J Wood Sci (2013) 59:10–16
DOI 10.1007/s10086-012-1295-1

ORIGINAL ARTICLE

Wood friction characteristics during exposure to high pressure: influence of wood/metal tool surface finishing conditions

Masako Seki · Hiroyuki Sugimoto · Tsunehisa Miki · Kozo Kanayama · Yuzo Furuta

Received: 1 March 2012 / Accepted: 29 August 2012 / Published online: 13 September 2012

Abstract Friction that arises during processing for the deformation of wood under relatively high pressure levels (ca. >1 MPa) is an important factor to be taken into account when wood is processed. However, few studies on such friction have been published. The present study was undertaken to evaluate the influence of surface finishing conditions on the nominal friction coefficient (μ) of the wood and metal tool surfaces. Sticking friction was likely to arise on a relatively coarse metal surface, and the type of metal tool surface finishing was found to have large impact on the friction mechanism. The friction characteristics during exposure to high pressure seem to be affected not only by the interface contact characteristics, but also by the deformation characteristics of wood during compressive load or measurement. The value of μ on water-saturated wood was equal or higher than that on dry wood, which suggests that the contact characteristics between these two types of wood are significantly different. The water content in wood was shown to affect both the interface contact and deformation characteristics of wood. The value of μ was not significantly affected by the wood surface finishing conditions; however, changes in μ during sliding differed slightly, depending on the finishing conditions.

Keywords Sliding friction · Surface roughness · Nominal friction coefficient · High pressure

Introduction

Friction is an important factor to be taken into account when various materials are utilized or processed. Several studies on friction of wood or wood-based materials have been published to date. Suzuki et al. [1] studied friction between human skin models and various materials to quantitatively analyze the sense of touch in humans. Murase et al. [2–8] conducted extensive evaluation of the influence of changes in various factors such as surface roughness, temperature, sliding speed, specific gravity, and moisture content on the friction characteristics during processing (cutting/shaving) of wood with tool, in which friction during exposure to relatively low pressure (up to 0.1 MPa) was discussed.

In addition to conventional techniques such as bending processing and compressive processing, new techniques have recently been developed to enable processing into more complex forms and improve the productivity of processing, such as wood plastic composite (WPC) processing and the utilization of bulk-form wood fluidity for processing aimed at forming [9, 10]. Relatively high pressure (≥1 MPa) is typically applied when wood-based materials are subjected to deformation processing with these new techniques. In such cases, the processed material is exposed to higher friction force arising between the material and the dies used. The increased friction force can alter the surface characteristics of the product and also have

M. Seki (✉)
Composite Materials Center, Gifu University,
1-1 Yanagido, Gifu, Gifu 501-1193, Japan
e-mail: m_seki@gifu-u.ac.jp

H. Sugimoto · T. Miki · K. Kanayama
National Institute of Advanced Industrial Science
and Technology, 2266-98 Anagahora, Shimo-shidami,
Moriyama-ku, Nagoya, Aichi 463-8560, Japan

Y. Furuta
Graduate School of Life and Environmental Science,
Kyoto Prefectural University, 1-5 Hangi-cho,
Shimogamo, Sakyo-ku, Kyoto 606-8522, Japan

a large impact on the forming limits of the material that determine the possibility of processing. For this reason, it is important to control the friction force generated during deformation processing. To this end, it seems essential to obtain basic data regarding friction on wood exposed to pressure levels during deformation processing.

We have focused on the influence of surface finishing conditions (generally known to have a large impact on friction characteristics) on the nominal friction coefficient to obtain the friction characteristics. The pressure load (normal load) in this study was set between 1 and 10 kN, which corresponds to the elastic range through the consolidated range of wood during compression perpendicular to the grain. To clarify the effect of the water content of wood on the friction characteristics, dry and water-saturated wood specimens were used.

