Regular Paper

Cutting Characteristics of Silicone Rubber Sheet with Respect to Indentation Velocity of Keen Wedge Blade

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(Received on December 21, 2018)

This research work is intended to reveal the cutting characteristics of a Shore A hardness of 50 silicone rubber sheet, which was stacked on a Shore A hardness of 90 silicone rubber underlay, indented with a 13.9° tungsten carbide blade. In a previous report (Mitsomwang et al., 2014), the velocity-dependent response was not sufficiently discussed. The cutting velocity of the blade was chosen to be in the range of 0.00167–0.29 mm·s⁻¹ to investigate the cutting characteristics derived from Eq. 5 the first inflection point P₁ and the peak maximum point P_{max} in the relationship between cutting line force and indentation depth. The correlation of points P₁ and P_{max} with the in-plane tensile testing characteristics was revealed with respect to feed velocity. Also, a dependence of the roughness of the cut surface on the cutting velocity was observed.

Key words: cutting, shear, speed effect, indentation, crack, silicone rubber.

1. Introduction

Silicone rubber is a kind of polymeric material that shows several unique properties such as bio-compatibility, wide range of service temperature (155 K to 589 K), high resistance to many chemicals. Because of such properties, it is often applied for several applications, e.g. electrical components, thermal insulation, food industry, medical application^{1)–5)}, compressive shock absorber⁶⁾ and so on. Silicone rubber is sometimes extruded or cast into sheet form as an initial product. Thus, a subsequent cutting process is often required for converting the sheet form into net shape products^{*1}. For the cutting of sheet materials, a wedge-blade indentation process is often chosen due to its advantages, such as high stability, high productivity rate, low operation cost⁷⁾. This indentation process seems to also be an attractive method for cutting the silicone rubber sheet. Shim et al. reported about the viscous hyper-elastic tensile and compressive constitute model⁸⁾ of specimens without any notches. As for the cutting resistance of natural rubber, Takahashi et al. discussed about a high speed cutting performance⁹⁾. That discussed the shock waves on the sheared zone. Mitsomwang et al. investigated the effects of a tip profile of keen tungsten carbide blade on the cutting load and sheared profile of silicon rubber sheet¹⁰⁾. However, the effects of feed velocity of indented blade on the torn surface state and the cutting load of the silicon rubber were not studied sufficiently. A certain level of high speed processing is necessary for the productive efficiency. To increase a production number of stripped patterns of rubber sheet in the manufacturing process is

directly linked to the economical profit. Therefore, in order to reveal the velocity effects of cutting characteristics, the relationship between the feed velocity of keen wedge blade and the cutting load response of a 1.1 mm thickness silicone rubber sheet was experimentally investigated when varying the cutting velocity. Also, the relationship between the blade edge profile and the surface roughness state of tore zone was discussed. Although the machining cost and time are fairly consumed, the tungsten carbide blade was chosen in order to investigate such effect of keen two-line and burrless profile of the wedge blade on the silicone rubber cutting.

2. Experiment Investigation

2.1 Material and Experimental apparatus

The material used in this study was a silicone rubber sheet with a 50-A Shore hardness (JIS-K6253-3) and a thickness $t_s = 1.04$ (1.02~1.06) mm. The specimen for tensile testing (JIS K 6251) is shown in Fig. 1. This rubber is referred to as “HS50A”.

Fig. 1 Shape of specimen used in tensile testing

The in-plane tensile stress-strain relationship of the HS50A worksheet is shown in Fig. 2. Here, the feed velocity was chosen as $V_{ts} = 0.05, 8.3$ mm·s⁻¹. Since the silicone rubber is a sort of viscous hyper-elastic materials, its elastic behavior as the stress by strain is not constant. However, seeing the stress-strain response of HS50A, the early stage gradient with the true stress

