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Friction of Wood Sliding on Various Materials

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Much of the works on the friction of wood is concerned with the friction between wood and steel. In this study, the frictional properties of wood sliding on various materials are examined under a variety of normal loads and wood moisture contents. It is shown that the coefficient of friction differs with each counterface material and is affected significantly by the moisture content of wood. The change in friction and the nature of adhesion are discussed.

INTRODUCTION

The frictional properties of wood are an important factor in wood machining processes. Much of the previous works on the friction of wood was therefore concerned with the friction between wood and steel (Atack and Tabor, 1958; Stôsić, 1959; McLaren and Tabor, 1961; McKenzie and Karpovich, 1968; Lemoine *et al.*, 1970; Knudson and Schniewind, 1972; Knospe, 1974; Murasc, 1977, 1978, 1979, 1980a, 1980b; Möhler and Herröder, 1979; Guan *et al.*, 1983). Thus although the fundamental data on the friction between wood and steel has been gradually accumulated, few investigations on the friction between wood and non-metallic material or non-ferrous metal have been conducted (Atack and Tabor, 1958; McKenzie and Karpovich, 1968; Möhler and Herröder, 1979). However, the measurements of the coefficient of friction for wood sliding against various materials are necessary to make clear the frictional mechanism of wood, because it is seen that the friction of wood arises from adhesion and deformation at the regions of real contact (Atack and Tabor, 1958).

In this study the coefficients of friction between wood and various materials including wood itself were determined under a variety of normal loads, and the effect of the moisture content of wood on the coefficient of friction also was investigated.

MATERIALS AND METHODS

Apparatus

The friction test was conducted by sliding the wood (upper specimen) ① on the counterface material (lower specimen) ②, as shown in Fig. 1. The frictional resistance between the upper and the lower specimens was measured by the load cell ③. The normal load was applied by dead weight ④. After

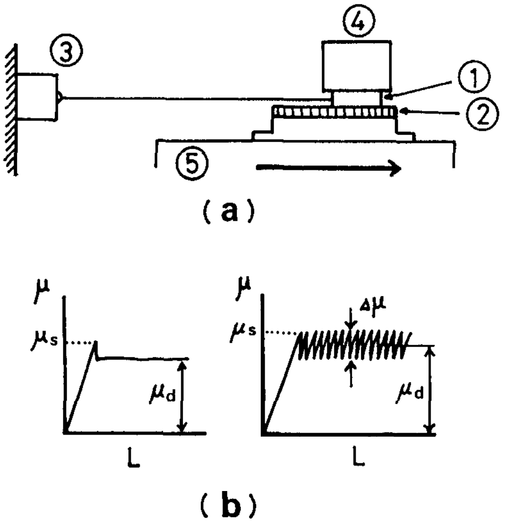

Fig. 1. Schematic representation of test apparatus (a) and coefficient of friction (is). ① Wood specimen, ② Counterface material, ③ Load cell, ④ Weigh, ⑤ Carriage. μ_s: Coefficient of static friction, μ_d: Coefficient of dynamic friction, $\Delta\mu$: Amplitude of stick-slip motion.

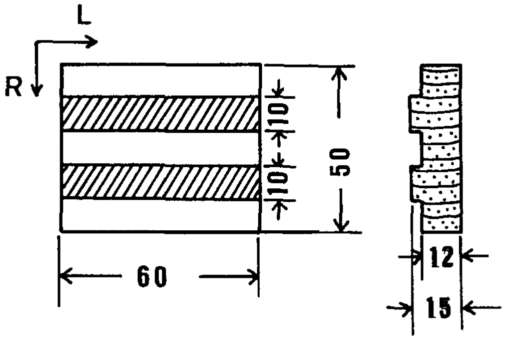

Fig. 2. Shape and dimension of wood specimen. The radial surface (hatching part) of wood specimen was slid parallel to fiber direction.

30 sec of loading time, the relative motion was provided at a constant speed of 25 mm/min.

