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Corrosive-wear characteristics of diamond-coated cemented carbide tools

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Abstract Continuous milling tests with diamond-coated and uncoated cemented carbide tools and polycrystalline diamond tools were carried out on air-dried and wet melapi (*Shorea* sp.) and western redcedar (*Thuja plicata D. Don*). These tools were examined for corrosive-wear characteristics of the tool-edge appearance, cutting-edge profile, edge recession, and cutting-power consumption. The tool surfaces were observed with a scanning electron microscope and were analyzed by energy-dispersive X-ray spectroscopy. Based on these examinations, the occurrence of corrosive wear while cutting wet woods was confirmed for the uncoated and polycrystalline diamond tools. In contrast, the coated tools did not exhibit corrosive wear, nor did delamitation or wear of the diamond film occur with any of the work materials. The diamond-coated tools showed high resistance not only to mechanical wear but also to corrosive wear.

Key words Diamond-coated tools · Cemented carbide
Polycrystalline diamond · Corrosive wear · Wood cutting

Introduction

High speed steel and cemented carbide have been widely used as tool materials for wood machining. However, there is a need for woodcutting tools with longer lifetime and better cutting performance. Polycrystalline diamond (PCD) tools have excellent wear resistance, leading to their wood machining application.

For cutting green or wet woods, a corrosive-wear mechanism, caused by chemical or electrochemical actions, has been noted to enhance tool wear with the mechanical-wear mechanism. High speed steel, cemented carbide, and PCD, mentioned above, have also been shown to exhibit marked corrosive wear while cutting green wood.[1] Because sawing or veneer cutting, when green and wet woods are cut, have been often conducted in wood machining, not only mechanical-wear resistance but corrosive-wear resistance is necessary for a long-life woodcutting tool. Such tools, therefore, should be developed.

The authors have made diamond-coated cemented carbide tools by the hot-filament chemical vapor deposition (CVD) method using a carbonized tantalum (TaC) filament.[2] The coated tools were experimentally investigated for the possibility of their application to wood machining.[3–8] As a result, the improvement in wear resistance with diamond coating has been clarified. Diamond also has high resistance to chemical action, so the diamond coating can be expected to show high corrosive-wear resistance.[8]

In this study, continuous milling tests with diamond-coated and uncoated cemented carbide tools and PCD tool were carried out on air-dried and wet melapi and western redcedar. The corrosive-wear characteristics of these tools are discussed.

Experimental

Cutting tools and work materials

The rake and clearance faces of the cemented carbide tips (throw-away type, K05 grade-91%–93% WC, 3.5%–4.5% Co, and 3%–5% other carbide) were coated with 20μm thick diamond films. The shape and size of the tips are the same as in our previous study (sharpness angle 55°).[8] The

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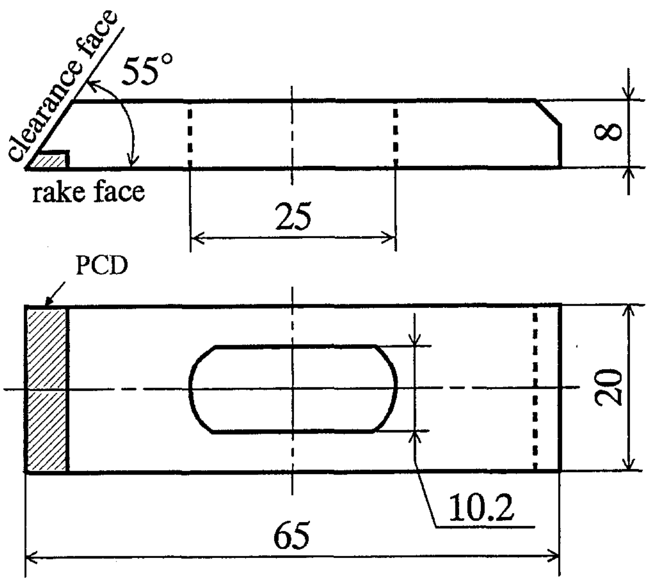


Fig. 1. Polycrystalline diamond (PCD)-brazed tool. Dimensions are in millimeters

diamond coating was applied with a H_2/5 vol% CH_4 gas mixture (total pressure of 4kPa) by the hot-filament chemical vapor deposition (CVD) method.[2] The filament power was 2.2kW. The tip surfaces were treated by sand-blasting, cobalt-etching, and scratching with ultrasonic vibration before coating to improve the adhesion strength of the diamond film.[3–8] Sand-blasting was done to increase the contact area between the diamond film and cemented carbide substrate. Cobalt-etching decreased the amount of cobalt on the substrate surface, which prevents the formation and growth of diamonds. Scratching with ultrasonic vibration was performed to enhance the formation of diamond nucleation.