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*1 <http://www.sk-co-ltd.com/menu/silicone/silicone4.html>,
accessed on October 02 2018

by true strain (<0.5) was estimated from Fig. 2. This gradient is defined here as the initial elastic modulus $E_{IT} = \Delta\sigma/\Delta\varepsilon|_{\varepsilon=0\sim0.5}$. The value of E_{IT} was 3.81 MPa at the tensile feed velocity of $V = 0.05 \text{ mm}\cdot\text{s}^{-1}$ while it was 3.88 MPa at $V = 8.3 \text{ mm}\cdot\text{s}^{-1}$. Namely, it is found that E_{IT} doesn't almost change with a tensile feed velocity V . On the other hand, according to an out-of-plane compressive test (JIS-K6250 Chap.8, K6254) of silicone rubber sheet of 1.04 mm thickness and square side length of 20 mm x 20 mm, the initial elastic modulus E_{IC} was 18.9 MPa at $V = 0.05 \text{ mm}\cdot\text{s}^{-1}$. Therefore, the HS50A rubber sheet had anisotropic elasticities with the in-plane tensile and out-of-plane compression.

Fig. 2 Results of tensile test using two kinds of silicone rubber

Fig. 3 Schematic of cemented carbide blade and cutting system

Table 1 Profile parameters of the blade

Profile parameters						
Width of tip $T/\mu\text{m}$	Angle $\alpha/^\circ$		Height $H/\mu\text{m}$			Thickness of blade $T_B/\mu\text{m}$
	Primary angle $\alpha_p/^\circ$	Secondary Angle $\alpha_s/^\circ$	Primary Height $H_P/\mu\text{m}$	Secondary Height $H_S/\mu\text{m}$	Total Height H_T/mm	
2.47	13.9	4.2	91.6	822.6	22.4	100

2.2 Experimental method of cutting

The HS50A worksheet was prepared for cutting test as a rectangle with a width (w_s) of 20 mm and a length (L_s) of 30 mm. As shown in Fig. 3(a), the worksheet was stacked on another silicone rubber underlay (HS90A underlay, thickness $t_u = 1.01\sim1.11$ mm, the initial elastic modulus $E_{IT} = 35.7$ MPa) in order to avoid the direct collision between the cemented carbide blade and hard steel plate. When choosing the feed velocity $V = 8.3 \text{ mm}\cdot\text{s}^{-1}$, the in-plane tensile stress-strain curve of the underlay rubber sheet was shown in Fig. 2. These stacked

work/underlay sheets were placed on the lower movable head of the pressing machine. The blade, which was fastened by the blade holder, was attached to the upper stationary head of the machine. The upward moving (cutting) velocity of the movable head was mainly controlled in the ranging of $0.0167\sim0.29 \text{ mm}\cdot\text{s}^{-1}$. As for inspecting the quality of wedged surface, the cutting velocity was varied up to $0.72 \text{ mm}\cdot\text{s}^{-1}$.

During the cutting test, the movable head was moved upward until the worksheet was completely separated. Indentation depth d and cutting load resistance F were measured by a dial gauge and a load cell (the capacity was 49 N), respectively. The quantity of d is defined as the zero position when the upper surface of the work sheet touches the blade tip. A CCD camera was also installed for investigating the side-view deformation of the worksheet.

A cemented carbide (FM10K) keen blade was chosen for cutting off the silicon rubber sheet. This blade form of two line wedge is often used for processing a sort of pseudo-plastic material such as a green ceramic sheet. The geometric profile of the blade defined in Fig. 3(b) was measured using optical and 3-D laser scanning microscopes. The measured results were shown in Table 1. Here, the surface roughness of the 1st facet (the part of H_p) was $1.37 \mu\text{m(Ra)}$ and that of the 2nd facet (the part of H_s) was $2.25 \mu\text{m(Ra)}$ in the blade width (longitudinal) direction.

All of the rubbers (worksheet and underlay) were kept in a temperature and humidity controlled room for a certain long period (longer than 24 hours before cutting). The cutting experiment was also performed in this controlled room. The temperature and relative humidity were controlled as $296 \pm 1 \text{ K}$ and $50 \pm 2 \text{ \%RH}$. The cutting was carried out using 10 specimens for each condition.

