JARQ 55 (3), 245-251 (2021) https://www.jircas.go.jp

Designing a Polyurethane-based Husker Roll for Long-grain Rice Using a Finite Element Model

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Abstract

Rice husking is an operation where the husks are peeled from rough rice, and a rubber roll husker conventionally consists of two rubber rolls with different peripheral velocities that rotate to provide the shear stress needed to husk rough rice. Both short- and long-grain rice, which have totally different shapes, affect rice husker performance, especially the husking ratio and wear of the husker roll. The performance with long-grain rice, which accounts for 80% of world rice production, is poorer than with short-grain rice. We analyzed the fundamental mechanisms of the roll husker, and then compared the performance for long- and short- grain rice using a finite element model. A husking simulation based on the constructed model revealed that long-grain rice exhibited more accumulated friction loss (121.6 mJ) than short-grain rice (40.1 mJ). The difference in accumulated friction loss at the roll surface may lead to increased friction heat, which in turn induces wear. Since sufficient shear force is needed with rough rice to achieve a higher husking ratio, the optimum coefficient of friction and Young's modulus of the husker roll for long-grain rice were calculated based on the model as being 0.8 and 8.1 MPa, respectively. Newly designed polyurethane-elastomer-based husker rolls based on these results showed a better husking ratio and durability than conventional rubber rolls in experiments undertaken in Thailand using long-grain rice. The results provide new opportunities to prepare new materials for the rice roll husker.

Discipline: Agricultural Engineering
Additional key words: accumulated friction loss, polyurethane elastomer, elasticity

Introduction

Rice processing consists of individual operations, namely husking, milling and polishing. The efficiency of these operations and quality of the final product affect profitability in terms of operational costs, and market value, respectively. Most modern rice processing systems were invented and designed for short-grain rice varieties, mainly *japonica*. However, long-grain rice varieties such as *indica* (Jena & Hardy 2012) account for about 80% of world rice production. As the grain shapes of both varieties are completely different, the processing efficiency is lower for long-grain rice varieties, especially the head rice yield after the milling process.

Rice husking is the process of removing the husks from rough rice, and is typically performed just before the milling process in many countries except Japan, where brown-rice-storage is common. Historically, husking was performed using a pestle and mortar or a hand mill and employing friction. Among the various types of rice husker, the impeller and rubber roll types are common in modern rice processing systems, and rubber roll huskers, which have been in use since the 1920s (Satake 1990), are generally preferred due to their excellent capacity for bulk and continuous rice processing. A rubber roll husker consists of two rubber rolls with different peripheral velocities rotating in opposite directions into which rough rice is fed. The rough rice is fed continuously into the roll gap and the husks are stripped off by the shear stress induced by the difference between the peripheral velocities (Fig. 1). Although this approach is widely accepted worldwide,

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Received 19 March 2020; accepted 29 September 2020.

the performance with long-grain rice is somewhat poorer than with short-grain rice in terms of husking ratio and husker roll wear. In fact, rice millers dealing with long-grain rice consider husker rolls to be short-term consumables because they wear out quickly, and can usually only provide a 24-30 hr. operation time (Imase 1971, Mizuno 2015). When used with short-grain rice, the same rubber-based husker roll normally provides a 48-60 hr. operation time. Replacement costs and operational complexity may result in further losses, which might pose a risk to rice processing operations (Fig. 2).

Recently, we accepted the challenge of changing the roll material for this friction-based husker as the currently used material has barely been improved since the 1920s. The introduction of a polyurethane elastomer successfully improved short-grain rice husking in terms of roll durability and is already commercially available (Bando Chemical Industry Ltd., 2017). However, we found that the same polyurethane-based roll could not provide better roll durability and a sufficient husking ratio for long-grain rice.

