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THE EFFECT OF MICRO-PITS TEXTURE ON THE COEFFICIENT OF FRICTION BETWEEN WOOD AND CEMENTED CARBIDE UNDER DIFFERENT WOOD MOISTURE CONTENT

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ABSTRACT

Friction is an important factor during cutting of wood. Micro-texture has been proven to be an effective measure for the improvement of material friction performance. This paper investigates the effect of the cemented carbide surface micro-pits texture on the performance of wood cutting tools with the purpose to reduce the coefficient of friction on knife/workpiece contact zone. Birch (*Betula* spp.) and pine (*Pinus sylvestris*) were selected as the research object, the impacts of wood moisture content and the load used on the friction coefficient of different micro-pits structures were assessed and compared. We found that at a diameter of the micro-texture of 60 μm, the coefficient of friction can be effectively reduced at different wood moisture contents. The average friction coefficient between cemented carbide and wood surface increased with increasing moisture content below fiber saturation point (FSP). But the increase in free water quantity can lead to a more considerable decrease in the friction coefficient. At a higher working load, the value of the average coefficient of friction between the surfaces increases.

KEYWORDS: Wood, cutting, friction, micro-texture, wood moisture content.

INTRODUCTION

Friction plays an important role during cutting of wood. Friction between wood and steel was examined by Klamecki (1976), McKenzie and Karpovich (1968) and Ohtani et al. (2016) and their results show that the friction coefficient between wood and steel was related to the moisture content, smoothness of steel surface, wood species, and direction of the grain. The changes in the coefficient of friction with duration of rubbing were discussed by Guan et al. (1983). Surface temperature and sliding speed also be taken into account at the interface between wood and steel (Murase 1978, Murase 1980a, Murase 1980b).

Focusing on the reduction of the friction coefficient of the tool surface during cutting, the domestic and foreign scholars start their research mainly from the following points: (1) to study new surface coating technologies, using materials, such as TiAlN, TiAlCN, carbon nitride (CN), diamond, and polytetrafluoroethylene (Kato 1991, Li 1991) as tool-coating materials; (2) to optimize tool structure, including examinations on tool bionic self-sharpening technologies, saw-tooth structure optimization, and so on (Ma 2008, McKenzie 1991); (3) to develop new super-hard ceramic and other tool materials, such as ultra-fine cemented carbide, cubic boron nitride, and aluminum oxide ceramics (Ma 2007). At present, although a variety of new tool materials and structures are emerging one after another, problems, such as high material manufacturing cost, fragility of the tool coating, and low thermal stability are still encountered. Cemented carbide is still the predominant material for woodworking tool manufacturing. The main way towards further enhancement of the processing efficiency and extension of the tool life, is to improve the surface friction of the knife/workpiece to reduce the cutting force and cutting temperature, which will diminish tool wear. Therefore, the development of an appropriate working surface of the tool has become an essential research direction of the research on new technologies aimed at wear reduction of woodworking tools.

Micro-texture technology has been proven to be an effective measure to improve material friction performance (Volchok et al. 2002). Micro-texture is a type of a surface functional structure, which is the micron-sized surface structure. Tribology and bionics research and practice show that the utilization of a proper micro-texture can effectively improve the surface performance and capacity of the anti-friction coating, especially under the condition of a lot of liquid involved in (Kawasegi et al. 2009, Sugihara and Enomoto 2009). Based on the characteristics of wood cutting, in this study, we applied surface micro-pits - texture on wood cutting tools for a reduction in the attrition and friction in the knife/workpiece contact zone. The controlled surface texture on the surface of cemented carbide was produced using a laser processing technology.

The influence of wood moisture content and the load used on the friction coefficient of different micro-structures were compared through friction performance tests. Our findings provide a novel anti-attrition technology. The present research is of theoretical and practical significance because its result will contribute to the extension of the service life of cutting tools.