Polycrystalline diamond-brazed tools (Fig. 1) were used in this test. The binder of PCD was mainly cobalt, and the sharpness angle was 55°, the same as with the coated and uncoated tools.

The work materials in this test included air-dried and wet melapi [*Shorea* sp.(Sabah)] and western redcedar (*Thuja plicata D. Don*). The specific gravity in the air-dried condition, moisture content, and pH for these materials are listed in Table 1. All pieces of work material were 910mm long, 300mm wide, and 12mm thick; and they were machined on the 910 × 12mm edge in orthogonal 90 to 0 cutting. Melapi contains a lot of silica, which causes mechanical tool wear.[9] Western redcedar contains tropolone, causing a chelation reaction in the extractives, resulting in corrosive tool wear.[10] The pH for each material was measured with a glass electrode pH meter for the slurry, which was made with each wood chip of 10g (oven-dried) and 100ml of pure water for 48h.

Cutting tests

A series of cutting tests were carried out on a single-spindle shaper.[8] The materials were cut by up-milling. Each tool with a 15° clearance angle (rake angle 20°) was set on the milling cutter, which had a 130mm diameter cutting circle. In this test, two milling cutters, different ones for the coated and the uncoated tools (four knives) and for the PCD tools (two knives) were used. The former has three balance-keeping tools, and the latter has one balance-keeping tool. A spindle speed of 3800rpm, a cutting speed of 25.9m/s, a feed of 1.2mm/revolution, and a depth of cut of 2mm were used as cutting conditions. The total cutting length reached approximately 910m (total cutting arc length was approximately 12.2km and the total cutting time approximately 200min).

Table 1. Specific gravity, moisture content, and pH for the materials used in the study

Material	Specific gravity (air-dried)	Moisture content (%)		pH
		Air-dried	Wet	
Melapi	0.47	15.1	131.2	6.8
Western redcedar	0.29	11.9	136.9	4.3

Measurement method

For the cutting tests the edge recession and cutting-power consumption were measured, and the cutting-edge profile of each tool was recorded for a constant cutting period. In addition, the tool edges were observed with a scanning electron microscope (SEM). Elemental analyses of the tool surfaces were conducted by energy-dispersive X-ray spectroscopy (accelerating voltage 15kV) after the cutting tests.

Edge recession was measured on the rake face with a microscope. Five indentations were made with a Vicker's hardness tester, and a total of five measurements were made along the 12mm long cutting edge. In this study the edge recession during cutting was represented by the largest value. The edge recession for the coated tool was represented by the recession of the cemented carbide substrate.[3–6,8] Because the edge of the substrate receded owing to the sand-blast treatment before coating, the mean recession value before cutting became approximately 11μm.

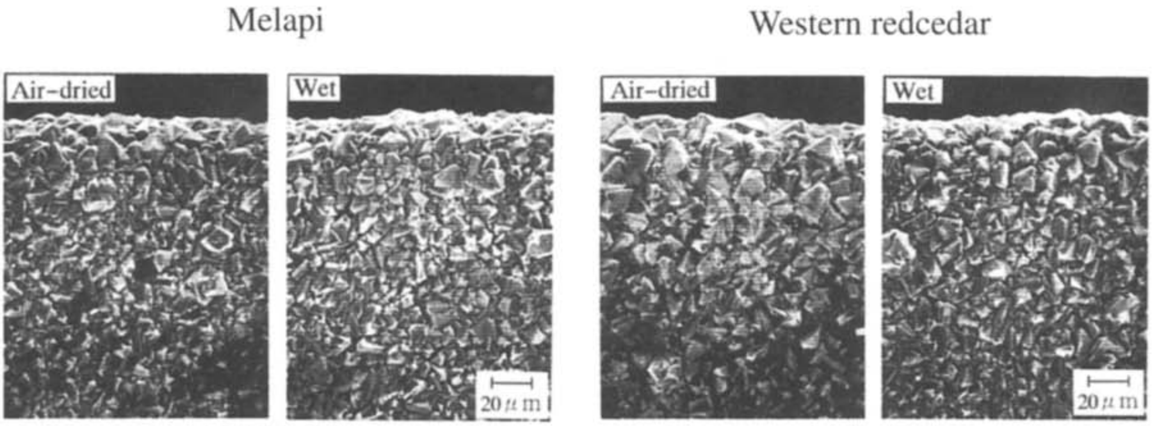
Cutting-power consumption was measured with a digital three-phase wattmeter and a pen recorder. The value was calculated by subtracting the power consumption during idle running from that during cutting.

