Research Paper

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Husking Characteristics of Short and Long grain Rice by Rubber roll Husker (Part 1)*

——Dynamic Analysis of a Single Grain Motion——

Douglas SHITANDA*1, Yoshio NISHIYAMA*1, Shoji KOIDE*1

Abstract

Dynamic analysis of grain motion in an experimental rubber roll husker was carried out using short and long grain rice. The short grain rice variety used was Akitakomachi and the long grain rice varieties were Delta and L201. Single grains used in the analysis were fed vertically and horizontally in between the rollers. Considering the direction of grain feed and the shape of the grain, a new equation for contact distance was derived based on the radius of curvature of the grain. The new equation gave a better estimation of contact distance compared to the traditional equation. Contact distance was used in the computation of grain speed, projected area and contact area. Grain motion was observed using a high-speed camera. Computed grain speed was found to be closer to the auxiliary roll speed than the main roll speed and at low roll deflection, projected area was close to contact area. Maximum shear stress determined from shear force caused by friction force and projected area occurred close to the maximum husking energy efficiency.

[Keywords] radius of curvature, contact distance, contact length, contact area, shear stress, rubber roll husker

I Introduction

Rubber roll husker consists of two rubber rolls made from synthetic rubber. The rolls rotate in opposite directions and at different speed so as to cause shear force by parallel friction force when the grain is inserted. The roll clearance is adjusted to reduce breakage, scratch and power consumption[1]. The grain dynamics as it moves between the rolls depends on the peripheral velocity difference ratio, the contact distance, the roll clearance and the grain properties. At a fixed peripheral velocity difference ratio, the husker performance is generally dependent on the roll clearance and the grain characteristics. During husking, contact distance, which is different from contact length, plays a significant role in the husker's performance. It is defined as the maximum distance parallel to the longitudinal axis of the roll that the grain can be in contact with the roll at a given roll clearance. It depends on the roll diameter, the grain size and shape and the roll clearance. From the traditional equation which assumes that the grain is flat[2], contact distance l_d is given by;

$$l_d = 2\sqrt{2r\delta - \delta^2} \tag{1}$$

where r is the roll radius and δ is the maximum roll deflection given by;

$$\delta = \frac{(h-c)}{2} \tag{2}$$

where h is the grain thickness and c is the roll clearance. However, conventional contact distance equation (1) does not consider the direction of grain feed and its shape. Thus the calculated contact distance exceeds the grain length as the roll clearance decreases. Nishiyama, when considering the specific husking energy for rubber roll husker theoretically proposed that it was proportional to the peripheral velocity difference ratio expressed in equation (15) in terms of the grain velocity[3)4)]. Kawamura suggested that since the main roll wear was twice that of the auxiliary roll, the grain speed was close to that of the auxiliary roll[5)]. However, values for the actual grain speed have never been documented. Since husking occurs mainly by shear, consideration of shear stress becomes vital in the husker's performance analysis. This paper therefore sets out to ; (1) derive contact distance considering the radius of curvature of the grain, (2) compute contact length, maximum contact area and projected contact area between the grain and the roll, (3) establish the relationship between auxiliary roll speed and grain speed, (4) evaluate the husking shear force by considering the direction of grain feed.

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*1 JSAM Member, Faculty of Agriculture, Iwate University, Morioka, 020-8550 Japan

II Theoretical Consideration

1. Contact distance

Figure 1 (a) shows schematic diagrams for the grain's three perpendicular planes that are used to define the radius of curvature. Thus the direction of grain length is taken as the X-axis, that of the thickness as the Y-axis and that of the width as the Z-axis. The radius of curvature of the grain in the X-Y plane is r_z (longitudinal radius of curvature), in the Y-Z plane is r_x (X-transverse radius of curvature) and in the X-Z plane is r_y (Y-transverse radius of curvature). The direction parallel to the axis of rotation of the roll is taken as the transverse axis of the roll and that perpendicular to it in the direction of grain motion is taken as the longitudinal axis of the roll. When the X-axis of the grain is parallel to the vertical axis of the roll, the grain feed is considered vertical and when it is parallel to its horizontal axis, the grain feed is considered horizontal. The contact between the grain and the rubber roll for the analysis of the contact distance is shown in Figure 1 (b). Assuming paddy rice has curved surfaces and is rigid compared to the rubber roll, maximum roll deflection δ is generally given by;

$$\delta=\alpha+\beta=\frac{(h-c)}{2} \tag{3}$$

At the point of maximum contact, contact distance l_d is expressed in terms of the radius of curvature of the grain r_g and that of the roll r as shown in equation (4).