MATERIALS AND METHODS

Test materials

The tool material was cemented carbide (grade YG8): a cylinder with a density of 14.7 $g \cdot cm^{-3}$, a diameter of 6 mm, and a height of 6 mm. The end face of the cylinder surface roughness was Ra = 0.4 μm. The nano-scale pulsed laser was used for micro-pit processing on its surface and a processing accuracy of ± 10 μm for all directions. Images of the configuration of micro-pits on the surface of the cemented carbide under a microscope can be seen in Fig. 1a,b,c. While carrying out laser micro-molding on the surface of the test piece, the molten residue caused burr, which had to be cleaned around the micro-pit. All the cemented carbide samples were treated with sandpaper and the burrs were cleaned with 1000# (Granularity: 5~7μm) metallographic sandpaper. After removing the burrs, the samples were cleaned with an ultrasonic cleaner. The cleaning solution was acetone. Images of the configuration of micro-pits (d = 60 μm, 120 μm and 180 μm) on the surface of the cemented carbide under 3D profiler can be seen in Fig. 1, which contains the information of surface state of micro-pits, 3-D surfaces and 2-D profiles.

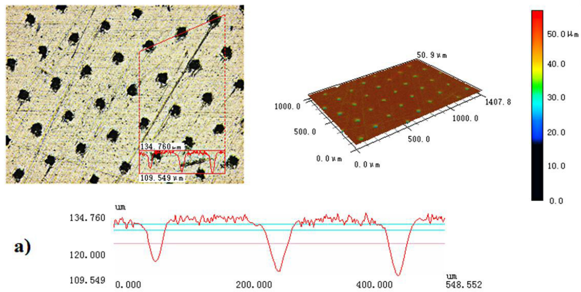

Fig. 1a: Configuration of micro-pits on the surface of the cemented carbide under 3D profiler: a) d = 60 μm.

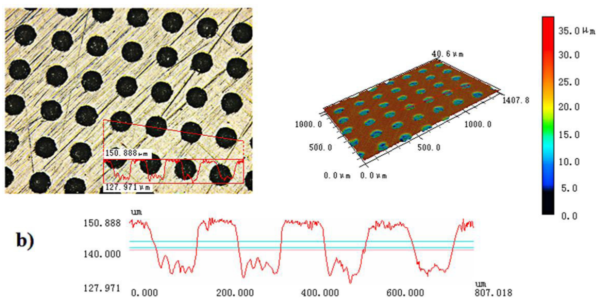

Fig. 1b: Configuration of micro-pits on the surface of the cemented carbide under 3D profiler: b) d = 120 μm.

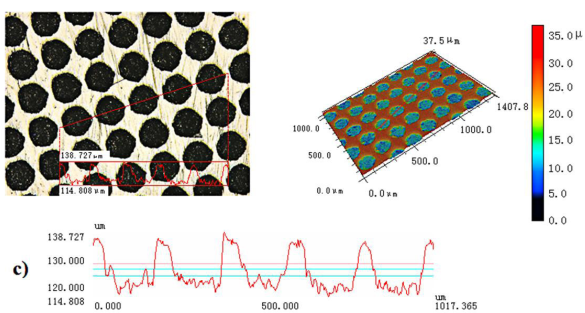

Fig. 1c: Configuration of micro-pits on the surface of the cemented carbide under 3D profiler: c) d = 180 μm.

Wood samples from birch (*Betula* spp.) and pine (*Pinus sylvestris*) were purchased and used in the experiments, with an air-dry density of 0.65 g·cm^{-3} and 0.48 g·cm^{-3}, dimensions of 70 (longitudinal direction) × 70 (tangential direction) × 5 (radial direction) mm, and an air-dry moisture content of 12%. The wood samples were rubbed against the cylinder with the radial section of two different surface roughnesses (birch: 9.6 μm and pine: 13.8 μm). The samples were getting from one board. In the preparation of the test specimen, the moisture contents level of the test pieces were respectively adjusted to water-saturated, green, fiber-saturated, air-dried, and oven-dried specimen. The adjustment method of moisture content level is shown in Tab. 1. After adjustment, the actual moisture content of water-saturated, green, fiber-saturated, air-dried, and oven-dried specimen were 124%, 72%, 29%, 12% and 0%, respectively.