The cutting-edge profile was recorded with a stylus-type surface measuring instrument: The rake face of each tool was perpendicularly fixed to the instrument table, and the cutting edge was then traced with a knife-edge stylus (material was diamond, with an edge radius 5μm, edge angle 90°, and load 4mN).

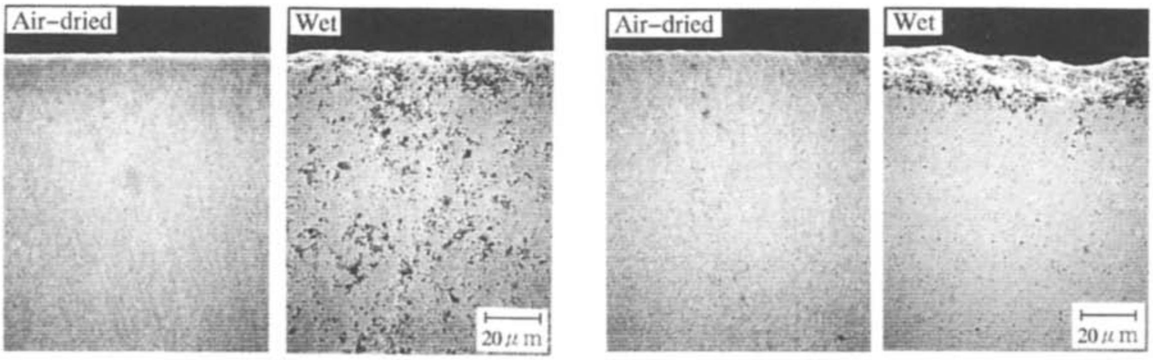
Results and discussion

SEM observations

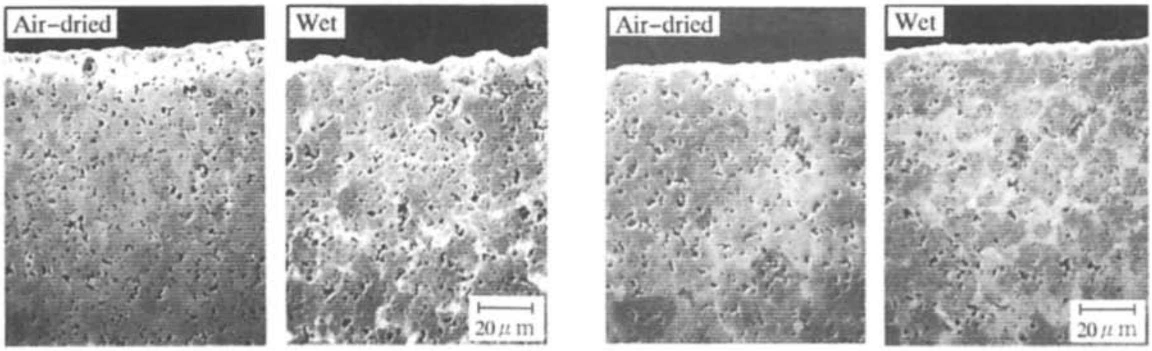
The SEM micrographs of the tool rake faces after cutting air-dried and wet melapi and western redcedar are shown