$$l_d=2\sqrt{2r\alpha-\alpha^2} \tag{4}$$

where α is given by ;

$$\alpha=\frac{(2r_g\delta-\delta^2)}{2\,(r_g+r-\delta)} \tag{5}$$

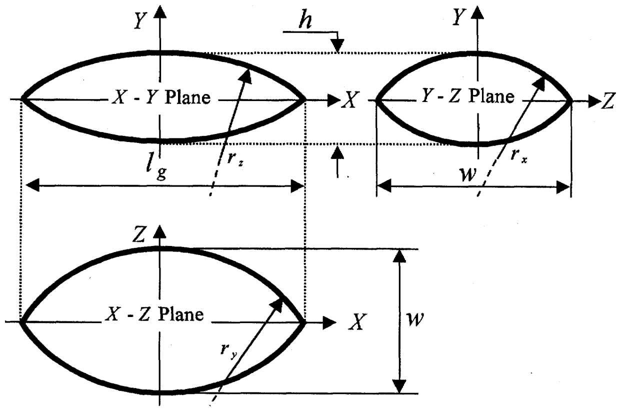
The radius of curvature r_g is defined as the radius of curvature of the grain in the plane perpendicular to the transverse axis of the roll. Thus the actual maximum length that the grain is in contact with the roll in its longitudinal direction (longitudinal contact length) l_c is computed as shown below.

$$l_c=2r_g\tan^{-1}\left(\frac{l_d}{\sqrt{4r_g^2-l_d^2}}\right) \tag{6}$$

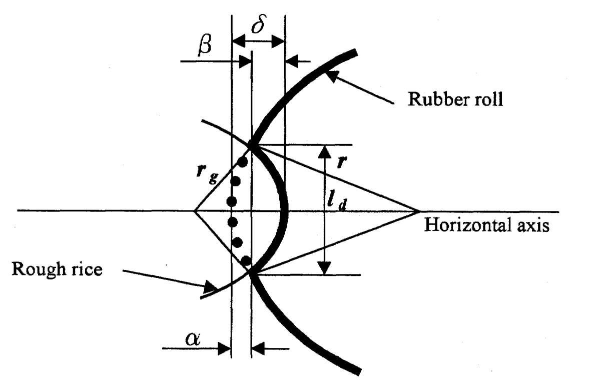
Contact length differs from the contact distance in that it is measured along the grain profile whereas contact distance is the vertical distance between extreme points of contact. Since the roll is not curved in its transverse direction, the transverse contact length (l_t) in the transverse direction of the roll is given by;

$$l_t=2r_{gt}\tan^{-1}\left(\frac{2r_{gt}\delta-\delta^2}{r_{gt}-\delta}\right) \tag{7}$$

where r_{gt} is the radius of curvature of the grain in the horizontal plane. Thus for vertical grain feed, r_g is equal to r_z and r_{gt} is equal to r_x whereas for horizontal grain feed, r_g is equal to r_x and r_{gt} is equal to r_z.



(a) Schematic diagrams for the three perpendicular planes of rough rice



(b) Schematic diagram for contact between the grain and the rubber roll

Figure 1 Schematic diagrams for grain planes and roll-grain contact

Considering the grain curvature as an arc of a circle, the grain's radius of curvature is determined as one of the parameters in the circle equations below using least square method.

$$y=a+\sqrt{r_x^2-x^2} \text{ or } y=a+\sqrt{r_z^2-x^2} \tag{8}$$

where y is grain height in the Y-axis direction and x is length in the X-axis direction.

2. Contact area

Contact area is important for the analysis of shear stress between the grain and the roll. It is defined as the maximum area of contact between the roll and the grain at a given roll clearance. Considering half of the grain viewed on X-Z plane (see Figure 2), for vertical grain feed, the maximum theoretical contact area (A_c) can be obtained by integrating equation (9).

$$A_c=2\int_0^{\frac{l_d}{2}} j\left\{\sqrt{\left(\frac{dj}{dx}\right)^2+4}\right\}dx \tag{9}$$

where j is the contact arc length between the grain and the roll sustained by an angle 2θ on the Y-Z plane. Assuming the variation of radius of curvature is proportional to that of the roll deflection, then j is calcu-

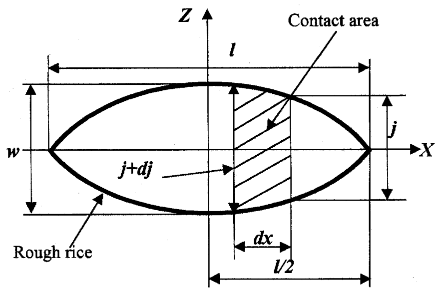


Figure 2 Top view schematic diagram of rough rice for computation of contact area

lated from equation (10) below.

$$j = 4 r_x \theta \frac{y}{h} \tag{10}$$

where y is the roll deflection in the Y- direction and h is the grain thickness. Projection of contact area gives the projected area, which is computed from the equation below by assuming that the projected areas are similar.

$$A_p = 2 r_{cy}^2 \tan^{-1}\left(\frac{l_g}{2 r_y - w}\right) - \frac{l_d^2}{2 l_g}(2 r_y - w) \tag{11}$$

where r_{cy} is the contact radius of curvature in the X-Z plane. The variation of radius of curvature is assumed to be proportional to contact distance as expressed in equation (12).

$$r_{cy} = \frac{r_y l_d}{l_g} \tag{12}$$

3. Grain Speed

As the grain enters in between the rolls, it leans towards the high-speed roll as the husk is squeezed and then removed by the rolls. Based on the radius of curvature of the grain, the distance that the grain moves through while in contact with roll is twice the contact distance. Thus grain speed V_g is given by ;

$$V_g = \frac{2 l_d}{\Delta t} \tag{13}$$

where Δt is the time the grain is in contact with the roll (contact time). Thus the calculated grain speed is double compared to that obtained using the former equation[5]. Since it is difficult to define the direction of feed for random grain feed, grain speed can be considered as the average for vertical and horizontal grain feed.