Tab. 1: Moisture content (MC) conditioning of specimens.

Specimens	Conditioning methods	MC (%)
Water-saturated specimen	Place the green specimens in water for at least 2 months until the specimens are no longer weighted.	124±2
Green specimen	The specimens cut from the log stored in cold storage (-6 %) for preparation.	72±3
Fiber-saturated specimen	After drying the green specimens in the air drying shed for 2 months, place them in a double sealed container with distilled water at the bottom until the balance occurred.	29±1
Air-dried specimen	After drying the green specimens in the air drying shed for 2 months, place them in constant temperature and moisture content box with temperature of 20°C and relative moisture content 65% until the water balance occurred.	12±1
Oven-dried specimen	After drying the green specimens in the air drying shed for 2 months, and then place them in a oven at 103°C for at least 48 hours, until the changes of water content was less than 0.5%.	0~2

Method

The cemented carbide was the upper sample and the wood was the lower sample.

A reciprocating friction and wear tester was used for the friction characteristics test. As shown in Fig. 2, the upper sample was fixed on a clamp, whereas the lower sample was fixed on a tray. The contact form of the friction pair was surface to surface, and the wood section that made contact with the micro-texture part of the tool was the radial section. The clamp drove the upper sample to perform a reciprocating movement and avoid the impact of wood knots and other defects. The friction force (F) was produced between the upper and the lower sample under the normal force (Fn). Two groups of strain gauges were used to measure normal forces and friction forces simultaneously. According to the law of Coulomb friction, friction coefficient was automatically calculated and recorded. A diagram of the experimental principle is shown in Fig. 2a). To reduce the test error, the friction pairs were formed between the different micro-texture specimens and wood at different locations on the same piece of wood, moving time 5 min, as shown in Fig. 2b).

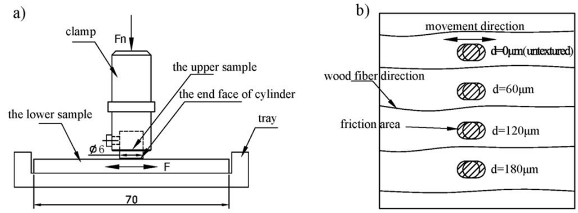

Fig. 2: Schematic diagram of the friction coefficient test: Fn is the test load (the normal force) and F is the friction force: a) the principle of test and b) the test positions.

The average value of the friction coefficient in the whole trip after the start of the record is taken as the final test result. After repeating the process for three times, the average value is obtained to ensure the reliability of the data. All tests were done by a new cement carbide sample and a new wood sample. Wood dust outside the contact area of the upper and lower samples will be vacuumed in time. Wettability of surface of cement carbide samples with different texture were measured by SPCA - X3 contact angle meter at room temperature, each volume of droplet control in 3 uL.

Test design

Experimental design as shown in Tab. 2. Reciprocating frequency 2 Hz, reciprocating distance 10 mm, moving time 5 min, and the angle between the movement and fiber was 0°. Wood samples with varying amounts of moisture were tested at different normal loads (5 N, 10 N, and 15 N respectively).

Tab. 2: Experimental parameters.

Parameter	Set value(s)
Movement frequency	2 Hz
Reciprocating movement displacement	10 mm
Test load	5 N, 10 N, 15 N
Pore diameter of micro-texture of upper sample	0 µm (non-textured), 60 µm, 120 µm,
180 µm	
Depth of micro-texture of upper sample	20 µm
Distance between hole centers	200 µm
Angle between movement and fiber	0°
Wood section	radial section

Four kinds of surface texture were tested, the pore diameter of micro-texture of upper sample were 60 µm, 120 µm and 180 µm, respectively. The pore diameter of micro-texture of 0 µm means surface without texture (non-textured).