(a) Coated (a) Coated



(b) Uncoated (b) Uncoated



(c) PCD (c) PCD

Fig. 2. Scanning election microscopy (SEM) micrographs of the rake faces of coated, uncoated, and PCD tools after cutting air-dried and wet melapi and western redcedar

in Fig. 2. The coated tools showed the uneven surface of the diamond film. The surface condition of each coated tool did not change during cutting. During the cutting of air-dried woods, the uncoated tools showed a smooth wear surface, probably due to mechanical wear. In contrast, the uncoated tools during cutting of wet woods exhibited corrosive wear, caused by selective separation of the cobalt binder by chemical or electrochemical action. Tungsten carbide grains on the uncoated tool surfaces were removed considerably during cutting of wet melapi, as the mechanical action on the tool edge in the corrosive environment was large. The difference in the surface condition during cutting of air-dried and wet woods was not observed for the PCD tools. The grain removal, observed in the uncoated tools, hardly occurred on the PCD tool surface. Although each PCD surface had many pores, they had formed during manufacturing of the PCD, not during cutting.

Elemental analyses of tool surfaces

Elemental analyses of the rake faces by energy-dispersive X-ray spectroscopy are shown in Fig. 3. These results were obtained before and after cutting air-dried and wet western redcedar and were almost the same as the results obtained when cutting melapi.

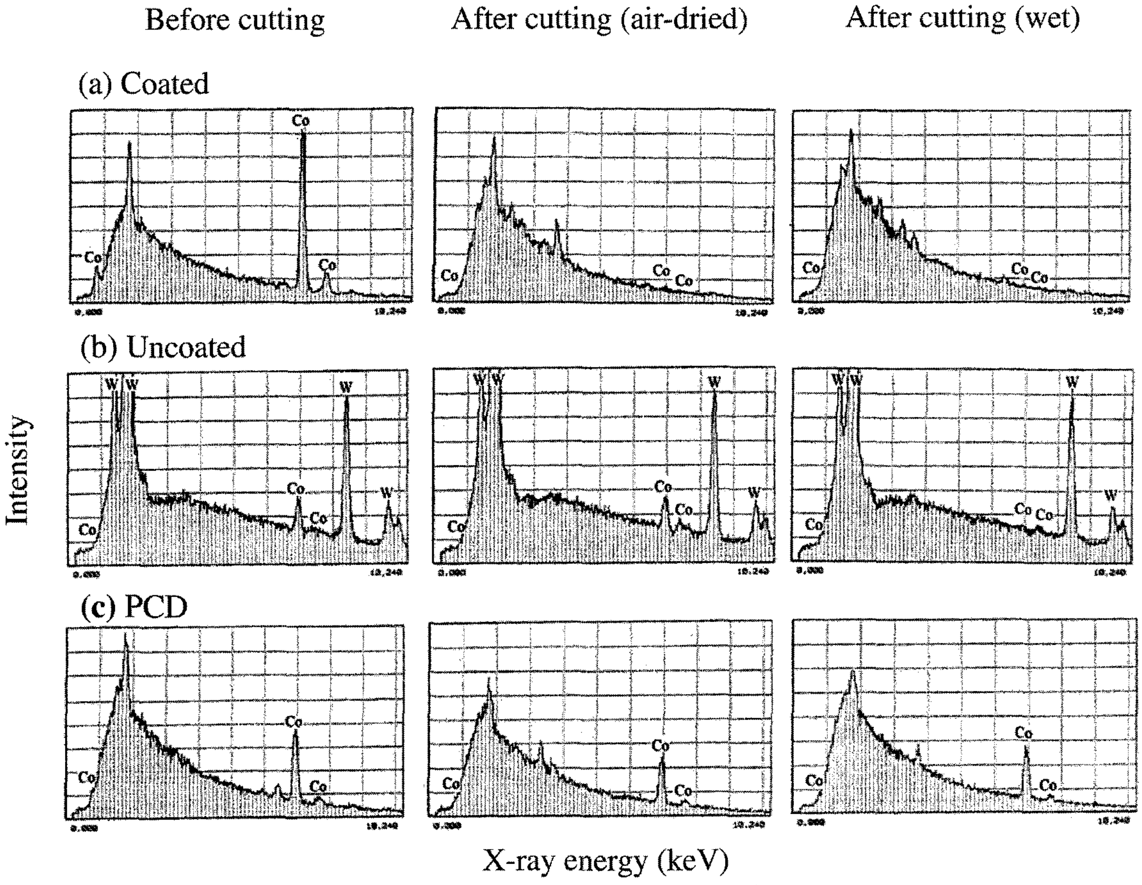


Fig. 3. Energy-dispersive X-ray spectra of the rake faces of coated, uncoated, and PCD tools while cutting air-dried and wet western redcedar. *Co*, cobalt; *W*, tungsten