Wood specimen (upper specimen)

Western hemlock (*Tsuga heterophylla*) was selected as the wood specimen. The shape and dimension of the specimens which were surfaced with a planer are shown in Fig. 2. They were conditioned to moisture contents of 1 %, 11.5 %, 29 % and water-saturated. The surface of water-saturated specimen was kept wet during testing by periodic application of water to the sur-

Table 1. Properties of counterface materials.

Materials	Density (g/cm^3)	Surface roughness (μm $R_{\max}$)	Indentation* hardness (kgf/mm^2)
Stainless steel	8.0	0.2	103
Mild steel	7.9	0.3	77
Copper	8.8	0.4	54
Aluminium	2.7	0.6	34
Polyvinyl chloride (PVC)	1.45	0.7	15
Polymethyl methacrylate (PMMA)	1.19	1.4	22
Polyethylene (PE)	0.94	4.3	5
Polytetra fluoroethylene (PTFE)	2.14	4.0	3
Rubber (butadiene styrene)	1.51	7.0	0.1
Glass	2.46	<0.02[3)]	500[3)]
Hemlock	0.48[1)]	19[2)]	1
Isunoki	1.09[1)]	5.4[2)]	5

* The indentation hardness in this investigation were measured for ball diameter D-9.5 mm, normal load $W=38.5$ kgf except for rubber ($D=9.5$ mm, $W=1.3$ kgf).

1) Based on air-dried weight and volume.

2) Obtained on radial surface parallel to the grain.

3) Derived from the literature.

face.

The sliding direction of each specimen was parallel to the grain on the radial surface. The air-dry specific gravity of these specimens was of 0.49.

Counterface material (lower specimen)

The various materials shown in Table 1 were chosen as a counterface material. These surfaces (except glass) were abraded with 1200 grit silicon carbide paper and cleaned with a brush. Prior to each run the surfaces (except wood) were cleaned with ethyl alcohol and a laboratory tissue. In the case of wood (lower specimen) the radial surface was tested in the direction parallel to the grain.

Procedure

The effect of normal load on the coefficient of friction was investigated for air-dry wood specimens, and the applied load was in the range of 0.71-19.8 kgf. The effect of the moisture content of wood was determined under a constant normal load of 11.6 kgf.

The frictional resistance was recorded throughout the test using a chart recorder, and the coefficients of both static friction (μ_s) and dynamic friction (μ_d) at 25 mm sliding distance were calculated. When a stick-slip motion occured, the amplitude of the stick-slip motion ($\Delta\mu$) also was obtained (refer to Fig. 1).

Three observations were made for each surface and the results averaged. Tests were conducted at room temperature.

RESULTS

Friction of wood on metals

The relationships between the coefficient of friction (μ) and the normal load (W) obtained for stainless steel, mild steel, copper and aluminium respectively are shown in Fig. 3. The inserts to Fig. 3 show the general trend of the change in friction with sliding distance (L) (under a normal load of 11.6 kgf). The coefficients of friction exhibit almost constant values from the beginning of sliding. Accordingly, the coefficients of both static and dynamic friction (μ_s, μ_d) show similar values and are approximately independent of normal load.

The relationships between the coefficient of friction and the moisture content of wood obtained for each metal are shown in Fig. 4. The coefficient of friction for each metal increases with increasing moisture content in the range below fiber-saturation point (FSP), but is about the same in the moisture content range from FSP to water-saturated condition.

The author pointed out in earlier papers (Murase, 1978, 1980a) that the coefficient of friction for water-saturated condition decreased as compared with that at FSP. In the present case, it seems that as the sliding speed adopted