4. Husking energy efficiency

The specific work w [kJ/kg] done by the two rolls during husking depends on the coefficient of friction μ [−], specific normal force p [kN/kg] and the total slip length l_s [m] between the roll and the grain as expressed in equation (14).

$$w = \mu p l_s = 2 \mu p \phi_g l_d \tag{14}$$

Product of coefficient of friction and specific normal force gives the specific friction force f [kN/kg]. Specific friction force is friction force divided by the grain mass. It is also specific shear force since friction force by the main roll is equal in magnitude but opposite in direction to that by the auxiliary roll. If the main roll has a diameter D [m] and rotates at N [rad/s] and the auxiliary roll has a diameter d [m] and rotates at n [rad/s], then the peripheral velocity difference (PVD) ratio with respect to grain velocity ϕ_g [−] is given by[4] ;

$$\phi_g = \frac{DN - dn}{2 V_g} \tag{15}$$

Traditionally, PVD ratio is expressed with respect to the main roll speed as shown below[6) 7)].

$$\phi_N = \frac{DN - dn}{DN} \tag{16}$$

However, Nihei had earlier proposed that PVD ratio could also be expressed with respect to the auxiliary roll speed[8].

$$\phi_n = \frac{DN - dn}{dn} \tag{17}$$

Since husking is mainly by shear force, husking force f [kN/kg] can be considered as a function of the projected area A_P [m^2] in contact with the roll. Thus equation (14) can also be expressed as shown below in terms of the husking shear stress τ (kN/m^2).

$$w = \frac{2 \tau A_P \phi_g l_d}{m}, \quad \tau = \frac{mf}{A_P} \tag{18}$$

where m is the mass of the grain. Husking energy efficiency η [kg/kJ] of the husker can therefore be expressed as a function of the husked ratio H [−] and the projected contact area as shown below[4].

$$\eta = \frac{H}{w} = \frac{mH}{2 \tau A_P \phi_g l_d} \tag{19}$$

The optimal roll clearance C_{OPT} is thus defined as the roll clearance when the husking energy efficiency is maximum.

III Experiment Methodology

Grain dynamics of short and long grain rice was analyzed using a single grain husked by an experimental rubber roll husker (SATAKE THU). The husker had two equi-diameter rolls of synthetic rubber (SBR), 100 mm in diameter, 35 mm in thickness and Shore hardness 82. Varieties of rice used were short grain rice (*Japonica*) Akitakomachi and long grain rice (*Indica*) Delta and L201. Grain parameters determined were ; moisture content by air oven method (135℃-24 h), grain length, width and thickness by micrometer screw gauge, and weight by electronic balance (A & D HA 180M). Roll clearance was varied from 0.3 mm to 2.4 mm at an interval of 0.3mm by use of filler gauges. The longitudinal grain curvature r_z was determined by plotting points on the surface profile of magnified grain images. This was done with reference to the longitudinal axis (grain length). The images were obtained by fixing the grains on a hard

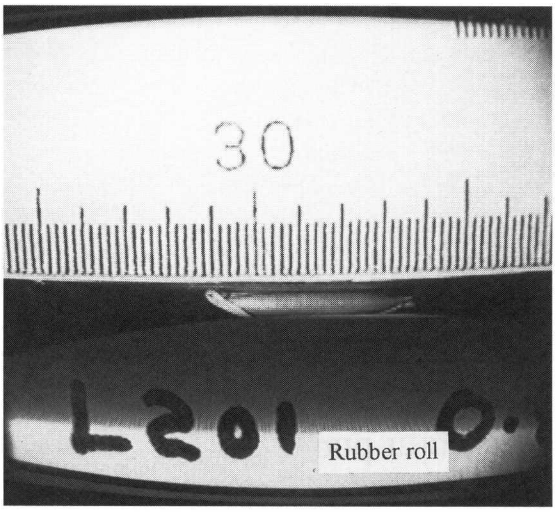


Figure 3 Se-up for measuring contact distance

paper using an adhesive bond with the X-Z plane perpendicular to the paper. This gave the projected images in the X-Y plane of the grain. Using the circle equation (8) to fit the grain's curvature, the longitudinal radius of curvature was determined as one of the parameters in the circle equation. Contact distance was determined by placing the grain in between the rolls vertically and varying the roll clearance as shown in Figure 3. Along one of the rolls was glued a scale with an accuracy of 0.2 mm parallel to the transverse axis of the roll. Using a digital camera (PANASONIC NV-DJ100), the set-up was magnified and the image relayed to a monitor. Contact distance was read from the magnified scale on the monitor. The obtained results were compared to those by equation (4). Surface area was determined by peeling the rice husk and magnifying it four times. The magnified images were scanned into the computer and the area determined using an image processing software (Scion Image Processor). Results were compared to those obtained using equation (9). Grain speed between the rolls was evaluated at low speed (N=0.0164 rad/s, n=0.0089 rad/s) for both vertical and horizontally single grain feed. A stress-strain tester (SHIMPO FG 50 V) shown in Figure 4 was used to rotate the rolls by pulling a thin sheet of plastic tied around a pulley attached to the auxiliary roll. The shear force and contact time were recorded simultaneously by a computer. Shear force curves were plotted and the peak values used in the analysis. From the husking time and contact distance, the grain speed was calculated. Husking was also carried out at high roll speed (N=198.4 rad/s, n=108.4 rad/s) by feeding single grains vertically and horizontally in between the rolls. At rated PVD ratio (ϕ_n) of 0.83, the auxiliary roll speed was varied from 4.2 m/s to 7.8 m/s to evaluate the effect of roll speed on grain speed.