A large peak for cobalt was observed for the coated tool before cutting, attributed to cobalt droplets on the film surface formed during the coating.[3] Because the droplets were removed by mechanical or corrosive action during cutting, the cobalt peak disappeared after cutting airdried and wet woods. Tungsten and cobalt peaks were observed for the uncoated tool before cutting. Although the spectrum for the uncoated tool after cutting air-dried wood was similar to that before cutting, the cobalt peak disappeared after cutting wet wood. It was caused by selective separation of the cobalt binder. The PCD tool showed a cobalt-binder peak before cutting, and the spectrum was not changed during cutting both air-dried and wet woods, which was different from the results for the uncoated tool.

Cutting-edge profiles

The cutting-edge profiles of each tool before and after cutting wet woods are shown in Fig. 4. During the cutting of air-dried woods, each tool mainly exhibited mechanical wear, resulting in a smooth cutting edge. Marked changes in the cutting-edge profiles, therefore, were not observed.

The cutting edges of the coated tools before cutting were extremely rough, which is mainly attributed to the sandblast treatment before coating, and they maintained the initial condition throughout the cutting test. In contrast, the cutting edges of the uncoated and PCD tools before cutting were relatively smooth. Their cutting edges, however, became extremely rough during the final cutting period. Considerable chipping occurred in the PCD tools, which is attributed to diamond-grain removal. Although the PCD tools did not show clear differences in the results of SEM observation and elemental analysis of the tool surfaces, their cutting-edge profiles obviously indicated the occurrence of corrosive wear while cutting wet woods. Thus the coated tools maintained their initial cutting-edge condition while cutting wet woods, whereas the other tools did not.

Edge recession

The progression of the edge recession for each tool is shown in Fig. 5. The edge recession for the uncoated tools while cutting wet woods, caused by corrosive wear, increased rapidly compared with that seen while cutting air-dried woods. The PCD tools also showed large edge