3. Experimental Results and Discussion

3.1 Effects of indentation velocity on cutting resistance

Fig. 4 shows representative photographs of silicone rubber subjected to wedge blade indentation at the depth positions $d/t_s = 0, 0.17, 0.40$, and 0.75 . A large warp occurred beneath the blade against the underlay, and a subduction was observed on the upper surface. Fig. 5 shows a photograph of sheared profile of silicone rubber. Here, the feed velocity was $V = 0.05 \text{ mm}\cdot\text{s}^{-1}$. The sheared profile was straight and flat in the thickness direction, nevertheless the upper zone of rubber largely deformed as shown in Fig. 4. Because the cutting deformation seemed to be almost symmetric breakage without any plastic flow. According to preliminary experiment using a side wedge blade¹¹⁾, the cut trace tended to be oblique-straight line. This seems to be caused by the asymmetric wedge and its thrust force. Therefore, any symmetric wedge seemed to be superior to generate a straight and flat cut surface without any oblique attitude. Also, there were not any burr profile on the lower corner and any wear profile on the upper corner of the rubber sheet. These cut trace appears to be caused by the elastic-breaking without any plastic flows.

Fig. 6(a) shows the relationship between the line force f ($=F/w_s$) and the normalized indentation depth d/t_s at the representative cutting velocities of 0.0167, 0.05, and 0.2 $\text{mm}\cdot\text{s}^{-1}$. As an overall tendency of line force model, three referenced points were detected in every cutting process as shown in Fig. 6 (b): the first inflection point P_1 (f_i , d_i/t_s), the peak maximum point P_{peak} (f_{peak} , d_{peak}/t_s) and the breaking point P_{break} (f_{break} , d_{break}/t_s).

Fig. 4 Side views of silicone rubber subjected to wedge blade indentation with $V = 0.05 \text{ mm}\cdot\text{s}^{-1}$. (a) $d/t_s = 0$, just fitted, (b) $d/t_s = 0.17$, start of indentation, (c) $d/t_s = 0.4$, inflection point of load, and (d) $d/t_s = 0.75$, peak maximum force ($t_s = 1.04 \text{ mm}$)

Fig. 5 Side view of silicone rubber after cutting at $V = 0.05 \text{ mm}\cdot\text{s}^{-1}$

(a) $V = 0.0167\text{--}0.2 \text{ mm}\cdot\text{s}^{-1}$ (b) Line force model

Fig. 6 Relationship between cutting line force f and indentation depth d/t_s at various cutting velocities V and force model

As seen in Fig. 6, the line force f almost linearly increases with d/t_s until reaching the first inflection point P_1 . The gradient $\partial f / \partial (d/t_s)$ was almost independent to V in the surface push stage ($d/t_s = 0\text{--}d_i/t_s$). The first inflection point P_1 appeared to be related to a crack initiation or a surface damage of the worksheet.

This observation based on the photographs of surface initial state was confirmed seeing Fig. 7.

In the process $0\text{--}P_1$, the surface was not damaged by the wedge contact, as shown in Fig. 7(a). Here, the rubber was elastically compressed by the wedge (pushing stage). The correspondence of the first inflection point and the surface crack initiation was already discussed by Mitsomwang et al.¹⁰⁾ Also, the peak maximum point P_{peak} occurred at $d/t_s = 0.6\text{--}0.8$.

(a) before inflection (b) after inflection point

Fig. 7 Top views of upper face of rubber sheet. A half-cut breakage line was observed after passing the inflection point

In the process of $P_1\text{--}P_{\text{peak}}$, the wedge was penetrated into the rubber by cracking without plastic flow (penetrated stage). Here, since the warpage of rubber increased, the cutting load seemed to non-linearly increase due to the increasing of pressure on the wedge surfaces. At the same time, since the contact length of wedge increased with the cracked depth, the cutting load increased. In the latter half process $P_{\text{peak}}\text{--}P_{\text{break}}$, since the indentation depth of wedge increased more than 50%, the warpage of rubber was weakened and then the pressure of wedge surface decreased. This deformation appeared to be a sort of necking stage.