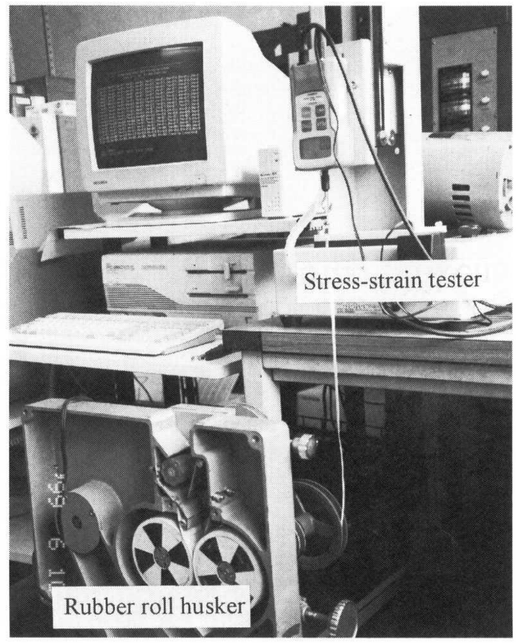


Figure 4 Apparatus for measuring husking shear force

Husking was done at the optimal roll clearance C_{OPT} given in Table 1[9]. In this case, husking time was obtained from a high-speed camera (NAC HSV 400) used to observe the grain motion. Equation parameters were obtained by non-linear least square method.

IV Results and Discussion

1. Grain -roll contact analysis

Table 1 gives the grain properties for the three varieties of rice used. The longitudinal radius of

Table 1 Properties of the three varieties of rough rice

Property	Akitakomachi	Delta	L201
M_C [%]	15	15	15
l_g [mm]	7.3	10.0	9.8
w [mm]	3.3	3.2	2.5
h [mm]	2.3	2.2	2.0
A [mm^2]	24.8	33.8	27.1
A_c [mm^2]	24.7	25.6	21.3
A_P [mm^2]	16.7	21.8	16.5
S [—]	0.52	0.41	0.37
m [mg]	28.6	37.4	27.5
C_{OPT} [mm]	1.8	1.5	1.3
r_{z1} [mm]	5.8	11.3	12.8
r_{z2} [mm]	6.4	11.9	12.5
r_x [mm]	1.8	1.7	1.3

MC : moisture content, l_g : length, w : width, h : thickness, A : surface area (experiment), A_c : maximum contact area (computed), A_P : maximum projected area (computed), S : sphericity, m : mass, C_{OPT} : Optimal roll clearance, r_{z1} : longitudinal radius of curvature (eqn. 8), r_{z2} : longitudinal radius of curvature (eqn. 20), r_x : X-transverse radius of curvature (eqn. 20)

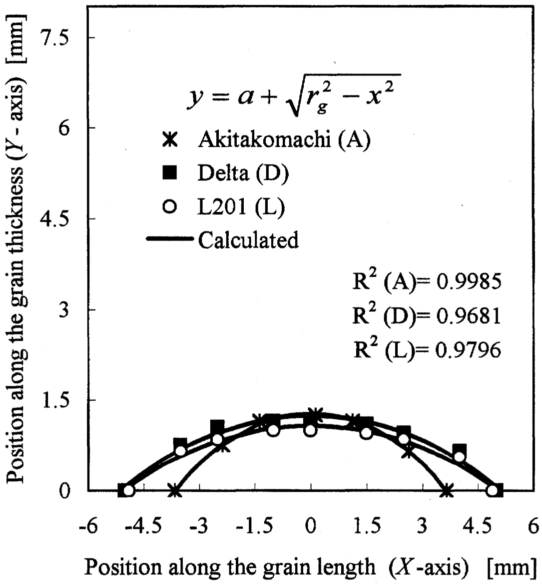


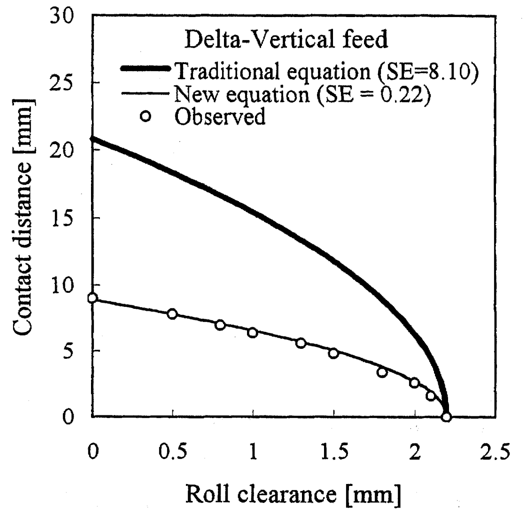
Figure 5 Grain surface profile for the three varieties of rough rice

curvature for the three varieties of rice obtained using equation (8) were; 5.8 mm, 11.3 mm and 12.8 mm for Akitakomachi, Delta and L201 respectively. Using the above radii, the curvatures of the three varieties of rice in the X-Y plane were drawn. There was a good agreement between the experimental and the computed results for a single grain as shown in Figure 5. If the grain's curvature is considered circular, then equation (20) can also be used to calculate the radius of curvature of the grain with a high degree of accuracy.