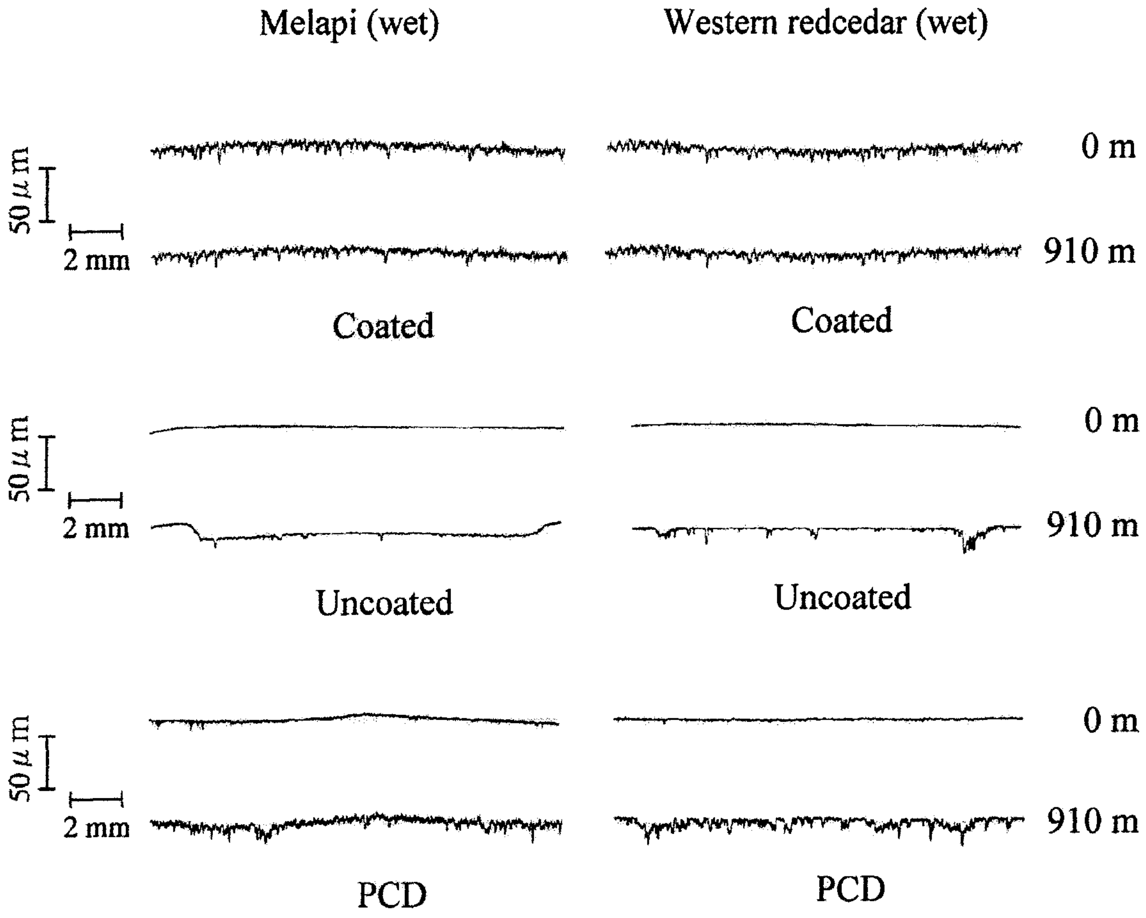


Fig. 4. Cutting-edge profiles of coated, uncoated, and PCD tools while cutting wet melapi and western redcedar (cutting lengths 0 and 910m)

recession while cutting wet woods. This value, however, was smaller than that for the uncoated tools for all work materials. Although the edge recession for the uncoated and PCD tools became larger when cutting melapi at both moisture contents, these tools were found to exhibit marked corrosive wear while cutting wet western redcedar; the difference in the edge recession between air-dried and wet woods was larger than that for melapi. The effect of corrosive action was much more apparent in the PCD tools than in the uncoated tools. Because PCD tools have a high resistance to mechanical wear but not to corrosive wear, the relative magnitude of the corrosive effect probably increases.

In contrast, the coated tools did not exhibit corrosive wear, and delamination and wear of the diamond film did not occur at all. The coated tool maintained its initial value (approximately 11 μm) throughout the cutting period. This value was almost the same as for the PCD tools while cutting air-dried woods and was smaller than that for the PCD tools while cutting wet woods.

Diamond films are formed by bonding diamond crystals and do not contain a binder, whereas the binder exists in cemented carbide and PCD. The diamond-coated tools, therefore, showed high corrosive-wear resistance while cutting both wet melapi and western redcedar.

Cutting-power consumption

Variations in cutting-power consumption over the duration of the cutting period are shown in Fig. 6. The differences in moisture contents and wood species of the work materials appeared in the cutting-power consumption for each tool: The consumption values became smaller in the case of cutting wet woods and larger when cutting melapi, which has a higher specific gravity.

Although the edges of the uncoated and PCD tools receded considerably while cutting both air-dried and wet woods, the power consumption values for these tools slightly increased during cutting. In contrast, each coated tool maintained almost the same consumption value during cutting. The coated tool used to cut wet western redcedar consistently showed a larger consumption value than did the other tools, which is attributed to the tool-edge dullness and the uneven surface of the diamond film. While cutting the other three work materials, the coated tools also showed a larger value of consumption during the initial stage of cutting; however, the value after cutting a length of approximately 500 m tended to decrease compared to that seen with the other tools.