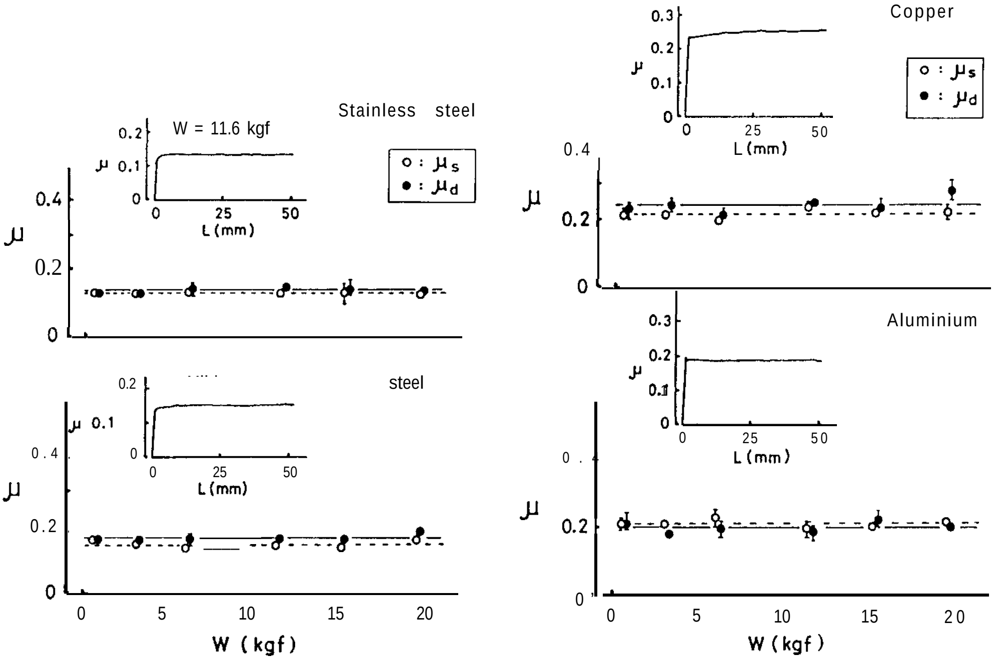

Fig. 3. Relationships between coefficient of friction (μ) and normal load (W) for metals. ○: Coefficient of static friction, ●: Coefficient of dynamic friction.

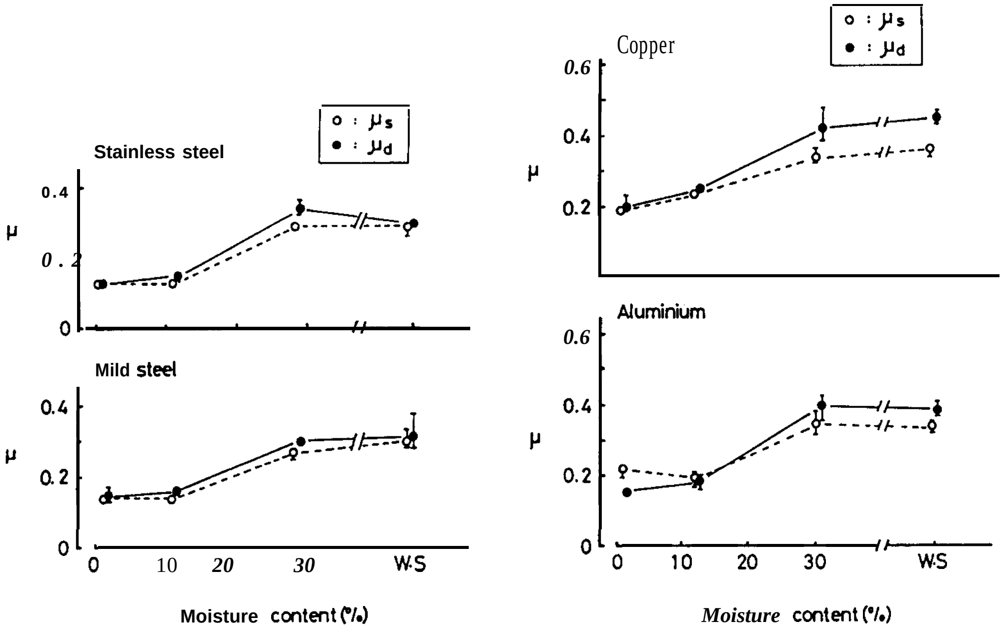

Fig. 4. Relationships between coefficient of friction (μ) and moisture content of wood for metals. Marks; the same as Fig. 3.

is very low the lubricating action of free water for water-saturated specimen does not appear.