RESULTS AND DISCUSSION

Fig. 3 shows the changing curve of the friction coefficient (no texture, air-dried, load 10 N). As can be seen in Fig. 3, friction coefficient changes with time. At the beginning of the test, the friction coefficient shows an upward tendency with the increase of friction time. This is mainly due to the fact that at the beginning of contact, the wood in the contact area will deform quickly under certain pressure, the wood fibers will break, wrinkle and other damage, which makes the surface roughness of the friction pair increase and the friction coefficient increase. However, after a period of friction and extrusion, the change of friction coefficient tends to be stable, mainly because the wood in the contact area has been gradually compressed at this stage, and its surface state tends to be flat, which makes the friction coefficient tend to be flat.

In addition, the variation of friction coefficient on pine surface is more obvious than that of birch. After a period of time, the friction coefficient of both kinds of wood tends to be stable. The friction coefficient on the pine surface is greater than that on the birch surface. This may be due to pine is softer than birch, and is easy to cause the larger actual contact under the certain pressure.

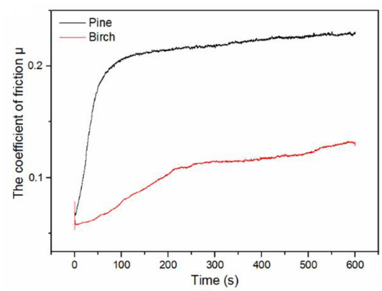

Fig. 3: The changing curve of the dynamic friction coefficient (no texture, air-dried, load 10 N).

Influence of different loads on the average friction coefficient

Fig. 4 shows the influence of the loads on the friction coefficient of different friction pairs under wood moisture content of 12%, with d = 60 μm and without texture samples, respectively. The general trend was that with increasing the load was increasing friction coefficient for both tested wood species.

These results could have been obtained due to the increase in the normal force with the elevation of the load used, which led to defects such as fractures and wrinkles of the fiber on the wood surface in the process of the reciprocating movement. The damage increased the surface roughness, resulting in augmentation of the values of the friction coefficient between the surfaces. The friction coefficient from pine surface is bigger than the friction coefficient from birch surface. In addition, when the loads increase, the adhesion effect of the interface between wood and cemented carbide would be strengthen. This can lead to friction coefficient increased.

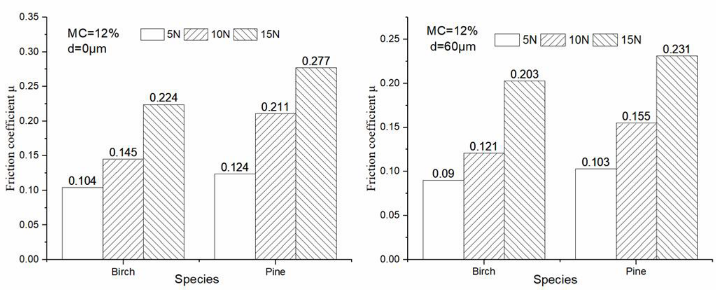

Fig. 4: Influence of different loads on the average friction coefficient with d = 60 μm and without texture samples under moisture content of 12%.

Influence of different wood moisture contents on the average friction coefficient

Fig. 5 shows the influence of the wood moisture content on the friction coefficient of different friction pairs under various load conditions, with d = 60 μm and without texture samples, respectively.