In this work, the effects of cutting velocity V on the referenced line forces f_i , f_{peak} were carefully investigated. The relationships between the cutting velocity $V = 0.00167\text{--}0.29 \text{ mm}\cdot\text{s}^{-1}$ and the two referenced points: P_1 , P_{peak} were arranged in Fig. 8(a) and (b). Linear approximations of the average based referenced points in Fig. 8 were derived with the term $\ln(V)$ as Eq.(1)~(4). This logarithmic forms were considered due to the non-linear response with the cutting velocity V (>0).

$$f_i = k_{i0} + k_{i1} \ln(V) \quad (1)$$

$$f_{\text{peak}} = k_{\text{peak}0} + k_{\text{peak}1} \ln(V) \quad (2)$$

$$d_i/t_s = c_{i0} + c_{i1} \ln(V) \quad (3)$$

$$d_{\text{peak}}/t_s = c_{\text{peak}0} + c_{\text{peak}1} \ln(V) \quad (4)$$

Here, the coefficients of Eq. (1), (2) were $k_{i1} = 0.028$, $k_{i0} = 0.589$, $k_{\text{peak}1} = 0.039$ and $k_{\text{peak}0} = 0.718 \text{ N}\cdot\text{mm}^{-1}$, while that of Eq. (3), (4) were $c_{i1} = 0.008$, $c_{i0} = 0.439$, $c_{\text{peak}1} = 0.031$ and $c_{\text{peak}0} = 0.827$, respectively. When increasing the velocity up to $V = 0.72 \text{ mm}\cdot\text{s}^{-1}$, the cutting of worksheet was successfully done although the sampling interval was about $\Delta(d/t_s) = 0.063$. As the precision of measurement of the line force f and the indentation depth d/t_s was low when $V = 0.72 \text{ mm}\cdot\text{s}^{-1}$, the relative errors of measured data with the approximations Eq. (1)~(4) were investigated as a

reference and shown in **Table 2**. Here, the experimental data measured was a sample for picking the image-scanned data of sheared surface up. The experimental data at $V = 0.72 \text{ mm}\cdot\text{s}^{-1}$ appeared to be a little larger but not so much than the estimated values of Eq. (1)-(4) which were derived in the range of $V = 0.0167\text{--}0.29 \text{ mm}\cdot\text{s}^{-1}$.

(a) $f_{\text{peak}} - V$ and $f_1 - V$

(b) $d_{\text{peak}} - V$ and $d_1 - V$

Fig. 8 Relationship between the reference line force points, indentation depth positions, and cutting velocity V

Table 2 Deviation of measured data at $V = 0.72 \text{ mm}\cdot\text{s}^{-1}$ from the approximation using of Eqs. (1) – (4)

	Measured data	Data derived from Eqs. (1) – (4)	Deviation from Calculations (%)
$f_{\text{peak}} / \text{N}\cdot\text{mm}^{-1}$	0.766	0.706	0.06 (8.6%)
$f_1 / \text{N}\cdot\text{mm}^{-1}$	0.609	0.579	0.03 (5.1%)
$d_{\text{peak}} / \text{mm}$	0.885	0.817	0.068 (8.3%)
d_1 / mm	0.492	0.437	0.055 (12.7%)

As there was a similar tendency between Eq. (2) and Eq. (4) with respect to V , and also there was that between Eq. (1) and Eq. (3), the relationship between the referenced line forces f_1 , f_{peak} and the corresponded positions d_1/t_s , d_{peak}/t_s was plotted in **Fig. 9**. The linear approximations of f_1 and f_{peak} were derived as Eq. (5) and Eq. (6) in Fig. 9.

$$f_1 = 2.5 (d_1 / t_s) - 0.53 \quad (5)$$

$$f_{\text{peak}} = 1.3 (d_{\text{peak}} / t_s) - 0.33 \quad (6)$$

It was found that the referenced points (f_1 , d_1/t_s) and (f_{peak} , d_{peak}/t_s) were almost linear with $\ln(V)$, while the referenced line

forces f_1 , f_{peak} had a positive-linear relationship with the corresponded positions d_1/t_s , d_{peak}/t_s , respectively.