Materials and methods

Sample preparations

Hinoki (*Chamaecyparis obtusa*) wood specimens of 30 mm (*L*, longitudinal direction) × 30 mm (*R*, radial direction) × 5 mm (*T*, tangential direction) were used. The density of a completely dried specimen was 0.39–0.43 kg/m^3. The average annual rings width was 0.8–1.12 mm. The friction surfaces of wood [30 mm (*L*) × 30 mm (*R*)] were finished using three different methods: planer, rim saw and band saw. Surface profiles and scanning electron microscopy (SEM) photographs of the wood friction surfaces are shown in Figs. 1 and 2. Specimens were conditioned into two moisture states; oven dried (OD) completely at 105 °C, and water saturated (WS) under reduced pressure, and they were then stored at 20 °C. These specimens were pasted to the upper and under surfaces of a free-cutting brass cube (35 mm) using cyanoacrylate adhesive to reduce the creep deformation of the wood specimens throughout the measurement. Figure 3 shows a schematic illustration of a wood sample prepared for measurement.

Measurement of nominal friction coefficient

The wood samples were rubbed against a metal tool (SK3 carbon tool steels, HRC: 61). The friction surfaces of the metal tools were finished by polishing or grinding, and the surface roughness of the sliding direction was measured by the stylus method using a surface roughness tester (Mitutoyo, SV-C3100), as shown in Fig. 4.

The nominal friction coefficients were measured using a dynamic biaxial testing system (Saginomiya; V-1815). A schematic illustration of the measurement setup is shown in Fig. 5, and the measurement was conducted as follows. Firstly, the wood sample was placed in contact with the metal tool surface and compressed by a normal load perpendicular to the contact surfaces (i.e., tangential direction of the wood). The stem was moved parallel to the contact surfaces by displacement control (5 mm/min) from the right side. The sample was slid 10 mm while the force loaded to the stem (*F*) was recorded. The lower compression plate was fixed by displacement control and the upper compression plate was controlled under load to maintain a constant normal load throughout the measurement, because woods have stress relaxation characteristics themselves.

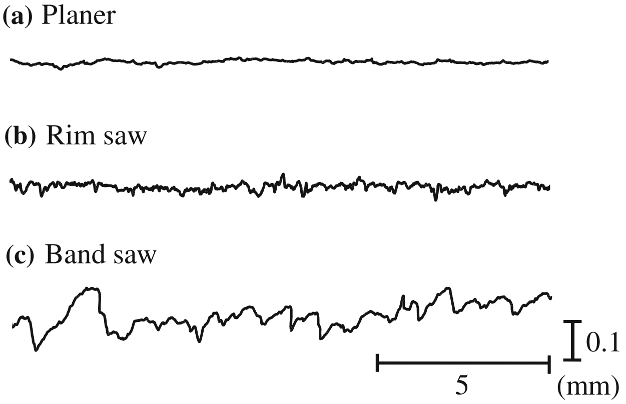


Fig. 1 Surface profiles of the wood specimens finished using different methods

The upper and the lower axis loads are shown in Fig. 5 as F_1 and F_2, respectively. N_s is the friction force between the stem and the brass cube surface. The equilibrium of force is expressed as:

$$F = \mu_1 F_1 + \mu_2 F_2 \quad (1)$$

N_s was determined to be quite low so as to become negligible; therefore, it was assumed that the nominal friction coefficient arising from the upper surfaces (μ_1) was equal to that from the lower surfaces (μ_2). The nominal friction coefficient (μ) was calculated based on the following equation:

$$\mu = F/2F_1 \quad (2)$$

Wood samples were slid in the radial direction. Three normal loads (*N*) were set at 1, 5, and 10 kN (ca. 1.1, 5.5 and 11 MPa) to change the deformation conditions of the wood between the elastic and consolidated ranges. The metal friction surfaces were cleaned with acetone prior to each test. Measurements were conducted at room temperature and the metal friction surfaces were maintained at 20 °C. The sampling time was 10 ms. Three wood samples were employed for each measurement condition.