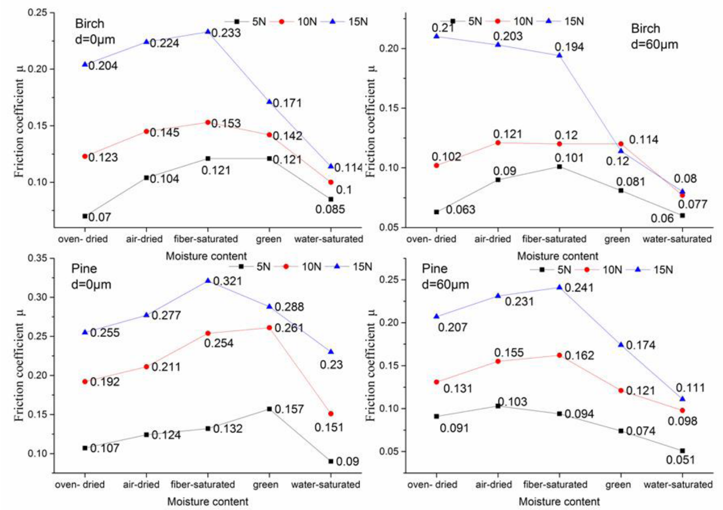

Fig. 5: Influence of different wood moisture contents on the average friction coefficient.

As shown in Fig. 5, for both species, there was a common tendency in the change of friction with different moisture content of wood. The average friction coefficient between on-textured (cemented carbide) sample and wood surface increased with increasing moisture content in the process from the oven-dried to fiber-saturated. The effect of the moisture content of wood on the coefficient of friction below 30% could be caused by the softening of wood surfaces. Bowden and Tabor (1954) indicated that as wet wood is somewhat softer than dry wood, the real contact area for wet wood will be greater than for dry wood for a fixed load. But within a relatively high range of moisture content (above 30%), the friction coefficient increased slightly or began to reduce. This phenomenon is mainly due to the fact that when the moisture content of wood above the Fiber Saturation Point (FSP), the amount of free water in the wood gradually increased, it can be used as excellent lubrication and cooling medium during the friction between the cemented carbide and the wood. It is conducive to improving the carbide-wood contact during friction, which is consistent with the results obtained earlier by McKenzie and Karpovich (1968).

When the load is lower, the friction coefficient began to decrease at the higher moisture content without texture samples. At a load of 5 N, the average friction coefficient was reduced from 0.121 to 0.085 when moisture content level of birch is green, and the average friction coefficient was reduced from 0.157 to 0.09 when moisture content level of pine is green .The friction coefficient began to decrease at the lower moisture content when the load is increased. The friction coefficient began to decrease at moisture content level of fiber-saturated (15 N, the friction coefficient: 0.233) with the birch and the friction coefficient also began to decrease at moisture content level of fiber-saturated (15 N, the friction coefficient: 0.321 with the pine. It may be due to that when the load is lower, free water in the wood is less by squeezing to infiltrate on the surface of the wood the lubrication effect is not obvious.

When there is a texture, the change tendency was also first increased, and then decreased with the moisture content of wood. But the basic trend was that the moisture content began to decrease after moisture content above 30%, and with the increase of load, the decreasing trend is more obvious. Whereas at a load of 15 N, the average friction coefficient decreased from 0.194 to 0.12 between birch and textured sample, and the average friction coefficient decreased from 0.241 to 0.174 between pine and textured sample. This is mainly due to the higher load, a lubrication interface is easier to form, which helps to reduce the friction coefficient under this condition. When the moisture content is water-saturated, the state of the moisture content is close to water saturated; its friction coefficient reaches its lowest value.

Influence of the micro-texture surface on the average friction coefficient

Fig. 6 shows a comparison between the friction coefficients of non-textured and textured samples under different loads and surface parameters. The friction coefficient of all textured samples (d = 60 μm) decreased under different loads used. The textured sample with d = 180 μm had a larger friction coefficient. However, there was no significant gap between the friction coefficient of the textured sample (d = 120 μm) and the friction coefficient of the non-textured sample.