In this study, we report the fundamental mechanisms of long-grain rice husking compared with

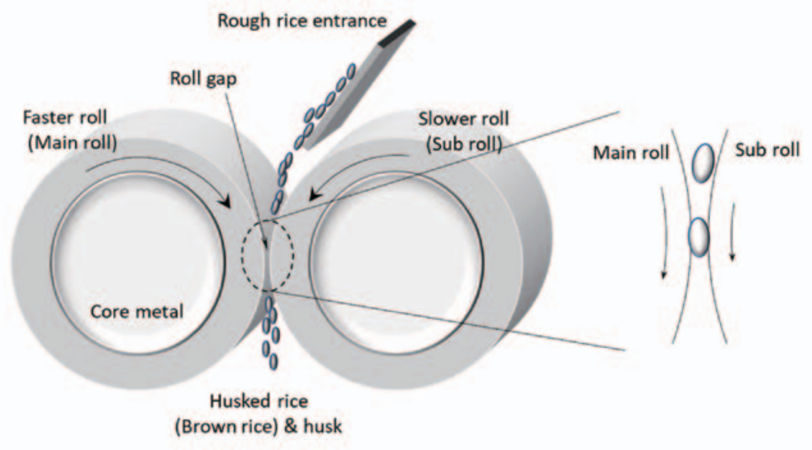

Fig. 1. Schematic diagram of rice roll husker
Rough rice is supplied into the roll gap and the husk is removed. Different peripheral velocities for the main and sub rolls provide rough rice with sufficient shear stress (right) to remove the husk.

Fig. 2. Typical "used" rubber husker rolls abandoned at a rice mill in Thailand

those of short-grain rice by constructing a finite element model. The results obtained with the model were used to design new polyurethane-based husker rolls, and the rolls were employed in husking experiments with long-grain rice in Thailand to confirm the results.

Materials and methods

1. Development of finite element model and optimization

A finite element model was constructed to calculate the mechanical characteristics of rice husking, with the model being applied for further optimization of parameters relating to roll wear. The mathematical analysis was based on the following assumptions:

(1) The elastic finite element model was constructed using SIMULIA / Abaqus Unified FEA software (Dassault Systèmes S.E., Vélizy-Villacoublay, France) with the implicit method. The half in roll width dimension of the model was reduced by its symmetry.

(2) Short- and long-rice grains were modelized as prolate spheroids, and divided with a hexahedral mesh, which had elasticity with a Young's modulus of 1,000 MPa, and a Poisson coefficient of 0.3, as reported previously (Shitanda et al. 2002). The difference was their shape, and minor and major axes of 3.0 mm and 5.0 mm, and 2.1 mm and 7.5 mm were used for short- and long-rice grain, respectively.

(3) The roll size was set with an outer diameter of 153 mm, an inner diameter of 120 mm, and a width of 60 mm (half of the full model) following a rice husker model used in high-speed camera observation described below. The core metals of the rolls were rigid and fixed to the inner surface, and the roll gap was set at 0.6 mm. The roll material was divided with a hexahedral mesh, which had elasticity with a Young's modulus of 70 MPa and a Poisson coefficient of 0.49, based on a typical polyurethane-elastomer-based roll material that is commercially available. The coefficient of friction between the rough rice surface and the rolls was set at 0.5.

(4) Single rough rice kernel was introduced into the roll gap. The rolls, which were rotating in opposite directions, had different peripheral velocities, and the peripheral velocity ratio was 0.8 following a rice husker model used in high-speed camera observation described below.

(5) As reported by Baker et al. (2012), rough rice can be husked with a sufficient shear stress of 1-2 MPa. However, the model described here was simulated without husking, and showed whether friction losses that may affect roll wear could occur.

(6) Numerical simulations were continued from just before the rough rice arrived in the roll gap until the rice exited the gap, and the accumulated friction losses on the roll surface were evaluated. Friction losses are calculated based on the model, from the shear stress and slip length.

(7) Based on the model, the roll coefficient of friction (0.5-0.8) and Young's modulus (5.0-15.0 MPa) were optimized by using JUSE-StatWorks software (Institute of Union of Japanese Scientists and Engineers, Tokyo, Japan) to reduce the accumulated friction loss between the rolls and rough rice surface, and increase the shear stress on rough rice.

A finite element model of a rice husker (Fig. 3, Table 1) was constructed based on the assumptions above.