Friction of wood on glass

The relationship between the coefficient of friction and the normal load for glass is shown in Fig. 5. The insert to Fig. 5 shows that the initial (static) coefficient of friction is large but as soon as sliding commences the friction falls to a low value. Accordingly, μ_s is always larger than μ_d and both coefficients of friction are independent of normal load.

By comparing Fig. 5 with Fig. 3, it is seen that the mean coefficients (μ_s, μ_d) for glass are larger than the values for stainless steel and mild steel in spite of the smoother surface of glass. This suggests that the adhesion between wood and glass is stronger than those between wood and stainless steel or mild steel.

The relationship between the coefficient of friction and the moisture content of wood obtained for glass is shown in Fig. 6. It can be seen that the trend for glass is almost similar to that for the above metal.

Friction of wood on polymers

The relationships between the coefficient of friction and the normal load obtained for polyvinyl chloride (PVC), polymethyl methacrylate (PMMA), polyethylene (PE) and polytetra fluoroethylene (PTFE) respectively are shown

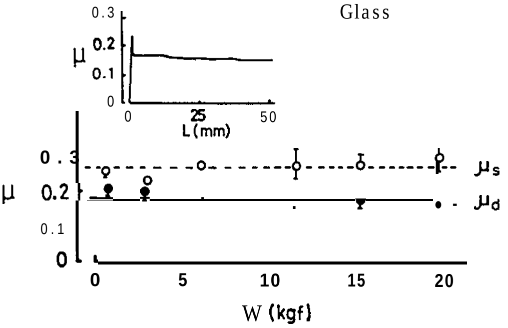

Fig. 5. Relationship between coefficient of friction (μ) and normal load (W) for glass. Marks; the same as Fig. 3.

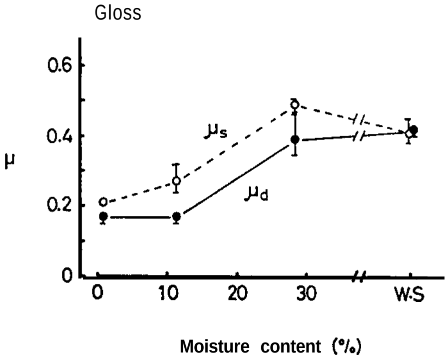

Fig. 6. Relationship between coefficient of friction (μ) and moisture content of wood for glass. Marks; the same as Fig. 3.

in Fig. 7. The friction for PVC and PMMA shows a stick-slip motion. This motion especially is remarkable for PMMA. In case of the friction for PE and PTFE, although the stick-slip motion is not observed the coefficient of friction tends to decrease gradually with increasing sliding distance. It is suggested that the decrease in friction with increasing sliding distance is caused by the formation of the transfer film of polymer on the wood surface. It can be seen that the coefficients of friction for each polymer are approximately independent of normal load, but there is a fair amount of scatter in the case of PVC. Comparing the mean coefficients for each polymer, the value becomes higher in the order of PTFE<PE<PVC<PMMA. This order agrees approximately with the order of the surface energy (Salomon, 1965) resulted from the molecular structure for each polymer (critical surface energy, $\gamma_c=39$ dynes/cm for PMMA and PVC, $\gamma_c=31$ dynes/cm for PE, $\gamma_c=18.5$ dynes/cm for PTFE). It is therefore suggested that the difference between the coefficients of friction for each polymer is due to the difference in adhesion between wood and polymer.