As shown in Fig. 6, when the load is 5 N, the minimum and maximum decrease of friction coefficient of the textured specimen (d = 60 μm) are 13.4% (air-dried, 0.104 to 0.09) and 33.1% (green, 0.121 to 0.081 using birch specimen, respectively. And the minimum and maximum decrease of friction coefficient of the textured specimen (d = 60 μm) are 15% (oven-dried, 0.107 to 0.091)and 52.9% (green, 0.157 to 0.074) using pine specimen, respectively. When a load of 10 N and 15 N were utilized, the ratio of the friction coefficient showed same change tendency with the increase of moisture content, the texture exerted more obvious friction reduction effects at elevated moisture content when d = 60 μm and d = 120 μm. More specifically, the friction coefficient curve declined more obviously with the increase of the water content above 30%.

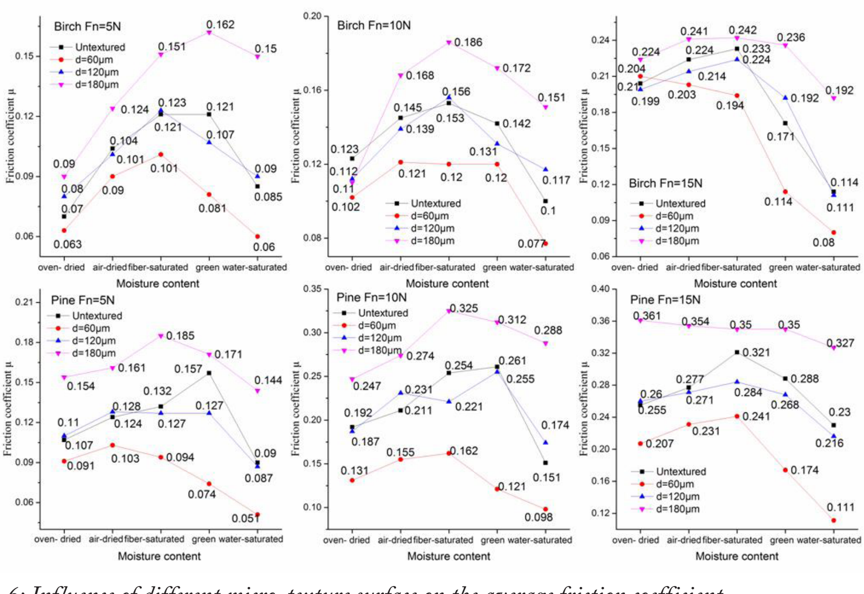

Fig. 6: Influence of different micro-texture surface on the average friction coefficient.

At room temperature, the fiber saturation point of wood is usually around 30%. However, at wood moisture content higher than 30%, the levels of free water in the wood gradually increase. Thus, it becomes easier for the free water in the cell cavities and cell gaps to penetrate into the material surface, forming a lubrication interface under certain pressure. All of these reasons apply to no texture, too. Generally, the friction coefficient of non-textured began to decline when the moisture content was more than 30%.The increase of free water content contributes to water extrusion by the pressure from loading. However, the hardness of the wood is also reduced, and damage is caused during friction, affecting the friction coefficient.

With the increase of the pore diameter of the micro-texture, the surface roughness increases, and this influences the friction coefficient. This is the main reason for the increase of the friction coefficient of the texture sample with a diameter d = 180 μm.

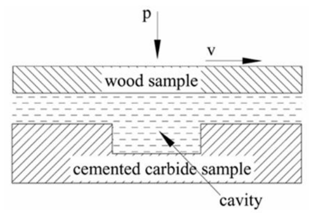

Fig. 7: Mechanism of action at a high moisture content.

When the moisture content of wood is close to that of wet material, under a certain pressure, the water flows out of the wood surface. Each pit on the micro-texture is equivalent to a fluid dynamic lubrication bearing. In the mutual movement of the friction pair, it enhances the fluid dynamic pressure and promotes the formation of a lubrication film of fluid dynamic pressure on the surface of the friction pair. This film contributes to a reduction in the friction and wear resistance (Fig. 7). This principle is similar to the shark skin in nature, its body surface is not completely smooth, and there is a certain tiny structural unit with a certain geometrical shape. These microscopic surface morphology characteristic of non smooth tend to have smaller friction resistance than smooth surface. The shark skin swimsuit can reduce the friction with the water greatly based on micro texture model design of v-shaped grooves type on the shark skin surface (Ball 1999).

