentation depth \( d \). The angle \( \theta \) linearly increased with \( d < 0.30 \text{ mm} \), and almost saturated to \( \theta_b \approx 28^\circ \) for \( d \geq 0.35 \text{ mm} \). The angle \( \theta \) seemed to be not sensitive to the specified variation of the indentation velocity \( V \). The gradient of \( \theta \) with \( d \) was approximately \( \beta = 63.7 \text{ deg.} \text{ mm}^{-1} \) when choosing \( V = 0.17 \text{ mm} \text{ s}^{-1} \) in the range of \( 0.10 < d < 0.30 \text{ mm} \).

\[
\beta = 63.7 \text{ deg.} \text{ mm}^{-1} (V=0.17 \text{ mm} \text{ s}^{-1})
\]

Fig. 13 The schematic of the two dimensional plane strain and a half symmetric wedge indentation FEM model. The wedge cutting blade was moved downward with the indentation velocity of \( V=0.05, 0.17 \text{ and } 0.42 \text{ mm} \text{ s}^{-1} \).

The element generation of the deformable body was controlled by using the Arbitrary Lagrangian-Eulerian (ALE) adaptive meshing method in order to perform successfully. All of the elements were assumed to have no crack and no fracture during the wedge indentation process. The acrylic PSA sheets and the underlay were connected with each other,
using rough friction model of Abaqus. The contact interface between the wedge cutting blade and the PSA sheet were also assumed to be modeled by rough friction.

The wedge cutting blade was moved downward with the indentation velocity of $V = 0.05, 0.17$ and $0.42 \text{ mm/s}$. The apex angle of the cutting blade was modeled as half symmetric of $\alpha/2 = 30^\circ$. The acrylic PSA sheet was assumed to be an isotropic linear viscoelastic material. The normalized amplitude of relaxation modulus $g_i$ and the relaxation time $\tau_i$ of the viscoelastic model were specified by using Eq. (5) and Table 1. As for the static-elastic modulus, it was assumed that the instantaneous elastic modulus was $E_0 = 0.7 \text{ MPa}$ and the Poisson’s ratio was $\nu = 0.49$, from the discussion in the section 2.1. This was derived from the relationship between the experimental and the simulated results of the out-of-plane compressive test.

4.2 Simulation results and discussion

4.2.1 Effects of velocity on cutting force

The $60^\circ$ wedge cutting blade was numerically indented to the acrylic PSA sheet. Figure 14 shows the relationship between the simulated cutting line force $f$ and the indentation depth $d$ for indentation velocity $V = 0.05, 0.17$ and $0.42 \text{ mm/s}$, and the corresponding experimental results were compared. As shown in this figure, the simulated response of $f$ was well matched the experimental response for $d < 0.30 \text{ mm}$, when varying the velocity $V$. In the range of $0.30 \leq d < 0.40 \text{ mm}$, the simulated response of $f$ was smaller than that of experiment and its deviation increased with $d$. As for $d \geq 0.40 \text{ mm}$, the simulation was unstably failed to continue the further indentation, due to occurrence of a certain-large distortion of divided elements.

Seeing Fig. 14, it was confirmed that the simulated response of the cutting line force $f$ was affected by the indentation velocity $V$, and its velocity effect was characterized by the use of relaxation model (described in Fig.1, Table 1, Eq. (6), (7)). Namely, it was clarified that the time-dependent wedge indentation resistance of the acrylic PSA sheet was well predicted for $d/\tau_W < 0.6$ by the use of the equivalent Young’s modulus $E_0$ in the out-of-plane compressive test for $\varepsilon < 0.3$ and a linear viscoelastic response of shear stress relaxation test.

4.2.2 Subduction profile

Figure 15 and 16 shows the distribution diagrams of the maximum principal stress and the minimum principal stress in the acrylic PSA sheet subjected to a $60^\circ$ wedge cutting blade indentation at $d = 0.30$ and $0.40 \text{ mm}$, when choosing the velocity $V = 0.05, 0.17$ and $0.42 \text{ mm/s}$. From these figures, the subduction zone on the upper surface of the PSA sheet was observed and the inclined angle $\theta$ was measured as shown in Fig. 12.