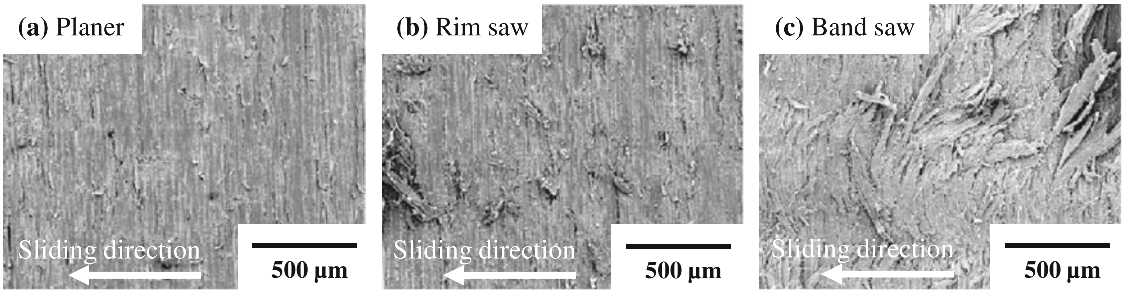


Fig. 2 SEM micrographs of wood surfaces finished using a planer (**a**), rim saw (**b**), and band saw (**c**)

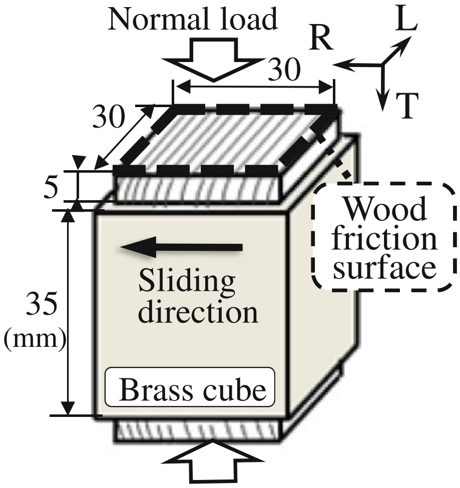


Fig. 3 Schematic illustration of a wood sample prepared for friction coefficient measurements

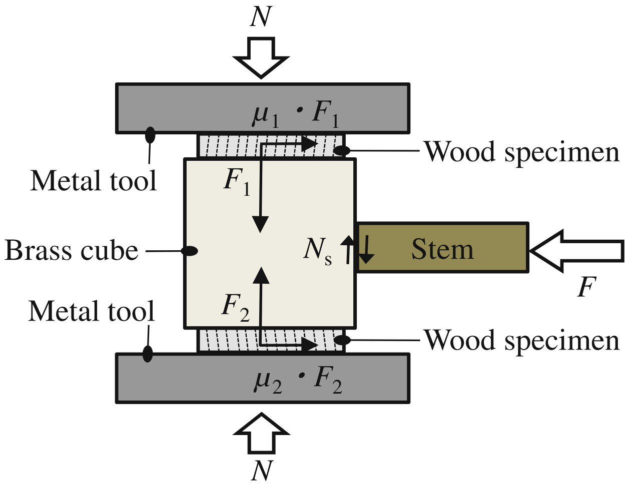
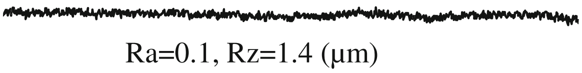


Fig. 5 Schematic illustration of the experimental setup for nominal friction coefficient measurements

(**a**) Polishing surface



(**b**) Grinding surface

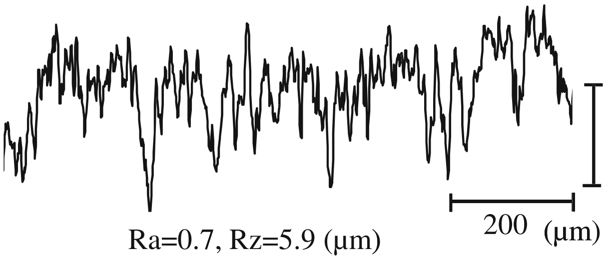


Fig. 4 Surface roughness of the metal tools. *Ra* arithmetical mean deviation of the assessed profile, *Rz* maximum height of the profile

Results and discussion

Wood deformation conditions during the measurements

Wood is significantly deformed by compression perpendicular to the grain caused by high pressure, because the cell walls are buckled and the volume of the cell lumen is decreased. The deformation of wood can have a large influence on the interface contact characteristics, and thus significantly alter the value of μ. Therefore, to estimate the deformation of wood during measurement, the nominal compressive strain of each wood specimen was calculated from the magnitude of dislocation of the upper and lower compression plates of the testing device. Table 1 shows the nominal compressive strain when the sliding distance was 10 mm. The maximum change in the nominal compressive strain from the start to the end of the measurement was approximately 5 % relative to the baseline thickness of the wood specimen. When the specimen was compressed using 3 different magnitudes of *N*, three different nominal compressive strains were recorded. When *N* was 1 kN, the wood specimen was within the elastic range. When *N* was over 5 kN, the wood specimen appeared to be in a somewhat consolidated state (the deformed range), due to cell wall deformation [11]. As expected, the nominal compressive strain at a given load was higher with the WS wood specimens than with the OD specimens.