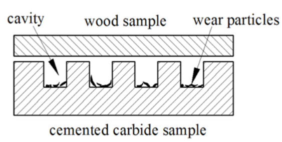

Fig. 8: Mechanism of action at low moisture content.

We found that decrease in the moisture content of the wood resulted in lower free water levels in the wood. Furthermore, the surface texture of the pits can reduce the actual contact area between the friction pair. Meanwhile, the surface texture can hold and contain wood chips or hard particles such as quartz in the wood that reduce the increase of surface roughness caused by wood chips or hard particles, leading to a reduction of the friction coefficient (Fig. 8).

In addition, it can be concluded that the contact angle is 81.2° (d = 0 μm), 36.9° (d = 60 μm), 61.1° (d = 120 μm) and 72.8° (d = 180 μm), respectively, according to the contact angle measurement on different surface, as shown in Fig. 9a,b,c,d.

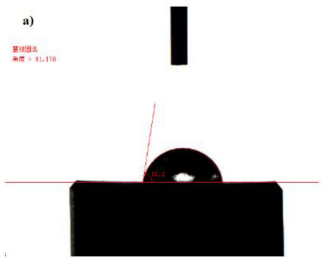

Fig. 9a: Contact angle measurement: a) d = 0 μm (81.2°).

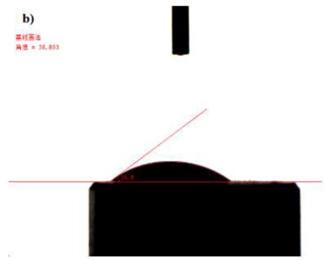

Fig. 9b: Contact angle measurement: b) d = 60 μm (36.9°).

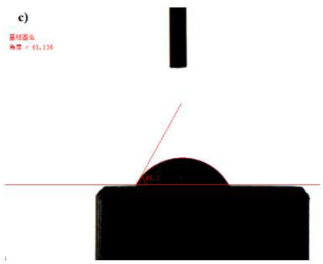

Fig. 9c: Contact angle measurement: c) d = 120 μm (61.1°).

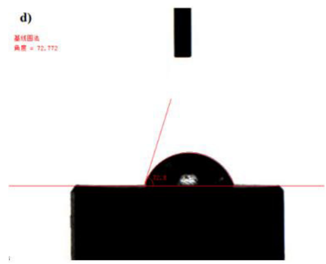

Fig. 9d: Contact angle measurement: d) d = 180 μm (72.8°).

When the diameter of microstructure is 60 μm, the surface wettability is superior to plane, more hydrophilic, it also conforms to the Wenzel model (Wenzel 1936) about the theoretical calculation of the surface wettability. Wenzel think some rough surface structure can enhance the wettability of the surface, due to the concave and convex surface can lead to increase the real contact area of solid and liquid, solid-liquid interface energy or solid-gas interface energy was also increase, the solid-liquid actual contact area of rough surface is greater than the apparent contact area. And strong hydrophilic surface is more conducive to the formation of lubricating film, thus the surface friction coefficient was reduced.

CONCLUSIONS

The friction coefficient between the surfaces increases with the elevation of the working load. This may be because the positive pressure is augmented with the increase of the load used, and it becomes easier to cause defects in the process of reciprocating friction movement, such as fractures and wrinkles of the fiber. The increased surface roughness leads to a higher friction coefficient between the surfaces.