As for the breaking line force point P_{break} (f_{break} , d_{break}/t_s), the tendency of variation with V was similar to that of P_1 and P_{peak} , although the values of f_{break} , d_{break}/t_s appeared to depend on the stiffness of underlay, when seeing Fig. 6(a).

Fig. 9 First inflection and peak maximum points for specified cutting velocity ($0.0167\text{--}0.29 \text{ mm}\cdot\text{s}^{-1}$)

3. 2 Relationship between tensile and cutting resistance with respect to the velocity

Seeing the in-plane tensile test shown in Fig. 2, since the tensile strength (stress) was $\sigma_B = 40 \text{ MPa}$ by the feed velocity $V_{\text{ins}} = 8.3 \text{ mm}\cdot\text{s}^{-1}$ and $\sigma_B = 31 \text{ MPa}$ by $V_{\text{ins}} = 0.05 \text{ mm}\cdot\text{s}^{-1}$, an approximation of σ_B with the logarithmic term $\ln(V_{\text{ins}})$ was estimated as Eq. (7). Here, the coefficients were $s_1 = 1.76 \text{ MPa}$ and $s_0 = 36.27 \text{ MPa}$.

$$\sigma_B = s_1 \ln(V_{\text{ins}}) + s_0 \quad (7)$$

In order to investigate the correlation between the velocity effect of in-plane tensile test and the velocity effect of wedge cutting resistance, a ratio of a linear term by a constant term was calculated from Eq. (5), (6) and (7). The derived ratios were shown in **Table 3**.

Table 3 Ratio of coefficients in Eqs. (1), (2) and (7)

k_{10} / k_{11} on f_1	$k_{\text{peak}1} / k_{\text{peak}0}$ on f_{peak}	s_1 / s_0 on σ_B
0.048	0.054	0.049

Seeing Table 3, the ratio of s_1/s_0 on σ_B was almost the same as the ratio of k_{10}/k_{11} on f_1 and the ratio of $k_{\text{peak}1}/k_{\text{peak}0}$ on f_{peak} . It was found that the relationship between the tensile feed velocity V_{ins} and the tensile strength (stress) σ_B had the similar tendency as the relationship between the cutting velocity V and the referenced line forces f_1 , f_{peak} .

3. 3 Effects of indentation velocity of blade on penetrated stage

The gradient $\partial f / \partial (d/t_s)$ in the pushing stage was almost independent from the indentation velocity V , as shown in Fig. 6. This seemed to be owing that the pushing stage was based on the elastic compressing deformation without any cracking. As for the penetrating stage (in the P_1 - P_{peak} process), the average

gradient $\partial f/\partial(d/t_s)$ was estimated as the approximation $G_{\text{pnt}} = (f_{\text{peak}} - f_i)/(d_{\text{peak}} - d_i)/t_s$ from the raw data. The calculated average gradient was shown in Fig. 10 and the approximation Eq. (8) was derived with $\ln(V)$. Furthermore, as the gradient G_{pnt} can be also derived from Eq. (1)-(4), its outcome was shown as Eq. (9). It was confirmed that the coefficients of the first-order term of $\ln(V)$ were almost equal with Eq. (8) and Eq. (9).

$$G_{\text{pnt}} = 0.3324 + 0.0146 \ln(V) \quad (8)$$

$$G_{\text{pnt}} = 0.3423 + 0.0147 \ln(V) \quad (9)$$

Seeing Fig. 10 and Eq. (8) or Eq. (9), it was found that the average gradient of force in the penetrated stage was a little increased with the indentation velocity V .

Fig. 10 Relationship between the average gradient and indentation velocity in the penetrated stage (P_1 – P_{peak} process)

3.4 Effects of indentation velocity of blade on roughness of sheared surface

Regarding the sheared profile of silicone rubber using the symmetric wedge blade, the cut edge was fairly flat and parallel to the blade-indented direction as shown in Fig. 5. In order to confirm the smoothness of the cut surface, the cut surface was observed using the laser microscope and the optical microscope.