The relationships between the coefficient of friction and the moisture

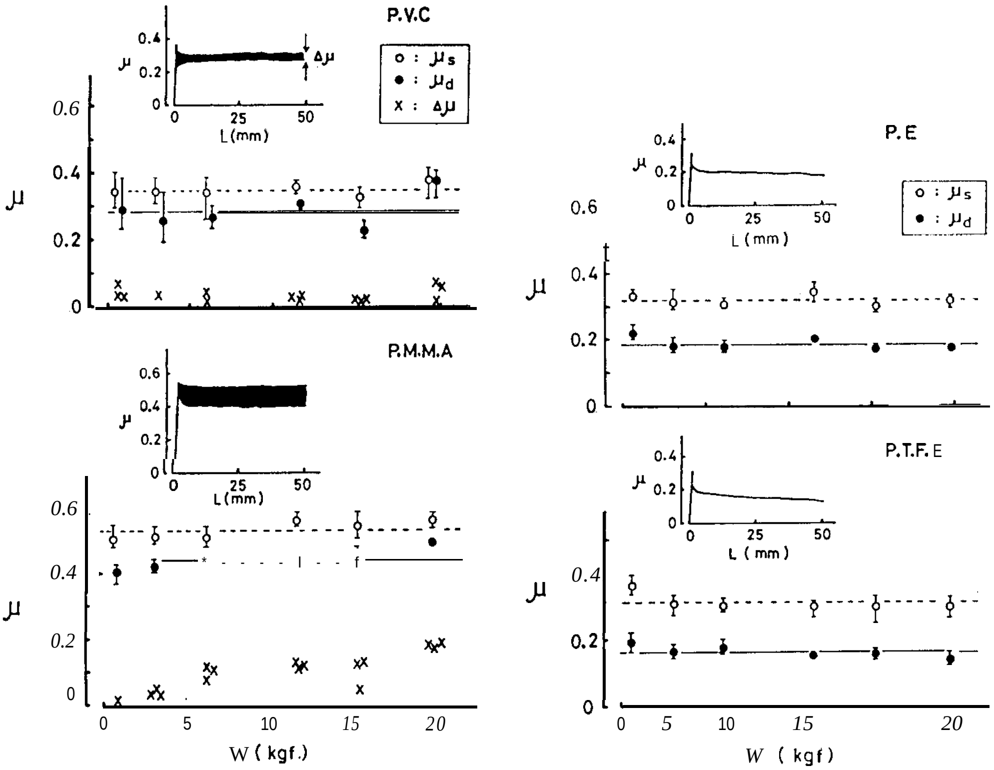

Fig. 7. Relationships between coefficient of friction (μ) and normal load (W) for polymers. ○: Coefficient of static friction, ●: Coefficient of dynamic friction, ×: Amplitude of stick-slip motion.

content of wood obtained for each polymer are shown in Fig. 8. It is obvious that the change in the coefficient of friction with the moisture content of wood depends on the types of polymer. The coefficients of friction for PVC and PMMA increase with increasing moisture content, as with the above metals or glass. On the other hand, the those for PTFE and PE decrease. It is therefore evident in the range of moisture content below FSP that an increase of water in wood increases the adhesion component of friction with polymers such as PVC and PMMA, and reduces that with polymers such as PTFE and PE. Although it is predicted that the reciprocal effect of water in wood is closely connected with the molecular structure of polymers, this will be discussed later.

Friction of wood on rubber

The relationship between the coefficient of friction and the normal load for rubber (butadiene styrene) is shown in Fig. 9. The insert to Fig. 9 shows that the coefficient of friction does not change with increasing distance of sliding very much. It is obvious that the coefficient of friction for rubber is