Seeing Fig. 15, a high tensile state was detected in the vicinity of the wedge cutting blade tip and on the upper surface of the PSA sheet. When the cutting blade was sunk on the upper surface, the adhesion model between the cutting blade and the PSA sheet was assumed to be completely fixed without sliding, the subduction profile on the upper surface was generated.

Seeing Fig. 16, a high compressive state was detected in the bottom zone of the PSA sheet beneath the wedge.
cutting blade. The higher compressive state was detected when increasing the velocity \( V \). Namely, when increasing the velocity \( V \), the stress relaxation hardly progressed, and the cutting line force \( f \) increased.

Figure 17 shows the relationship between the inclined angle \( \theta \) and the indentation depth \( d \) for the indentation velocity \( V = 0.05, 0.17 \) and 0.42 mm\(\cdot\)s\(^{-1}\) with their corresponding experimental results. In the experimental result, the angle \( \theta \) linearly increased with respect to the depth \( d < 0.30 \) mm and showed a constant value of \( \theta_5 \approx 28^\circ \) for \( d \geq 0.35 \) mm. However, in the simulated result, the inclined angle \( \theta \) linearly increased with respect to the depth \( d < 0.40 \) mm.

In the case of the velocity \( V = 0.17 \) mm\(\cdot\)s\(^{-1}\), the gradient of inclined angle with indentation depth \( \beta \) obtained from the simulated results for \( 0.10 < d < 0.40 \) mm was \( \beta = 80.1 \) deg. \(\cdot\)mm\(^{-1}\), while the experimental gradient was \( \beta = 63.7 \) deg. \(\cdot\)mm\(^{-1}\).
deg. \( \cdot \) mm\(^{-1} \) for 0.10 < \( d < 0.30 \) mm. The simulated gradient \( \beta \) was about 26% larger than of experimental observation for \( d < 0.30 \) mm but they showed the similar tendency as a linear increasing, whereas the simulated gradient \( \beta \) was far different from that of experiment for \( d > 0.35 \) mm. Since the experimental cutting seemed to include a certain shear slipping on the boundary of the cutting blade and the PSA sheet, and also there was a certain yielding (stress-dependent plastic) behavior in the PSA sheet, these mismatching seemed to be observed. In order to reveal the saturated response of \( \beta \) for \( d > 0.35 \) mm, the stress state in the simulation was investigated here.

Figure 18 shows the Y-axis component of the displacement \( u_y \) of the upper surface of the acrylic PSA sheet and the maximum principal stress \( \sigma_{p1} \) with respect to the length \( L_a \) on the upper surface at \( d = 0.30 \) and 0.40 mm. The plotting was considered for covering the intermediate position \( d = 0.35 \) mm at which the inclined angle \( \theta \) was saturated. The length \( L_a \) was defined to be zero at the position of the symmetry axis. The displacement \( u_y \) was not changed by the indentation velocity \( V \) for \( L_a < 0.12 \) mm at \( d = 0.30 \) mm in Fig. 18(a), and also for \( L_a < 0.2 \) mm at \( d = 0.40 \) mm in Fig. 18(c). Seeing Fig. 18(b), (d), comparing the maximum principal stress near the contact area between the cutting blade and the upper surface of the PSA sheet, it appeared that the experimental saturation of inclined angle \( \theta \) occurred at when \( \sigma_{p1} = 0.15~0.2 \) MPa. Therefore, the value of \( \sigma_{p1} = 0.2 \) MPa seemed to be the yield stress limit for making the saturated inclined angle.

In the FEM model, the contact interface between the wedge cutting blade and the acrylic PSA sheet was assumed to be fixed without sliding by using rough friction model. Namely, the FEM model did not consider the spreading of wetting contact. In the experimental result, the inclined angle \( \theta \) saturated at the indentation depth \( d \geq 0.35 \) mm. It seemed to be caused by a spreading of wetting contact area due to the yield flow resistance (as the stress dependent flow resistance limit) of the upper surface area and slip of the interface. In the simulation, it seemed that the angle \( \theta \) linearly increased for \( d \geq 0.35 \) mm owing that the yielding behavior and the slippage were not considered. Therefore, regarding the cutting line force at \( d \geq 0.35 \) mm, one of the reasons why the experimental results was higher than the simulated results seemed to be the effects of spreading of wetting phenomena. Hence, the experimental increasing of cutting line force for \( d > 0.30 \) mm seemed to be caused by an increase of the wetting contact area between the upper surface and the cutting blade.