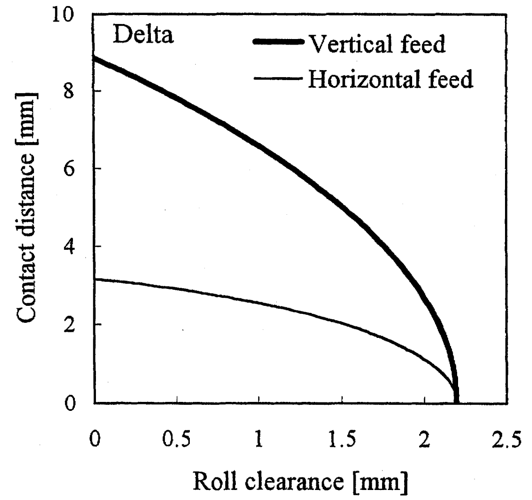
$$r_g = \frac{k^2 + l_g^2}{4k} \tag{20}$$

where k is the grain's thickness h (when $r_g = r_z$) or width w (when $r_g = r_x$) and l_g is the grain's length. When r_g is equal to r_y, then k becomes the grain thickness and l_g the grain width. The r_z values obtained from equation (8) and (20) were very close as shown in Table 1. For vertical grain feed, the computed maximum contact length were 7.7 mm, 10.3 mm, and 10.1 mm for Akitakomachi, Delta, and L201 respectively. Maximum contact length was slightly higher than the grain length (l_g). Equation (4), which considered the radius of curvature of the grain, gave better results for contact distance compared to the traditional equation (1) as shown in Figure 6 (a). For the Delta variety, graphical fit of experimental data by the new equation had a standard error of 0.22 mm compared to 8.10 mm for the traditional equation. Considering the direction of feed, horizontal grain feed had low contact distance compared to vertical feed due to the difference in the radius of curvature. Figure 6 (b) shows the variation of contact distance with roll clearance for different directions of grain feed.

From the experimental data, Delta had the highest



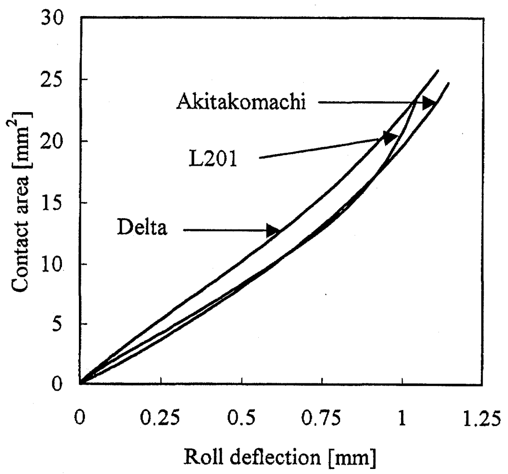
(a) Contact distance for vertical grain feed computed by traditional and new equation



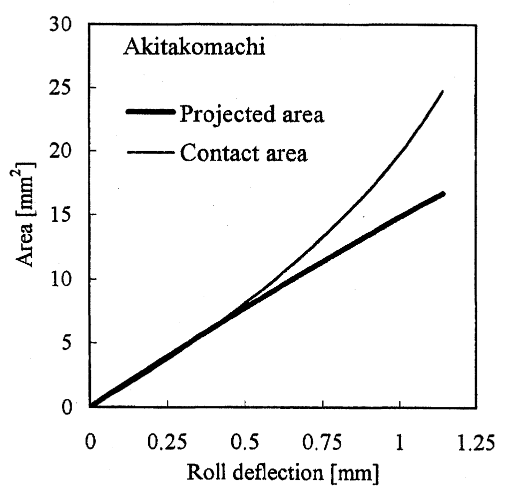
(b) Contact distance for different directions of grain feed computed by the new equation

Figure 6 Variation of contact distance with roll clearance

surface area followed by L201 and then Akitakomachi for one side of the grain (see Table 1). Using theoretical equation (9), the maximum computed contact areas (when $c = 0$ mm) were ; 25.9 mm^2, 24.7 mm^2 and 23.3 mm^2 for Delta, Akitakomachi and L201 respectively. Figure 7 (a) shows the variation of computed contact area with roll deflection for the three varieties of rice. Although Akitakomachi had high maximum computed contact area compared to L201, the order and value changed below 0.5 mm roll deflection. Contact area for L201 also increased sharply above 0.9 mm roll deflection compared to Akitakomachi and Delta. Projected area (A_P) for Akitakomachi computed using equation (11) was proportional to the roll deflection as shown in Figure 7 (b). Below 0.5 mm roll deflection, contact area was very close to projected area but