2. High-speed camera observation of rice husker

A rice husker (type 25M, Ohya Tanzo Seisakusho Co., Kiyosu, Japan) with a roll gap of 0.6 mm was used for the tests. The cover of the rubber or polyurethane-elastomer-based rolls was replaced with a transparent acrylic cover with the same design as the original cover. A high-speed camera (Chronos 1.4, Kron Technologies Inc., Burnaby, Canada or Speeder V2, Photoron, Tokyo, Japan) was used to record the rice and roll movements in the husker using an external LED light. The short-grain *japonica* rice variety (Koshihikari) and the long-grain *indica* rice variety (IR64), which were grown in a research field at the Japan International Research Center for Agricultural Sciences (JIRCAS, Tsukuba, Japan), were used for the observations. Rough rice (200 g) with a moisture content of approximately 14% was introduced into a rice husker, with its first five seconds in the roll gap area being recorded with a high-speed camera set at 2,400 frames per second (for a total of 12,000 frames). The observed movements were then evaluated by using frame-by-frame playback.

3. Preparation of optimized husker roll made of polyurethane elastomer

Polyurethane elastomers were prepared using a prepolymer obtained from polyether polyol (Mn=1,500) with 4,4-diphenylmethane diisocyanate, 1,4-bis (β-hydroxyethoxy) benzene as a chain extender, and silicone oil to adjust the coefficient of friction. The blend ratio of the selected elastomer exhibited a coefficient of friction of 0.699 as measured with TriboGear type 14 (Shinto Scientific, Tokyo, Japan; Wada 1997) and elasticity of elastomer (tan δ) at 90°C of 0.033 in reference to Young's modulus of the roll, as measured

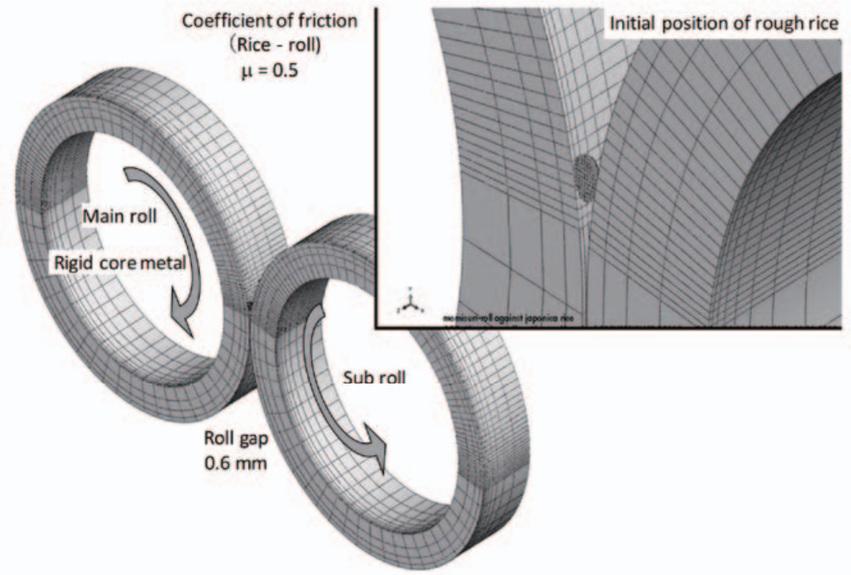

Fig. 3. Finite element model for rice roll husker

Numerical model constructed based on indicated assumptions listed in Table 1.

Table 1. Parameters of the finite elemental model

Model Parameter	Value	
Rice physical properties		
Young's modulus	1,000 MPa	
Poisson coefficient	0.3	
Rice grain shape (spheroid)	Short-grain rice	Long-grain rice
Minor axis	3.0 mm	2.1 mm
Major axis	5.0 mm	7.5 mm
Roll properties		
Young's modulus	70 MPa	
Poisson coefficient	0.49	
Coefficient of friction	0.5	
Outer diameter	153 mm	
Inner diameter	120 mm	
Width	60 mm	
Roll gap	0.6 mm	

by the Rheogel-E4000 (UBM, Kyoto, Japan). The polyurethane elastomer was cast on the aluminum core metal (for a 10-inch roll, ϕ 229.0 mm × 254.0 mm) of the husker roll to obtain an optimized sample that was 25-mm thick to realize a ϕ 254.0 mm × 254.0 mm roll (as a 10-inch roll).