Effect of the metal tool surface finishing conditions on the friction properties

Typical SEM micrographs of a metal tool surface finished by grinding before and after sliding of an OD wood sample are shown in Fig. 6. Observation after wood specimen processing revealed the adherence of wood components to the surface of all metal tools finished by grinding. However, the surfaces of metal tools finished by polishing showed no significant change after processing, which suggests that the friction mechanism differs according to the manner of metal tool surface finishing. The friction with a relatively smooth metal tool surface is sliding friction at the interface, while friction with a coarse metal tool surface involves sliding inside the wood (i.e., destruction) in addition to sliding friction and may be referred to as sticking friction.

Figure 7 shows the influence of metal tool surface finishing on the value of μ, where μ is plotted as a function of stem displacement, D. With $D = 0$ serving as the starting point of sliding, (a) through (c) indicate the results with an OD wood sample, (d) through (f) show the results with a WS wood sample, and (g) through (j) show the graphs with magnification along the x-axis.

Friction force is accepted as being composed of an adhesion component (F_t) and a deformation component (F_d) [12]:

$$F = F_t + F_d \tag{3}$$

where F_t is the total friction force arising from interface adhesion between the sliding surfaces, and is thus significantly dependent on the real contact area (S_t). F_d includes the force generated by the wood through sticking friction or deformation to overcome the irregularities on the metal tool surface. According to the past reports on friction during exposure to low levels of pressure, F_d has almost no contribution to F, whereas F_t has a strong influence on F [2, 13]. However, during exposure to high levels of pressure, the F_d contribution is probably not negligible, based on the occurrence of sticking under high pressure.

Table 1 Nominal compressive strain of wood specimens during measurement of the nominal friction coefficient ($n = 12$, where n is the number of samples)

Normal force (kN)	Nominal compressive strain	
	OD specimen	WS specimen
1	0.03	0.06
5	0.29	0.57
10	0.51	0.66

The value of μ showed no significant difference with the type of metal tool surface finishing (grinding or polishing) when a load within the elastic range was applied to an OD wood sample. However, when a load of magnitude over the consolidated range was applied to the OD wood, the values of μ for the two metal tool surface finishes were significantly different, with an approximately twofold higher μ for the metal surface finished by grinding than that finished by polishing. These results suggest that the influence of the metal tool surface finishing condition on μ is associated with the deformation characteristics of the wood.

Now, we consider the mechanism for friction in each pressure range applied to OD wood using Equation 3. When the applied load is within the elastic range (1 MPa), sticking friction appears on the metal surface finished by grinding, which suggests that F_d is higher on a coarse surface (surface finished by grinding) than on a relatively smooth surface (surface finished by polishing). However, μ did not differ according to the friction surface; therefore, F_t seems to be lower with a coarse surface than with a smooth surface. On a coarse surface, the wood surface is in contact with points of irregularities on the metal tool surface; therefore, S_t seems to be smaller with a coarse surface than with a smooth surface. When the load is over the consolidated range (>5 MPa), μ is much higher with the coarse surface than with the smooth surface. The results suggest that S_t and the sticking of wood components were increased for the coarse metal surface, because the wood components dig into the hollows formed by the irregularities on the metal tool surface. Thus, both F_t and F_d become