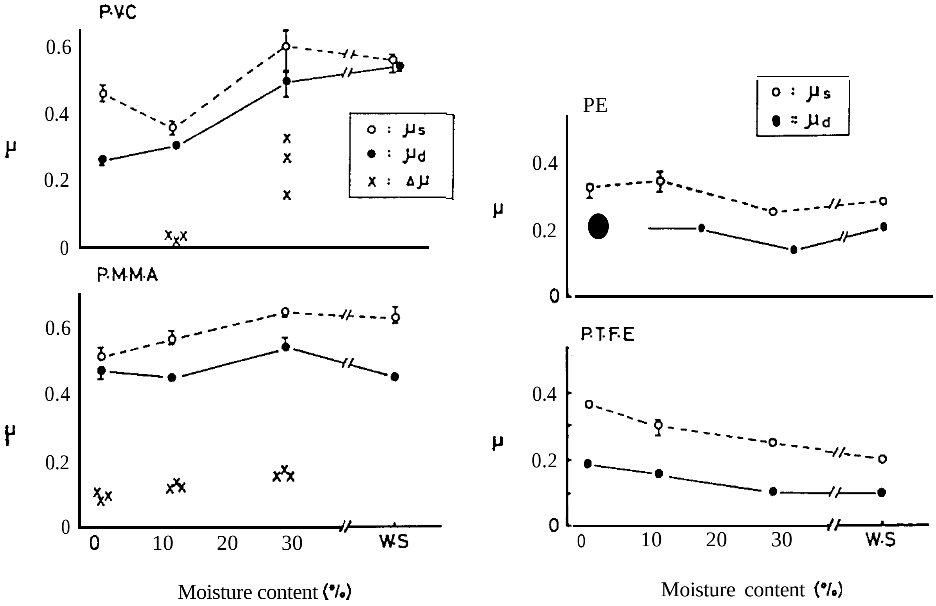

Fig. 8. Relationships between coefficient of friction (p) and moisture content of wood for polymers. Marks; the same as Fig. 7.

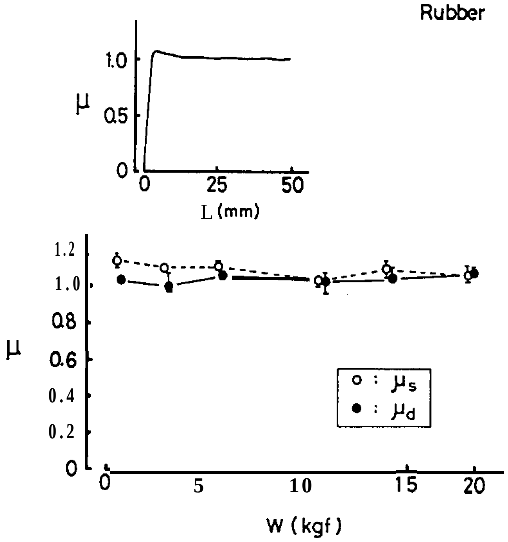

Fig. 9. Relationship between coefficient of friction (μ) and normal load (W) for rubber. Marks; the same as Fig. 3.

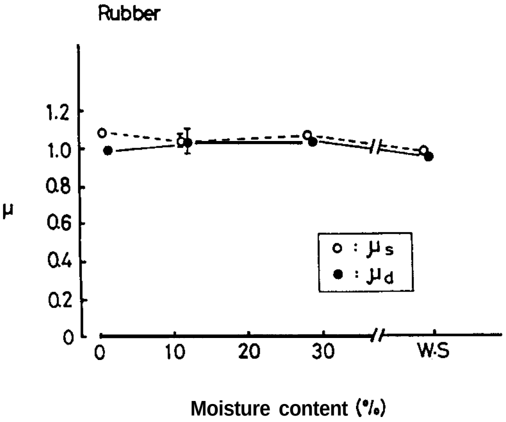

Fig. 10. Relationship between coefficient of friction (p) and moisture content of wood for rubber. Marks; the same as Fig. 3.

independent of the normal load and the mean coefficient is much higher as compared with those for other materials.

The relationship between the coefficient of friction and the moisture content of wood obtained for rubber is shown in Fig. 10. It is clear that the coefficient of friction for rubber (butadiene styrene) is independent of the moisture content of wood.

Friction of wood on wood

The relationships between the coefficient of friction and the normal load for wood (hemlock) sliding on both lower wood specimens of hemlock and isunoki are shown in Fig. 11. The inserts to Fig. 11 show that the friction of wood sliding on wood gives rise to a stick-slip motion. Although there is a certain degree of scatter, it seems that the coefficient of friction is independent of the normal load. In addition to the adhesion component of friction, the deformation component caused by the tissue of wood also may play an important part in the case of wood sliding on wood.