![Path-plotting diagrams](https://example.com/path-plotting-diagrams)

Fig. 18 Path-plotting diagrams of the displacement in Y-axis \( u_y \) and the maximum principal stress \( \sigma_{p1} \) with respect to the length \( L_a \) of the upper surface of the acrylic PSA sheet at the indentation depth \( d = 0.30 \) and 0.40 mm.

### 4.2.3 Effect of wedge angle on cutting force

In order to verify the applicability of the estimated instantaneous elastic modulus \( E_0 = 0.7 \) MPa and viscoelastic properties specified as Eq. (5) and Table 1 to the variation of apex angle of wedge, the FEM simulation using the wedge cutting blade of \( \alpha = 42 \) and/or 16° was carried out and compared with the experimental results.
Figure 19 shows the relationship between the cutting line force $f$ and the indentation depth $d$ when using the wedge cutting blade of apex angle $\alpha = 42^\circ$. Here, all the lines denoted the corresponding FEM simulations and square symbols were the experimental results with respect to the velocity $V = 0.05, 0.17$ and $0.42$ mm s$^{-1}$. The simulated response of $f$ was well matched the experimental response for $d < 0.25$ mm, while the simulated response of $f$ was smaller than that of experiment for $d > 0.25$ mm. Figure 20 shows the relationship between the cutting line force $f$ and the depth $d$ at the apex angle of blade $\alpha = 16^\circ$. The simulated response of $f$ was well matched the experimental response for $d < 0.20$ mm.

Seeing the cutting line force response in three cases of $\alpha = 60, 42$ and $16^\circ$, the variation rate of cutting line force $f$ against the indentation depth $d$ has a positive correlation with the apex angle. This tendency can be explained from a classical theory of wedge cutting of plasticity (Grunzweig, et al., 1954). In addition, the cutting line force increased when using the sharp apex angle. In order to investigate the influence of relative mismatching with the apex angle, the deformation state and the maximum principal stress distribution was compared. Since the difference of deformation state was small with the apex angle of $\alpha = 42, 16^\circ$.

Seeing the relative mismatching(gap) of $f$ between the simulation and the experimental results, it was found that the range of indentation depth, where the relative mismatching of $f$ could not be negligible, increased when using the sharp apex angle. In order to investigate the influence of relative mismatching with the apex angle, the deformation state and the maximum principal stress distribution was compared. Since the difference of deformation state was small with the apex angle of $\alpha = 42, 16^\circ$.

Fig. 21 Side views of wedged zone of 0.5 mm thickness acrylic PSA sheet at the indentation depth $d = 0.15$ and $0.30$ mm when choosing the indentation velocity $V = 0.17$ mm s$^{-1}$. Subduction zones on upper surface were observed for the apex angle of $\alpha = 42, 16^\circ$.

Fig. 22 Distribution diagrams of the maximum principal stress in the acrylic PSA sheet at $d = 0.15$ and $0.30$ mm when choosing $V= 0.17$ mm s$^{-1}$. A quite high tensile stress was detected near the corner of wedge cutting blade on upper surface. The inclined angle of upper surface increased when using the sharp apex angle.
indentation velocity in the case of $\alpha = 60^\circ$ (as shown in Fig. 18(a) and (d)), the case of indentation velocity $V = 0.17 \text{mm/s}$ was here discussed as the representative case.

Figure 21 shows the side-view photographs of wedged zone of the acrylic PSA sheet at the indentation depth $d = 0.15$ and 0.30 mm when choosing the indentation velocity $V = 0.17 \text{mm/s}$. The subduction zone on the upper surface was observed and its inclined angle was measured for each apex angle. Figure 22 shows the deformation profile and distribution (contour band) diagrams of the maximum principal stress at $d = 0.15$ and 0.30 mm when choosing $V = 0.17 \text{mm/s}$. The deformation profile of the simulated results well agreed with the experimental profile. Seeing Fig. 22, as also shown in Fig. 15, a certain high tensile state was detected in the vicinity of the cutting blade tip and on the upper surface of the PSA sheet. The inclined angle of the upper surface increased when using the sharp apex angle.