4. Field husking tests using long-grain rice

Field husking tests were conducted at a rice mill in Suphanburi, Thailand. The tests entailed the use of three varieties of rolls: rubber roll (Bando white roll, Bando Chemical Industries, Ltd.), Polyurethane-based roll designed for short-grain rice (Yellow boy, Bando Chemical Industries, Ltd.), and the roll optimized for long-grain rice described above. The rolls were installed in rice huskers (DSA-304A, Yont Phol Dee, Nakhon Sawan, Thailand) in the same rice processing plant, and their operation temperature was observed using an infrared thermometer (3443, Hioki, Nagano, Japan) at 1 and 2 hrs. The hardness of the rolls was also observed with a durometer (GS-719N, Teclock, Nagano, Japan), and their husking ratio and broken rice ratio were monitored. At the rice mill plant, the roll gap was controlled pneumatically, and was the same as the pneumatic pressure used to control the roll gap with conventional rubber rolls. The rice variety Pathumthani 1, a typical long-grain aromatic rice, was used for the tests. The husking and broken rice ratios (Thai Agricultural Standard, TAS 4001-2008) were measured by manually sorting 100 g of obtained husked samples, expressed based on weight ratio. After 2 hrs. of initial operation, the rolls were kept running for 72 hrs. to ensure durability. Roll durability was estimated based on the remaining roll thickness of the main roll (higher velocity) after 72 hrs. A roll was replaced when its thickness reached 5 mm.

Results and discussion

1. Elastic finite element model of roll rice husker and difference by grain shape

The finite element analysis of the roll husker showed that grain shape has a huge influence on accumulated friction loss as shown in Figure 4. In the simulation, long-grain rice exhibited a three-times higher accumulated friction loss of 121.6 mJ than short-grain rice at 40.1 mJ. Short-grain rice could rotate in the roll gap as shown in Figure 5, and so fewer relative slips led to less friction loss during operation. However, long-grain rice has difficulty rotating due to its grain shape, and more relative slips occurred. As a result, the larger shear stress induced by the rolls was lost as friction loss. Friction loss is caused when the rolls slip on the long-grain rough rice surface, and can be released by roll wear or friction heat, which may relate directly to roll durability. Slipping also releases the energy input needed to peel the husk from long-grain rice by friction, with less vertical force being applied due to the shorter minor axis. Therefore, sufficient shear stress for husking may not be achieved in the model. These are potential causes of the different husking performance found with short- and long-grain rice. High-speed camera observations by a small-scale rice husker also revealed a phenomenon similar to that shown by the model. In order to improve long-grain rice husking, we must thus achieve less friction loss during husking and maximize the shear stress for rough rice on the roll surface.

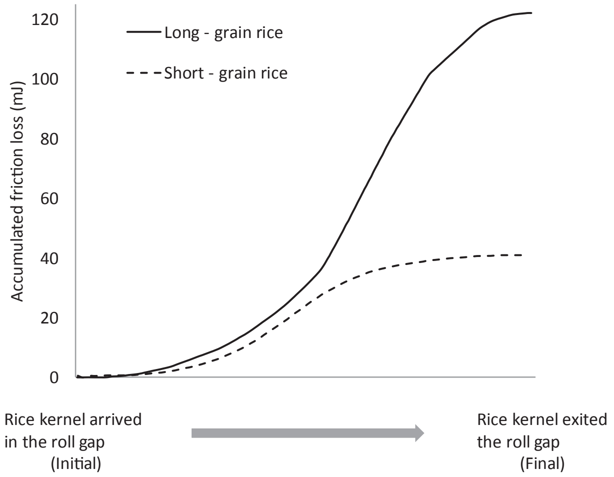

Fig. 4. Difference between accumulated friction losses for long- and short-grain rice husking simulated with the constructed model

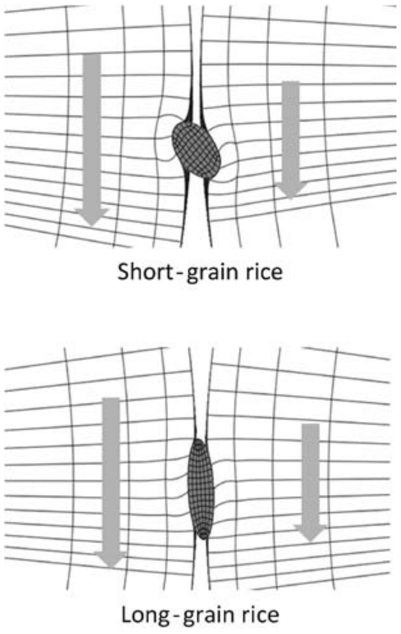

Fig. 5. Differences between short- and long-grain rice in the roll gap in the finite element model

Short-grain rice could rotate and receive shear stress generated by the difference in peripheral velocities, but long-grain rice could not rotate, and less shear stress was received with slip. This resulted in a higher accumulated friction loss for long-grain rice than for short-grain rice.