The average friction coefficient between cemented carbide and wood surface increased with increasing moisture content below fiber saturation point (FSP). But within a relatively high range of moisture content (above 30%), the friction coefficient increases slowly or began to reduce. Especially, the increase of free water content can lead to a more obvious decrease in the friction coefficient. The rise in the free water content contributes to water squeezing under the pressure from loading. However, free water also reduces the hardness of the wood and causes damage during friction, thus affecting the friction coefficient.

Regardless of whether there is low or high moisture content, reasonable micro-texture form (d = 60 μm) can effectively reduce the friction coefficient between wood and cemented carbide. Its mechanism of action is different and affected by the wood moisture content, load used, and other factors.

The water contained in the wood is involved in wood cutting, especially in the processes of cutting of new material and veneer peeling and slicing. Since the wood is anisotropic porous material, further analysis of the relationships between wood characteristics, such as wood structure and different sections with micro-texture parameters, is one of the future research directions. In addition, our results will improve the cutting efficiency and machining quality, and reduce the loss of wood and cutting energy consumption.

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REFERENCES

1. Ball, P., 1999: Engineering: Shark skin and other solutions. Nature 400: 507-508.
2. Bowden, F.P., Tabor, D., 1954: The friction and lubrication of solids. Maruzen, Tokyo, Pp 82–85, 158–159 pp.
3. Guan, N., Thunel, B., Lyth, K., 1983: On the friction between steel and some common Swedish wood species. European Journal of Wood and Wood Products 41: 55-60.
4. Kato, C., 1991: The wear characteristics of a woodworking knife with chromium plating III. The self-sharpening characteristics in orthogonal cutting of wood parallel to the grain. Mokuzai Gakkaishi 37: 1004-1010 (in Japanese).
5. Kawasegi, N., Sugimori, H., Morimoto, H., Morita, N., Hori, I., 2009: Development of cutting tools with microscale and nanoscale textures to improve frictional behavior. Precision Engineering 33(3): 248-254.
6. Klamecki, B.E., 1976: Friction mechanisms in wood cutting. Wood Science and Technology 10: 209-214.
7. Li, L., 1991: Advances in research on wood cutting tools plated with membranes. China Wood Industry 21: 1-4 (in Chinese).
8. Ma, Y., 2007: The new development of theory research in design of timber cutter abroad. Forestry Machinery & Woodworking Equipment 35: 4-8 (in Chinese).
9. Ma, Y., 2008: The development of theory of wood cutting abroad. Wood Processing Machinery 4: 35-39 (in Chinese).
10. McKenzie, W.M., 1991: Friction coefficient as a guide to optimum rake angle in wood machining. Wood Science and Technology 25: 397-401.
11. Mckenzie, W.M., Karpovich, H., 1968: The frictional behavior of wood. Wood Science and Technology 2: 139-152.
12. Murase ,Y., 1978: Effect of surface roughness of steel and wood variables on repeated friction between wood and steel. Mokuzai Gakkaishi 24: 865-872 (in Japanese).

13. Murase, Y., 1980a: Coefficient of friction and surface temperature in the sliding friction between wood and steel. Mokuzai Gakkaishi 26: 571-575 (in Japanese).
14. Murase, Y., 1980b: Friction properties of wood at high sliding speed. Mokuzai Gakkaishi 26: 61-65 (in Japanese).
15. Ohtani, T., Iida, R., Nakai, T., Adachi, K., Abe, K., Toba, K., 2016: Smoothness of a spruce surface rubbed with a metal tool under high-speed friction. Journal of Wood Science 62(4): 377-380.
16. Sugihara, T., Enomoto, T., 2009: Development of a cutting tool with a nano/micro-textured surface improvement of anti-adhesive effect by considering the texture patterns. Precision Engineering 33(4): 425-429.
17. Volchok, A., Halperin, G., Etsion, I., 2002: The effect of surface regular microtopography on fretting fatigue life. Wear 253: 509-515.
18. Wenzel, R.N., 1936: Resistance of solid surfaces to wetting by water. Industrial & Engineering Chemistry Research 28: 988-994.

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