Figure 23 shows the relationship between the inclined angle $\theta$ and the indentation depth $d$ when choosing the indentation velocity $V = 0.17 \text{mm/s}$. The experimental angle $\theta$ linearly increased with $d < 0.25 \text{mm}$ and reached a saturated state of $\theta_s \approx 35^\circ$ for $d \geq 0.30 \text{mm}$ when using $\alpha = 42^\circ$. The angle $\theta$ saturated to $\theta_s \approx 50^\circ$ for $d \geq 0.25 \text{mm}$ when using $\alpha = 16^\circ$.

Figure 23 shows the relationship between the inclined angle $\theta$ and the indentation depth $d$ in the case of $\alpha = 16, 42^\circ$ when choosing $V = 0.17 \text{mm/s}$. The experimental angle $\theta$ linearly increased with the depth $d$ for $d < 0.25 \text{mm}$ and saturated to a constant of $\theta_s \approx 35^\circ$ for $d \geq 0.30 \text{mm}$ when using $\alpha = 42^\circ$. The experimental angle $\theta$ saturated to $\theta_s \approx 50^\circ$ for $d \geq 0.25 \text{mm}$ when using $\alpha = 16^\circ$. The relation of $\theta_s$ with $\alpha = 60, 42$ and $16^\circ$ was linearly approximated as Eq. (15). The corresponded-saturated depth $d_s$, at which the mismatching of $f$ between the simulated and the experimental results began to increase, was also linearly estimated as Eq. (16).

![Graph](image1.png)

Fig. 23 Relationship between the inclined angle $\theta$ and the indentation depth $d$ when choosing the indentation velocity $V = 0.17 \text{mm/s}$. The experimental angle $\theta$ linearly increased with $d < 0.25 \text{mm}$ and reached a saturated state of $\theta_s \approx 35^\circ$ for $d \geq 0.30 \text{mm}$ when using $\alpha = 42^\circ$. The angle $\theta$ saturated to $\theta_s \approx 50^\circ$ for $d \geq 0.25 \text{mm}$ when using $\alpha = 16^\circ$.

![Graph](image2.png)

Fig. 24 Path-plotting diagrams of the displacement in Y-axis $\nu_y$ and the maximum principal stress $\sigma_{P1}$ with respect to the length $L_a$ of the upper surface of the acrylic PSA sheet at the indentation depth $d = 0.20$ and 0.25 mm when choosing the indentation velocity $V=0.17 \text{mm/s}$. 

![Graph](image3.png)
The simulated inclined angle $\theta$ linearly increased with the depth $d$ when choosing $\alpha = 60, 42$ and $16^\circ$, whereas all simulations were unstably stopped for $d > 0.40$ mm.

$$\theta_1 = -0.505 \alpha + 57.6$$

$$d_5 = 0.0022 \alpha + 0.212$$

In order to investigate the effects of shear slip on the contact area and the yielding behavior of the acrylic PSA sheet against the indentation of cutting blade, the stress state of the PSA sheet was numerically analyzed.

Figure 24 shows path-plotting diagrams of the displacement in Y-axis $u_Y$ and the maximum principal stress $\sigma_{pp}$ with respect to the length $L_a$ of the upper surface of the acrylic PSA sheet when choosing the apex angle of $\alpha = 60, 42$ and $16^\circ$ for the indentation depth $d = 0.20$ and $0.25$ mm. The displacement $u_Y$ of the upper surface depended on the apex angle $\alpha$, especially for the contact area between the cutting blade and the PSA sheet. Seeing the contact area ($0 < L_a < 0.15$ mm) in Fig. 24 (b) and (d), the maximum principal stress $\sigma_{pp}$ exceeded the yield stress limit of 0.2 MPa (estimated in the previous section 4.2.2 when $\alpha = 60^\circ$) when reaching $d = 0.25$ mm in the case of $\alpha = 16$ and $42^\circ$. It was found that the relative mismatching of $f$ increased with the indentation depth $d$ when the sharp apex angle was used.