The effect of the moisture content of wood (upper specimen) on the friction between woods is shown in Fig. 12. The lower specimen adopted was always air-dry wood, but was conditioned to the moisture content of water-saturated when the upper specimen was a water-saturated wood. As shown in Fig. 12, a stick-slip motion occures in the range of moisture content below FSP and the amplitude ($\Delta\mu$) increases with increasing moisture content of wood (upper specimen). And the coefficient of friction also increases similarly. In the case of water-saturated condition, however, a stick-slip motion does not appear although the coefficient of friction at water-saturated is about equal to that at FSP. It can be seen from Fig. 12 and Fig. 8 that the presence of a large quantity of free water does not cause a stick-slip motion.

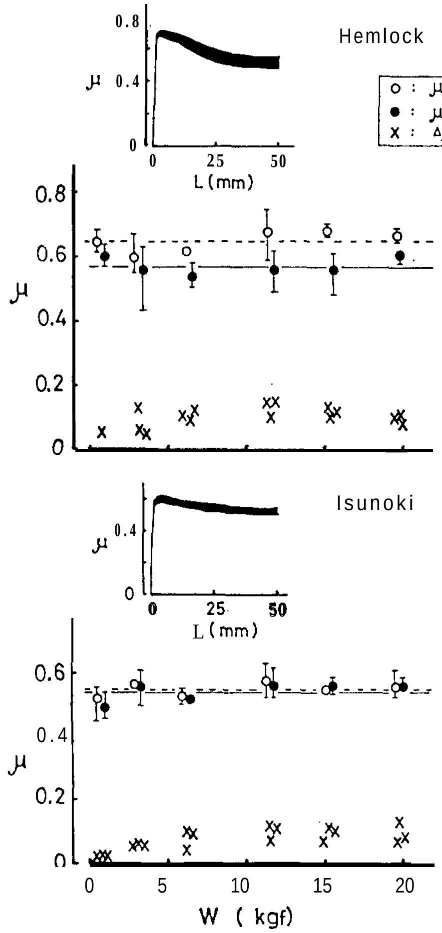

Fig. 11. Relationships between coefficient of friction (μ) and normal load (W) for wood sliding on wood. Marks; the same as **Fig. 7.**

DISCUSSION

From the above results it is clear that the coefficient of friction is almost independent of the normal load in this experimental conditions. Thus the mean values of the coefficient of dynamic friction (μ_d) for each of the counterface materials are shown in Fig. 13. The mean value differs with each counterface material. These differences in the coefficient of friction are considered to be due to both adhesion and deformation components of friction between wood and counterface material. Since the deformation component becomes negligible with a smooth flat surface of a hard material, it can be seen that the friction for metals or glass in this experiment is due primarily to the adhesion component. With other materials except the above,

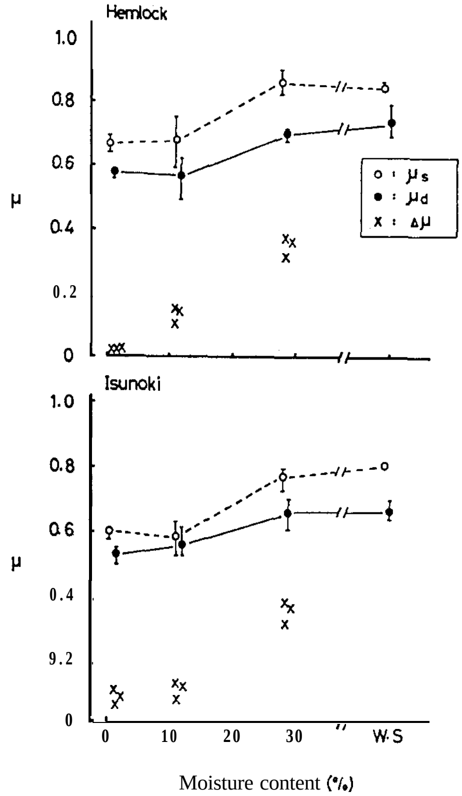

Fig. 12. Effect of moisture content of wood on coefficient of friction (μ) between woods. Marks; the same as **Fig. 7.**