2. Optimization of coefficient of friction and Young's modulus of husker rolls for long-grain rice husking

The constructed model was employed to optimize the roll coefficient of friction and Young's modulus, which affects roll elasticity (tan δ at 90°C) to reduce the friction loss of the rolls and maximize the shear stress on rough rice. The results showed that a highest coefficient of friction of 0.8 in the optimization and Young's modulus of 8.1 MPa may result in a lowest accumulated friction loss of 21.6 mJ and a highest shear stress of 17.4 MPa for long-grain rice in optimization. The short-grain rice model showed a lower accumulated friction loss than that of long-grain rice under any conditions. The first rubber roll husker was invented for short-grain rice (*japonica*) in the 1920s, but the methodology has only been optimized for short-grain rice, not for long-grain rice.

3. Field husking tests using long-grain rice

Field husking tests that were conducted at a rice mill in Suphanburi, Thailand, showed a significant difference regarding operating temperature versus typical husking conditions as compared with a temperate area, namely Japan. Rice husking in Japan is conducted during winter after the harvest, where the ambient temperature is below 20°C (Imase 1971). However, the ambient temperature in the tests was initially over 30°C and the roll surface temperature reached 90°C after 1 hr. of operation with both rubber and polyurethane-based rolls. Given the temperature-dependent elasticity of elastomers based on their polymer characteristics, and generally significant degradation of polyurethane performance at around 93°C (Yokoyama et al. 1971, Furukawa 2009), the elasticity at 90°C should be analyzed to optimize the roll properties.

Optimized rolls prepared with a polyurethane elastomer and selected based on the numeric model in this manuscript showed superior characteristics compared with conventional rubber rolls and polyurethane rolls designed for short-grain rice, as seen in Table 2. Rice roll huskers have a clogging and overload prevention mechanism by increasing the roll gap with sub roll shaft movements. When the roll elasticity declines in relatively higher the operating temperature, frequent sub roll shaft movements occur and lead to a lower husking ratio. And a lower coefficient of friction also leads to the roll surface slipping on rough rice according to the numeric model. These phenomena result in a low husking ratio and low roll durability with wear caused by rough rice slipping.

We investigated a rice roll husker using a finite element model, and used the model we obtained to design a new polyurethane-based husker roll for long-grain rice. The field tests showed the advantages of the newly designed roll for long-grain rice without any disadvantages for short-grain rice as shown in the model. These results offer new opportunities for reducing the operational costs of rice processing by reviewing current technology.

Table 2. Results from field husking tests at a rice mill in Suphanburi, Thailand

Husker roll	tan δ at 90°C	Coefficient of friction	Husking ratio	Broken rice ratio	Actual wearing	Estimated durability	Remarks
Rubber roll (conventional)	0.089	0.514	77-85%	7-8%	10-10.5 mm at 10 hr.	24-30 hr.	Replaced after 24hr operation in experiment
Polyurethane-based roll designed for short-grain rice	0.021	0.544	55-61%	5-7%	5-7 mm at 1 hr.	3.6-5 hr.*	Impossible to continue the test within 1 hr due to low husking ratio
Polyurethane-based roll designed for long-grain rice based on simulation results	0.035	0.699	82-88%	5-7%	7.3-7.4 mm at 72 hr.	242-243 hr.	nearly 10 times more durable

All experiments were duplicated, with the husking ratio, broken rice ratio, and wear being expressed as minimum and maximum values. Durability was estimated when roll wear reached 25 mm based on actual wear.

* As the rolls may not reach 90°C during the first hour of the test, the estimation here is inaccurate.

Acknowledgement

This paper reports the results obtained within the framework of collaborative research undertaken by the Japan International Research Center for Agricultural Sciences (JIRCAS) and Bando Chemical Industry, Ltd. as part of an international collaborative project entitled "Establishment of food value chain through value-addition of local food resources for sustainable rural development" supported by JIRCAS.

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