The mismatching(gap) between the simulated and the experimental results were calculated for the cutting line force $f$ and the inclined angle $\theta$ for $d = 0.25, 0.3, 0.35$ and $0.4$ mm. With the indentation velocity $V = 0.17 \text{ mm}\cdot\text{s}^{-1}$ as a representative example, Fig. 25 shows the relationship between the mismatching(gap) of cutting line force $f_{gap}$ N$^{-}\text{mm}^{-1}$ and the mismatching(gap) of inclined angle $\theta_{gap}$°. It was found that the correlation between $f_{gap}$ and $\theta_{gap}$ was positive and strong. Its relation was approximated with a power form Eq. (17). Here, the coefficients $F_e$ and $N_e$ of Eq. (17) were characterized by the apex angle $\alpha$, and they were approximated as Eq. (18) and Eq. (19). Table 4 shows the coefficients $b_1$, $b_2$ and $c$ for $V = 0.05, 0.17$ and $0.42 \text{ mm}\cdot\text{s}^{-1}$.

$$f_{gap} = F_e \theta_{gap}^{N_e}$$

$$F_e = b_1 \alpha b_2$$

$$N_e = ca$$

When choosing the indentation velocity $V = 0.05$ and $0.42 \text{ mm}\cdot\text{s}^{-1}$, the tendency of relationship between $f_{gap}$ and $\theta_{gap}$ was similar, compared to that of $V = 0.17 \text{ mm}\cdot\text{s}^{-1}$. The coefficients $b_1$, $b_2$ and $c$ were expressed as the following ranges: $b_1 = 2.20 - 77.7 \text{ N}^{-1} \cdot \text{mm}$, $b_2 = -3.16 - -2.07$, $c = 0.045 - 0.065$.

So far, the surface contact profile of acrylic PSA sheet against the indentation of cutting blade seems to be important for determining the indentation resistance in the deep indentation of blade.

![Fig. 25](image-url)

**Fig. 25** Relationship between the mismatching(gap) of cutting line force $f_{gap}$ and the mismatching(gap) of inclined angle $\theta_{gap}$ for the indentation velocity $V = 0.17 \text{ mm}\cdot\text{s}^{-1}$. The correlation between $f_{gap}$ and $\theta_{gap}$ was found to be expressed by the following Eq. (17) which is an approximation of a power.

**Table 4** The coefficients $b_1$, $b_2$ and $c$ in Eq. (18) and Eq. (19) for the indentation depth $d = 0.25, 0.3, 0.35$ and $0.4$ mm.

| $V$/mm$^{-1}$ | $b_1$ | $b_2$ | $c$ |
|-------------|-------|-------|-----|
| 0.05        | 77.7  | -3.159| 0.045|
| 0.17        | 4.37  | -2.272| 0.065|
| 0.42        | 2.20  | -2.074| 0.048|
5. Conclusions

In this work, the indentation resistance of a 0.5 mm thickness acrylic PSA sheet subjected to a wedge indentation was experimentally and numerically investigated at a constant temperature environment. As for the effect of apex angle of wedge blade, the cutting response by the angle $\alpha = 60^\circ$ was mainly analyzed and that of the angles of $\alpha = 42, 16^\circ$ were compared with the case of $\alpha = 60^\circ$. In order to verify the wedged deformation and its load response of acrylic PSA sheet based on the two dimensional viscoelastic FEM model, the equivalent Young’s modulus was experimentally estimated from the out-of-plane compressive test and the viscoelastic properties were experimentally estimated from the torsional shear stress relaxation test. When combining the indentation velocity of $V = 0.05, 0.17$ and $0.42 \text{ mm s}^{-1}$, and the apex angle of $\alpha = 60, 42$ and $16^\circ$, the response of cutting line force $f$ and the deformed shape (such as the inclined angle $\theta$) of the upper surface of acrylic PSA sheet were experimentally and numerically investigated. The followings results were obtained.

(i) The cutting line force $f$ monotonically increased with indentation depth $d$ without any peak maximum when the indentation velocity $V$ was kept in a constant. The cutting line force $f$ increased with the velocity $V$, as well as the depth $d$. The experimental cutting line force gradient $\Delta f/\Delta d$ was almost linear with $\ln V$. In addition, the gradient $\partial f/\partial d$ was separable into two independent functions with $d$ and $V$. Regarding the load response pattern, three stages were detected in the case of $\alpha = 60^\circ$: (1) exponential for $0 < dltw < 0.8$, (2) extreme increasing for $0.8 \leq dltw < 0.9$ and (3) saturated gradient for $0.9 < dltw < 1.0$.