(a) Variation of theoretical contact area for vertical grain feed



(b) Comparison between contact and projected area

Figure 7 Variation of theoretical area with roll deflection

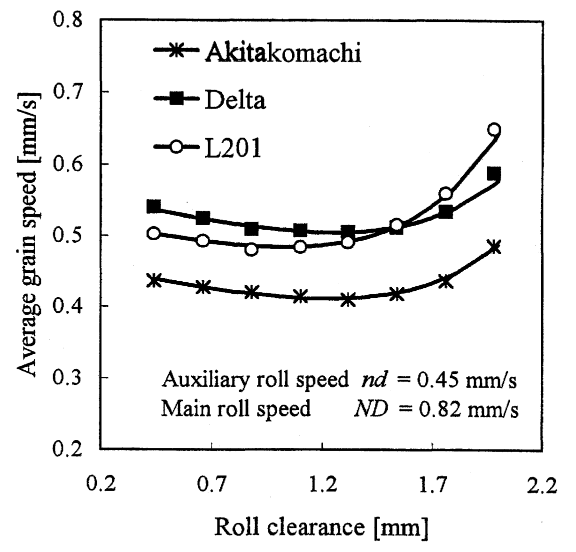


Figure 8 Variation of average grain speed with roll clearance

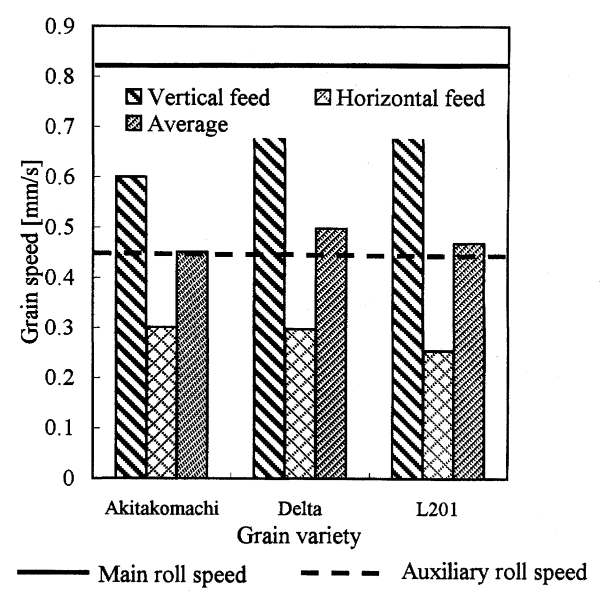


Figure 9 Grain speed for vertical and horizontal grain feed

diverged upwards as the roll deflection increased and the trend was similar for the other varieties of rice. Since husking is normally carried out below 0.5 mm roll deflection, contact area and projected area can be assumed to be the same at low roll deflection. Thus projected area can be used instead of contact area when computing shear stress. Table 1 gives the projected area at full contact for the three varieties of rice for vertical grain feed.

At low roll rotational speed, grain speed for the three varieties of rice decreased with the increase in roll clearance but the trend changed as the roll clearance increased further as shown in Figure 8. Vertical feed showed higher velocity compared to horizontal feed. Since the main roll speed was about 1.8 times higher than the auxiliary roll speed, the average grain speed was much closer to the auxiliary roll speed than the main roll speed (see Figure 9).

At high roll rotational speed, the grain speed generally increased with the roll speed as shown in Figure 10 and was also close to the auxiliary roll speed. Thus if the grain speed is considered close to that for the auxiliary roll, then PVD ratio with respect to grain speed is close to the PVD ratio with respect to auxiliary roll speed as shown below.

$$\phi_g \cong \phi_n = \frac{DN - dn}{dn} \tag{21}$$

Equation (21) is a better expression for PVD ratio since ϕ_n is close to ϕ_g, which is closely related to the roll's husking energy given in equation (14).

2. Shear force and shear stress

Figure 11 shows the recorded specific shear force

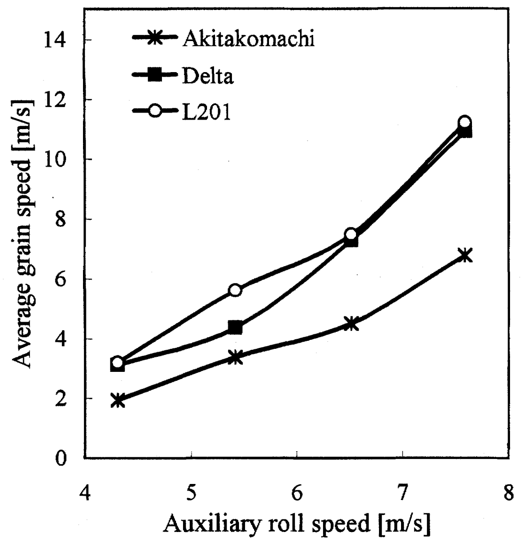


Figure 10 Variation of average grain speed with auxiliary roll speed

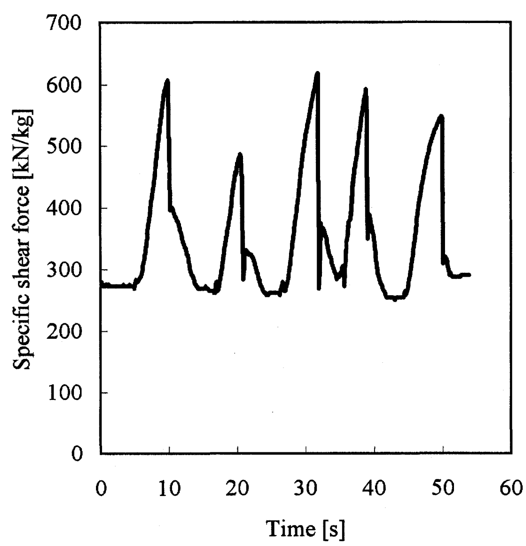


Figure 11 Recorded shear force curves for five L201 single grains husked vertically at optimal roll clearance