Fig. 11 shows the front views of the cut surface of silicone rubber sheet when choosing the cutting velocity of $V = 0.05$, $0.72 \text{ mm} \cdot \text{s}^{-1}$. Here, the cutting direction was set from the upper to the lower side in the figure. In these photographs, darken particles as air-bubbles of 10 – $20 \text{ } \mu\text{m}$ were randomly spread. The bubbles seemed to be filled in the medium for controlling the average hardness of the silicone rubber. In order to evaluate the smoothness of cut surface, nine positions of $100 \times 100 \text{ } \mu\text{m}$

Fig. 11 Front views of cut surface of silicone rubber sheet

squared area were chosen as shown in Fig. 12 and measured by the laser microscope.

Fig. 12 Measurement zones on sheared surface of silicone rubber

Table 4 Average surface roughness. Measured range: nine positions in square zone of $100 \times 100 \text{ } \mu\text{m}$. Resolution and analyzed pitch: $0.01 \text{ } \mu\text{m}$ and $1 \text{ } \mu\text{m}$, respectively

$V \text{ mm} \cdot \text{s}^{-1}$	Thickness direction		Width direction	
	Ra	Rz	Ra	Rz
0.05	5.67	55.49	5.61	45.89
0.72	6.21	54.86	3.96	34.06

The line roughness Ra (arithmetical mean deviation of the assessed profile, JIS-B0601), Rz (average distance between the five highest peaks and lowest valleys over the entire sampling length) of the cut surface was shown as the average of the nine squared zones in Table 4. Here, the measured length was $100 \text{ } \mu\text{m}$ for each square, and the analyzed pitch of roughness Ra, Rz was $1.0 \text{ } \mu\text{m}$, which was processed using the measuring resolution of $0.01 \text{ } \mu\text{m}$. Seeing these evaluation of the surface roughness Ra and Rz, it was revealed that the roughness of cut surface was stably not changed with the cutting velocity. The cutting trace and its surface roughness by a keen wedge indentation were almost independent from the cutting velocity in the investigated range. This result contributes to develop the similar keen wedge blade and to cut a similar rubber material off in smooth.

4. Conclusions

In this work, a stacked silicone rubber sheet (HS50) was subjected to a keen tungsten carbide blade indentation. The cutting velocity of blade V was experimentally varied in the range of 0.0167 – $0.29 \text{ mm} \cdot \text{s}^{-1}$. The cutting load response of silicon rubber was characterized with the referenced points: the first inflection point P_1 (f_i , d_i/t_s) and the peak maximum point P_{max} (f_{max} , d_{max}/t_s). The experimental results were revealed as follows:

(a) The referenced cutting line force f_i , f_{peak} linearly increased with the logarithmic function of cutting velocity $\ln(V)$ in the specified range. This dependency of the referenced line forces on the cutting velocity was quite similar to that of the tensile strength in the in-plane tensile test.

(b) The corresponded displacements d_i/t_s , d_{peak}/t_s of

referenced points P_1 , P_{peak} also increased with the logarithmic function of cutting velocity $\ln(V)$ in the specified range. Namely, the relationship between the referenced line forces and the corresponded displacements was independent to the cutting velocity.

(c) Seeing the items (a), (b), the correlation between the in-plane breaking strength and the cutting peak line force or the inflection line force was revealed with respect to the feed velocity. The criteria of wedge cutting is strongly related to the uni-axial tensile strength when changing the feed velocity.

(d) As the cutting velocity increased up to $V = 0.72 \text{ mm} \cdot \text{s}^{-1}$, the referenced points P_1 , P_{peak} were well estimated by the previous approximations, while the roughness of cut surface was not affected by the cutting velocity of blade.

(e) A permanent deformation as a straight splitting of the silicone rubber by a keen wedge blade was revealed from the aspect of velocity-dependent cracking without plastic flow.

Synthetically, the wedging criteria with the velocity is expected to predict the cutting trace with a silicone rubber. The results of this work contributes to develop a cutting simulation model.

Acknowledgements

The authors would like to acknowledge Ms. Azusa Sakamoto, a master student in the department of Mechanical Engineering, Nagaoka University of Technology, for her contributions to the laser-microscope measurement of the worksheet.

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