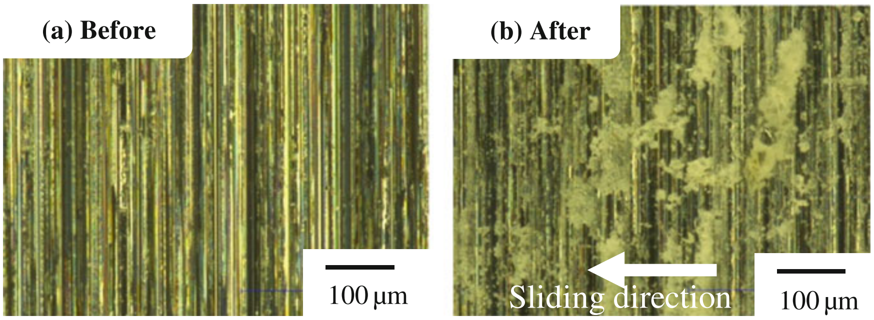


Fig. 6 SEM micrographs of the metal tool surfaces finished by grinding **a** before and **b** after sliding of an OD wood sample. (Normal load: 10 kN)

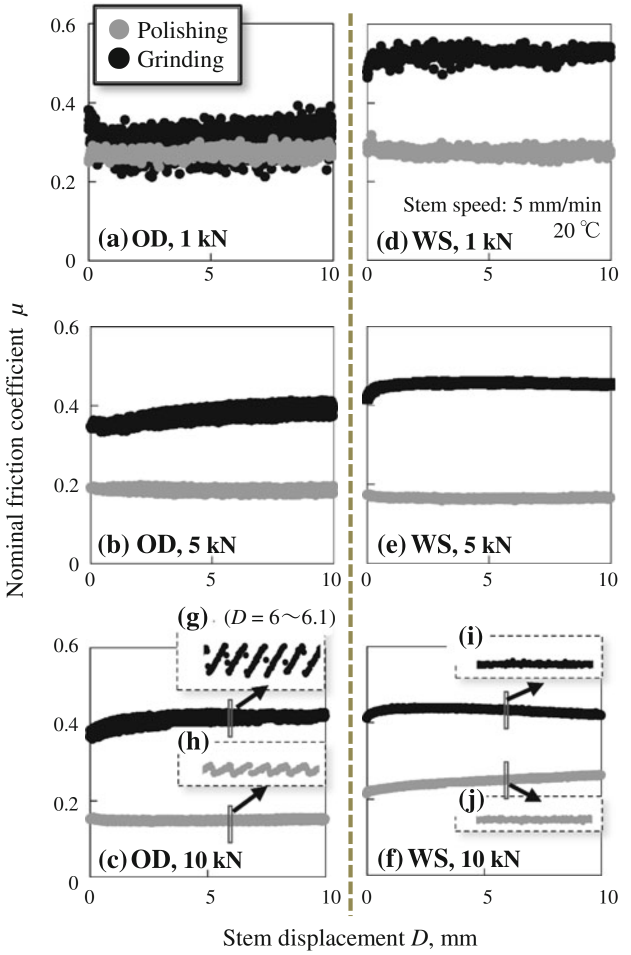


Fig. 7 Effect of the metal tool surface finishing conditions on the nominal friction coefficient of OD and WS wood samples. The wood surfaces were finished with a rim saw. **a–f** Overview, **g–j** enlarged view ($D = 6$–6.1 mm)