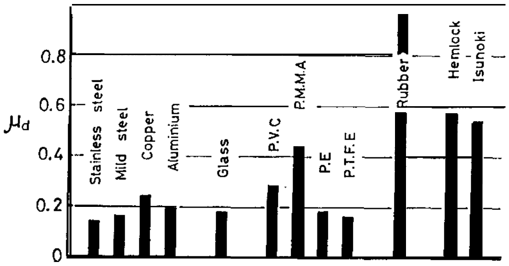

Fig. 13. Coefficient of dynamic friction (μ_d) of air-dry wood to various counterface materials.

however, the deformation component cannot be disregarded although the adhesion component must play an important part in friction.

It is also clear that the friction between wood and various materials is affected significantly by the moisture content of wood and the change with moisture content depends on the kinds of counterface materials. It is conjectured that the unique change in friction with moisture content is caused primarily by the adhesion component of friction. Accordingly, on the basis of the adhesion component, this change will be discussed subsequently.

As already well known, the adhesion component depends on both the size in the area of real contact and the shear strength of the junctions formed between materials. In relation to the interfacial adhesion for wood, Atack and Tabor (1958) concluded that the adhesion between wood and steel was probably due to hydrogen bonding between the hydroxyl groups of wood surface and the oxide layer on the steel surface, and McKenzie and Karpovich (1968) pointed out that Van der Waals forces also contributed.

In the present experiment, with counterface materials such as metal, glass, wood and some polymers (PVC, PMMA), the coefficient of friction increases similarly with increasing moisture content of wood. Metal, glass and wood are substantially hydrophilic materials, and the polymers such as PVC and PMMA have polar groups. Accordingly, the formation of hydrogen bonding with the hydroxyl groups in the surface of wood is expected commonly with the above materials. This suggests that the hydrogen bonding plays an important role in the change of friction with moisture content. It is conjectured from the general relationship between the strength (softening) and the moisture content for wood that the area of real contact increases with increasing moisture content in the range below FSP but is held constant in the moisture content range from FSP to water-saturated condition. This predicted change in the area of real contact with moisture content is in agreement with the change in the coefficient of friction with moisture content in the experiment. It can therefore be concluded that the adhesion between wood and the above materials is due primarily to the hydrogen bonding and the change in the coefficient of friction with moisture content is caused by the change in the area of real contact with moisture content.

On the other hand, with counterface materials which have no polar groups and are chemically stable, such as PTFE and PE, the coefficient of friction decreases with increasing moisture content and with non-polar rubber it is independent of the moisture content of wood. As the formation of hydrogen bonding with hydroxyl groups in the surface of wood cannot be expected with these counterface materials, the adhesion between wood and the above materials is considered to be due primarily to Van der Waals forces. With PTFE and PE, therefore, it can be interpreted that the presence of water in wood weakens the bond and the lowering of adhesion due to the presence of water is greater than the increasing of adhesion due to the increase in the area of real contact. With rubber (butadiene styrene) it can be interpreted that since the both effects are almost the same the friction is independent of the moisture content of wood, but with other polar rubber it may show a different behaviour.

CONCLUSION

The frictional properties of wood sliding on various counterface materials have been studied under a variety of normal loads and wood moisture contents. The conclusions of this study are:

(1) The coefficient of friction for various materials used is approximately independent of the normal load in this experimental conditions. The coefficient of friction differs with each counterface material chiefly because of the difference in adhesion between wood and counterface material.

(2) With materials such as metal, glass, wood and some polymers (PVC, PMMA) the coefficient of friction increases with increasing moisture content of wood. The adhesion between wood and these materials is considered to be due primarily to the hydrogen bonding.

(3) With materials such as PTFE and PE the coefficient of friction decreases with increasing moisture content of wood, and with rubber (butadiene styrene) it is independent of the moisture content. The adhesion between wood and these materials is considered to be primarily due to Van der Waals forces.

(4) In all the counterface materials in this experiment, the change in friction with moisture content can be explained on the basis of the adhesion component.

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