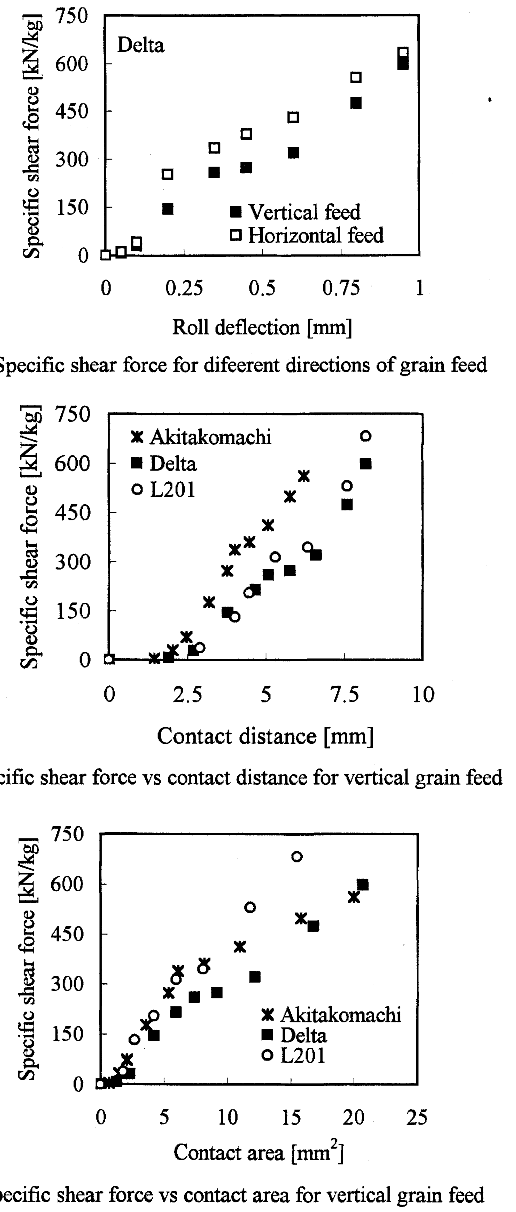


Figure 12 Variation of specific shear force for single grain feed

curves for five L201 single grains husked vertically at the optimal roll clearance. The peak force minus the minimum force for no load corresponds to the maximum specific shear force f [kN/kg] the grain is subjected to before going through the rolls at a given roll clearance. The average specific shear force for the three varieties of rice was used in the analysis. In Figure 12 (a), specific shear force for Delta increased with roll deflection but showed a variation in trend above 0.5 mm roll deflection. The point where the specific shear force trend changes is referred to as the husking zone from rough rice to brown rice or the yield zone for the rice husk. Thus above the husking zone, husked ratio increases sharply. Horizontal grain feed showed slightly higher specific shear force compared to the vertical grain feed. The trend was the same for all the three varieties of rice. For the same direction of grain feed, short grain rice had slightly low specific shear force compared to long grain rice. Specific shear force also increased with contact distance and contact area as shown in Figure 12 (b) and (c) respectively but was more displaced from the origin for contact distance. Below the husking zone illustrated in Figure 13, specific shear force was well expressed by the following exponential equation.

$$f=f_Y-f_Y\exp(-((a\delta)^b)) \qquad (22)$$

where f_Y is the yield specific shear force for the husk and a and b are equation parameters. For Delta fed

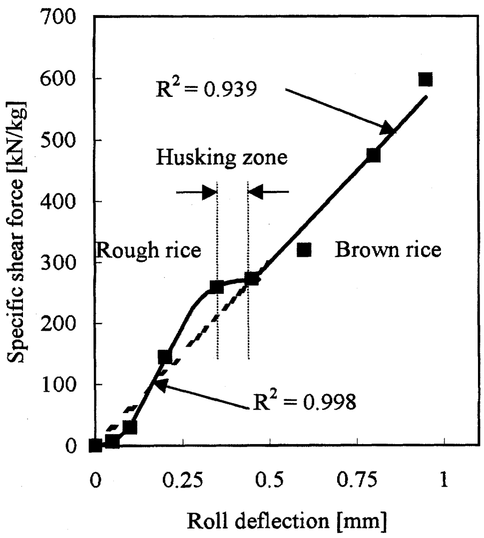


Figure 13 Specific shear force curve for Delta fed vertically showing the husking zone