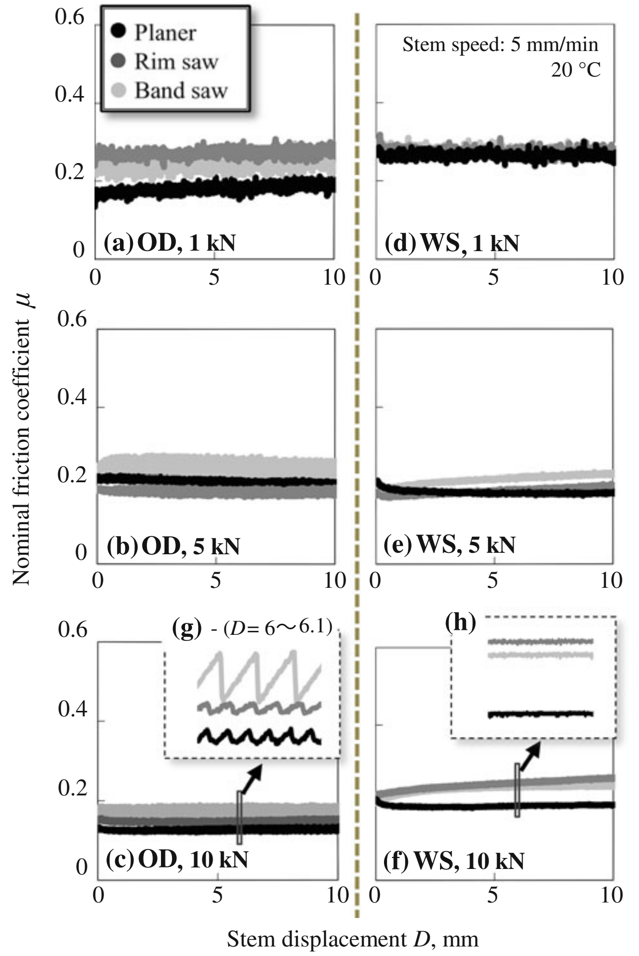


Fig. 8 Effect of the wood surface finishing conditions on the nominal friction coefficient of OD and WS wood samples. The metal tool surfaces were finished by polishing. **a–f** Overview, **g–h** enlarged view ($D = 6$–6.1 mm)

significantly increased with the coarse surface compared to that for the smooth surface.

The results for WS wood were unlike those for the OD wood. The value of μ for the WS wood was higher with a coarse surface than with a smooth surface at all load levels tested. Every μ for the WS wood was more than 0.1, which suggests that the friction on WS wood (under the experimental conditions adopted in this experiment) may correspond to a state referred to as boundary lubrication which is the severest lubrication condition [14].

When the results for OD wood are compared with those for WS wood at the same friction surface and load level, μ was equal or higher for the WS wood compared to OD wood. A previous study [7] in a low pressure range revealed lower μ with WS wood than with OD wood, while another study demonstrated higher μ with WS wood [13]. Guan et al. [13] suggested that the cause for such discrepancy was the influence of the water supply conditions during measurement. When exposed to high levels of pressure that can cause marked deformation of wood, water supply to the interface is difficult because the water retained in the lumen is drained out by pre-sliding compression. Therefore, it seems difficult to reduce the value of μ when a state of hydrodynamic lubrication exists under high pressure.

The friction characteristics at the contact plane between WS wood and the metal tool surface may be discussed using Equation 3. The resistance to deformation and the strength of wood generally decrease as the water content increases; therefore, F_d is expected to be lower for WS wood than with OD wood. Contrary to this expectation, F was higher for WS wood than for OD wood in the present experiment. The only possible explanation for this result is that the surface of the WS wood sample had become soft due to the water content, which resulted in significant changes in the contact characteristics. The softening cells near the surface seem to be deformable, which results in an increase of S_t. Thus, when considering the influence of the water content on the friction characteristics of wood, both the contact and the deformation characteristics of wood must be taken into account.

In Fig. 7g–j, the vibration (fluctuation) of μ caused by stick–slip in OD wood was not observed for WS wood, which indicates that water contained in wood is useful to suppress vibration.

Effect of the wood surface finishing conditions on the friction characteristics

Figure 8 shows the influence of the wood surface finishing conditions on μ. The wood surface finishing conditions had less impact on μ than the metal surface finishing conditions. This tendency is similar to that observed at low pressure levels [4]. One possible explanation for this result is that S_t does not significantly differ with change in the wood surface finishing conditions, compared with that for the metal surface finishing conditions. The irregularities on a coarse wood surface were deformed and became smooth, because the wood surface is much softer than the metal tool surface.

When OD wood was tested, the μ vibration characteristics differed slightly with the surface finishing conditions. Specifically, the stick–slip amplitude was greater with the band saw-finished wood (most coarse surface) than that with wood finished with other means (less coarse surfaces). This difference may be explained by the greater difference between the static and dynamic friction coefficients for a coarse wood surface, as revealed by the analysis of the equation of motion for friction-induced vibration [15].

In the present experiment, μ remained almost constant during sliding or increased slightly immediately after sliding was started under each testing condition. However, when WS wood with a relatively smooth surface (finished with a planer) was exposed to a pressure of magnitude $N = 5$ or 10 kN, μ decreased slightly once sliding was started and then gradually returned toward the baseline level. Measurements using WS wood specimens of varying surface roughness did not reveal significantly different results, but it was confirmed that the finishing conditions of the friction surface do have some impact on the lubrication properties.