(ii) When choosing the apex angle of $\alpha = 60^\circ$ wedge cutting blade, the simulated cutting line force $f$ well matched the experimental result for $dltw < 0.6$, when choosing $V = 0.05, 0.17$ and $0.42 \text{ mm s}^{-1}$. It was clarified that the time-dependent wedge indentation resistance of the PSA sheet was well predicted for $dltw < 0.6$ by the use of the equivalent Young’s modulus $E_0$ measured in the out-of-plane compressive test for $\varepsilon < 0.3$ and a linear viscoelastic parameters (3 factors of the proxy series) measured in the torsional shear stress relaxation test. In the range of $0.6 < dltw < 0.8$, the simulated line force $f$ was smaller than that of experiment and its mismatching increased with $dltw$.

(iii) By experimentally measuring the inclined angle $\theta$ on the upper surface of the PSA sheet against the wedge indentation in the case of $\alpha = 60^\circ$, the angle $\theta$ linearly increased with the indentation depth $d$ for $dltw < 0.6$ and saturated to a constant inclined angle of $\theta_0 = 28^\circ$ for $dltw \geq 0.7$. On the contrary in the simulated condition, the angle $\theta$ linearly increased with $dltw$ up to 0.8. Seeing the maximum principal stress $\sigma_{P1}$ in the contact area on the upper surface against the wedge indentation, the stress $\sigma_{P1}$ exceeded 0.15–0.2 MPa when $dltw > 0.7$. Therefore, the experimental angle $\theta$ seemed to saturate due to a certain stress-dependent yielding for $dltw \geq 0.7$. Namely, the increasing of contact area of wedge was the same effect as the spreading of wetting area due to the saturation of inclined angle. When indenting for $dltw > 0.7$, one of the reasons why the experimental line force was higher than that of simulation was explained as the effect of spreading wetting due to the yield flow of PSA sheet.

(iv) When using the apex angles $\alpha = 42, 16^\circ$, the simulated cutting line force $f$ well matched the experimental response for $dltw < 0.5$ when using $\alpha = 42^\circ$, and for $dltw < 0.4$ when using $\alpha = 16^\circ$ respectively. The experimental inclined angle $\theta$ linearly increased with $dltw < 0.6$ and saturated to a constant angle $\theta_0 = 35^\circ$ for $dltw \geq 0.6$ when using $\alpha = 42^\circ$. Similarly, the experimental angle $\theta$ linearly increased with $dltw < 0.5$ and saturated to a constant angle $\theta_0 = 50^\circ$ for $dltw \geq 0.5$ when using $\alpha = 16^\circ$. On the contrary in the simulated condition, the angle $\theta$ linearly increased with $dltw$ up to 0.8 when $\alpha = 42, 16^\circ$. Seeing the maximum principal stress $\sigma_{P1}$ in the contact area on the upper surface of the PSA sheet against the wedge indentation, the stress $\sigma_{P1}$ exceeded 0.2 MPa when $dltw > 0.5$ when $\alpha = 42, 16^\circ$. It was found that the relative mismatching of $f$ between the simulated and the experimental results increased when using the sharp apex angle.

(v) In the latter stage of indentation $0.5 < dltw < 0.8$, the correlation between the mismatching of cutting line force $f_{wq}$ and the mismatching of inclined angle $\theta_{wq}$ was positive and strong.
Regarding the chosen items for characterizing the deformation behavior of the acrylic PSA sheet, the current work was limited in a narrow condition. Several items which must be furthermore investigated are listed as follow: a) three dimensional behavior of width end of a specimen seems to be important at the final cutting stage because the width end of the specimen flows out in the width direction. b) A detaching behavior from the wedge blade and deformation profile of sheared surface after leaving are related to the quality of cutting trace and seems to cause any failures. c) The combination effects of thermal and strain rate variation on the material properties of PSA sheet, such as the Johnson–Cook model (He A. et al. 2013), seem to be useful for an advanced processing by controlling the temperature of work material. d) Effects of material composition on the wettability and sliding resistance of contact boundary surface with a wedge blade should be revealed for predicting a cutting performance of the specified wedge blade, and also any advantages of surface modification or surface coating of a wedge blade on the wettability of the wedge blade should be revealed.

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