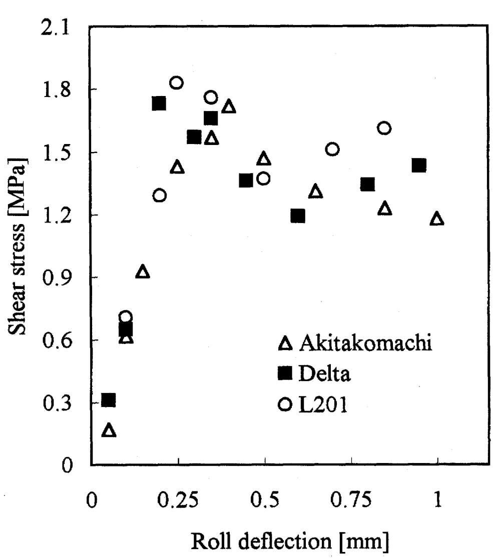


Figure 14 Variation of shear stress with roll deflection for vertical grain feed

vertically, the yield specific shear force was 271.6 kN/kg, a was 4.467 mm^{-1} and b was 2.59 [−]. Above the husking zone, the variation of specific shear force was relatively linear and husked ratio increased sharply. The husking zone can therefore be defined as the specific shear force range within which effective husking occurs in rubber roll husker.

Figure 14 shows the variation of shear stress for the three varieties of rice computed using the expression in equation (18) for vertical grain feed. Shear stress increased to a maximum and then decrease again showing some tendency to remain constant. Since the maximum shear stress occurred close to the husking zone and the optimal roll clearance (roll clearance when husking energy efficiency expressed by equation (19) is maximum), then maximum shear stress corresponds to the yield stress of the rice husk. The peak values were 1.72 MPa, 1.73 MPa, and 1.83 MPa for Akitakomachi, Delta and L201 respectively and their corresponding roll clearance values were 1.5 mm 1.8 mm and 1.5 mm respectively. The above results show that the yield stress for rice husk does not depend so much on the rice variety or size.

V Conclusion

Single grain dynamics in an experimental rubber roll husker was analyzed using long and short grain rice. The three varieties of rice used generally showed the same husking characteristic, which however differed in their magnitude. The following conclusions can be drawn from the results obtained.

1. Specific husking energy can be expressed in terms of the projected area, shear stress, PVD ratio with respect to grain speed and contact distance.
2. Consideration of radius of curvature in the new equation gives a better estimate for contact distance and contact length.
3. Grain velocity varies with the roll clearance and speed but is closer to the auxiliary roll speed than the main roll.
4. Short grain rice and vertical grain feed have relatively low specific shear force compared to long grain rice and horizontal grain feed.
5. Maximum shear stress occurs close to the optimal roll clearance and is not so much dependent on the rice variety and size.

References

1) Yamashita, R. : New Technology in Grain Post-harvesting, Farm Machinery Industrial Research Cooperation, Kyoto, Japan, 51-64, 1993
2) Kano, H., J. Shimizu, M. Goto, T. Saito, R. Ishihara, F. Miyazawa, T. Ashizawa, T. Miura : Study on husking ratio improvement for rice husker, Agricultural Machinery Research 21, Shin-Norinsha , 1959 (in Japanese)
3) Nishiyama, Y. : Rice Post harvest Technology, Food Agency, 341-346, 1995
4) Nishiyama, Y. : Agricultural Processing Machinery, New edition, Bun-eido, 8-19, 1991 (in Japanese)
5) Kawamura, N. : Agricultural Processing Machinery, Bun-eido, 7-16, 1980 (in Japanese)
6) Shoji, F. : Agricultural Machinery (rev. ed.), Yokendo, 1964 (in Japanese)
7) JSAM (ed.) : Bio-Production Machinery Handbook, Corona-sha, 1996 (in Japanese)
8) Nihei, T. : Grain Milling Machinery Experiments, Yokendo, 1953 (in Japanese)
9) Shitanda, D., Y. Nishiyama, and S. Koide : Husking characteristics of different varieties of rice by rubber roll and impeller husker, 58th Proceeding of Japanese Soc. of Agricultural Machinery, 517-518, 1999
10) Nishiyama, Y., Y. Kikuchi, and T. Shisai : Dynamical analysis of impeller husker (II)-Comparison between dehulling

experiments and the theory, J. Japanese Soc. of Agricultural Machinery, 54(6), 65-71, 1992 (in Japanese)

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「研究論文」

ロール籾すり機による長短粒種米の脱ぷ特性（第1報）*
—穀粒運動の動力学的解析—

ダグラス シタンダ [*1]・西山喜雄 [*1]・小出章二 [*1]

要 旨

ロール籾すり機を用いて長短粒種米（Delta, L201, あきたこまち）運動の動力学的解析を行った。単粒籾を垂直姿勢および水平姿勢でロールに挿入した。籾粒挿入時の粒の向きと形状を考慮し，籾粒の曲率半径から接触距離を求める新たな式を導出し，ビデオカメラによる実測値とよい一致を見た。ロール間の米粒の運動を，ハイスピードカメラにより実測し，穀粒速度は主ロールよりも副ロール回転速度に近く，副ロール周速度に対する周速度差率の妥当性が示された。米粒に加わるせん断力（摩擦力）は引張試験器を用いて測定し，投影接触面積からせん断応力を算出した。脱ぷエネルギー効率の最大値近辺でせん断応力は最大値となった。

［キーワード］曲率半径，接触距離，接触長さ，接触面積，せん断応力，ロール籾すり機

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*1 会員，岩手大学農学部（〒020-8550 盛岡市上田3-18-8 TEL 019-621-6180）