Conclusion

This study was designed to evaluate the friction characteristics of wood during deformation processing with relatively high levels of pressure (ca. >1 MPa). The nominal friction coefficient (μ) was analyzed with focus on the influence of both the metal tool and wood surface finishing conditions at a normal load (N). The results are summarized as follows:

1. Sticking friction appeared for a relatively coarse metal surface, which indicates that the metal surface finishing conditions have a significant influence on the friction mechanism. Under most testing conditions, μ was evidently higher with a coarse metal surface, while the friction on OD wood within the elastic range was not significantly affected by the metal surface roughness. These results suggest that the friction characteristics in the high pressure range are affected by both the contact characteristics at the interface and the deformation characteristics of the wood during compression and measurement.
2. The value of μ on WS wood was more than 0.1, which suggests that boundary lubrication occurs on WS wood surfaces. The value of μ tended to be higher with WS wood than with OD wood. The results suggest that the contact characteristics between these two types of wood are significantly different. The water content in wood affects both the contact characteristics at the interface and the deformation characteristics of the wood, so that precise identification of the contributions from the factors involved is not simple.
3. The impact of the wood surface finishing conditions on the value of μ was small, which suggests that the real contact area does not significantly differ with the wood surface finishing conditions. In contrast, the vibration characteristics (stick–slip) of OD wood and the change in μ for WS wood during sliding were dependent on the wood surface finishing conditions.

Acknowledgments The author is indebted to Mr. Hiroki Taguchi (Taguchi Seisakusho, Ltd.) for his valuable contribution to the preparation of tools for this study.

References

1. Suzuki M (1970) Studies on physical properties of wooden surface. I. Relationship between feeling of touch of fingers and frictional coefficient by sliding the models of human skin on surface of wood and other materials (in Japanese). Bull Gov For Exp Stn 231:1–25
2. Murase Y, Ota M (1973) Studies on the frictional characteristics of wood. I. the explanation based on the adhesion component and deformation component (in Japanese). Mokuzai Gakkaishi 19:421–425
3. Murase Y, Ota M (1974) Studies on the frictional characteristics of wood. II. Frictional components of wood (in Japanese). Mokuzai Gakkaishi 20:243–249
4. Murase Y (1977) Effect of surface roughness on friction between wood and steel (in Japanese). Mokuzai Gakkaishi 23:76–81
5. Murase Y (1978) Effects of surface roughness of steel and wood variables on repeated friction between wood and steel (in Japanese). Mokuzai Gakkaishi 24:865–872

6. Murase Y (1979) Effect of temperature on friction between wood and steel (in Japanese). Mokuzai Gakkaishi 25:264–271
7. Murase Y (1980) Frictional properties of wood at sliding speed (in Japanese). Mokuzai Gakkaishi 26:61–65
8. Murase Y (1980) Coefficient of friction and surface temperature in the sliding friction between wood and steel (in Japanese). Mokuzai Gakkaishi 26:571–575
9. Okamoto T (2003) Recent developments in wood/plastic composites. Extrusion of wood-based materials (in Japanese). Mokuzai Gakkaishi 49:401–407
10. Yamashita O, Yokochi H, Miki T, Kanayama K (2008) Forming of rotary-cut Japanese cedar veneer by taking advantage of its fluidity. J Jpn Soc Technol Plasticity 49:53–57
11. Norimoto M (1994) Transverse compression of wood and its application to wood processing (in Japanese). Mokuzai Kenkyu Shiryo 30:1–15
12. Bowden FP, Tabor D (1954) The friction and lubrication of solids. Maruzen, Tokyo, pp 82–85, 158–159
13. Guan N, Thunell B, Lyth K (1983) On the friction between steel and some common Swedish wood species. Eur J Wood Wood Prod 41:55–60
14. Mckenzie WM, Karpovich H (1968) The frictional behavior of wood. Wood Sci Technol 2:139–152
15. Bowden FP, Tabor D (1954) The friction and lubrication of solids. Maruzen, Tokyo pp, pp 95–100