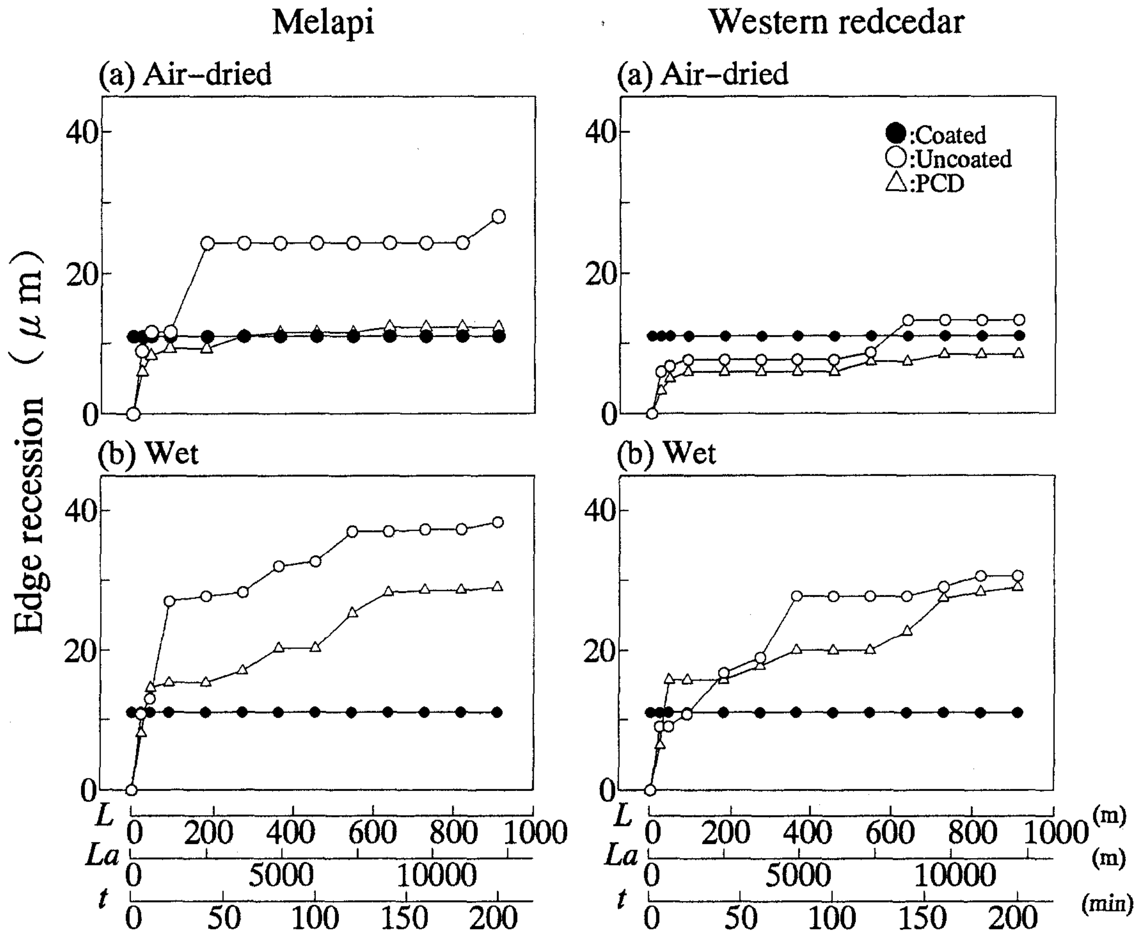


Fig. 5. Progression in the edge recession of coated, uncoated, and PCD tools in relation to cutting length (*L*), cutting arc length (*La*), and cutting time (*t*)

Conclusions

Diamond-coated and uncoated cemented carbide tools and PCD tools were tested while milling air-dried and wet melapi and western redcedar. The corrosive-wear characteristics of these tools were examined.

The edge recession for the uncoated tools while cutting wet woods increased rapidly compared to that while cutting air-dried woods. Based on the SEM observations and the elemental analyses of the tool surfaces, this change was confirmed to be caused by corrosive wear attributed to selective separation of the cobalt binder by chemical or electrochemical action. The PCD tools also showed a large edge recession while cutting wet woods. The value, however, was smaller than that for uncoated tools for all work materials. The uncoated and PCD tools exhibited marked corrosive wear while cutting wet western redcedar. In contrast, the coated tools did not exhibit corrosive wear, and there was no delamination or wear of the diamond film. The coated tool maintained its initial edge recession throughout the cutting test. The value was almost the same as for the PCD tools while cutting air-dried woods and was smaller than that for the PCD tools while cutting wet woods. When cutting wet western redcedar, the coated tool consistently showed larger cutting-power consumption than did the other tools, which was attributed to the tool-edge dullness and the uneven surface of the diamond film. When cutting with the other three work materials, the coated tools also showed a larger consumption value during the initial stage of cutting; however, the value after cutting tended to be lower than that for the other tools.

The results of this study illustrate an excellent performance of diamond-coated tools in regard to corrosive tool wear. The diamond-coated tools showed high resistance not only to mechanical wear but also to corrosive wear.

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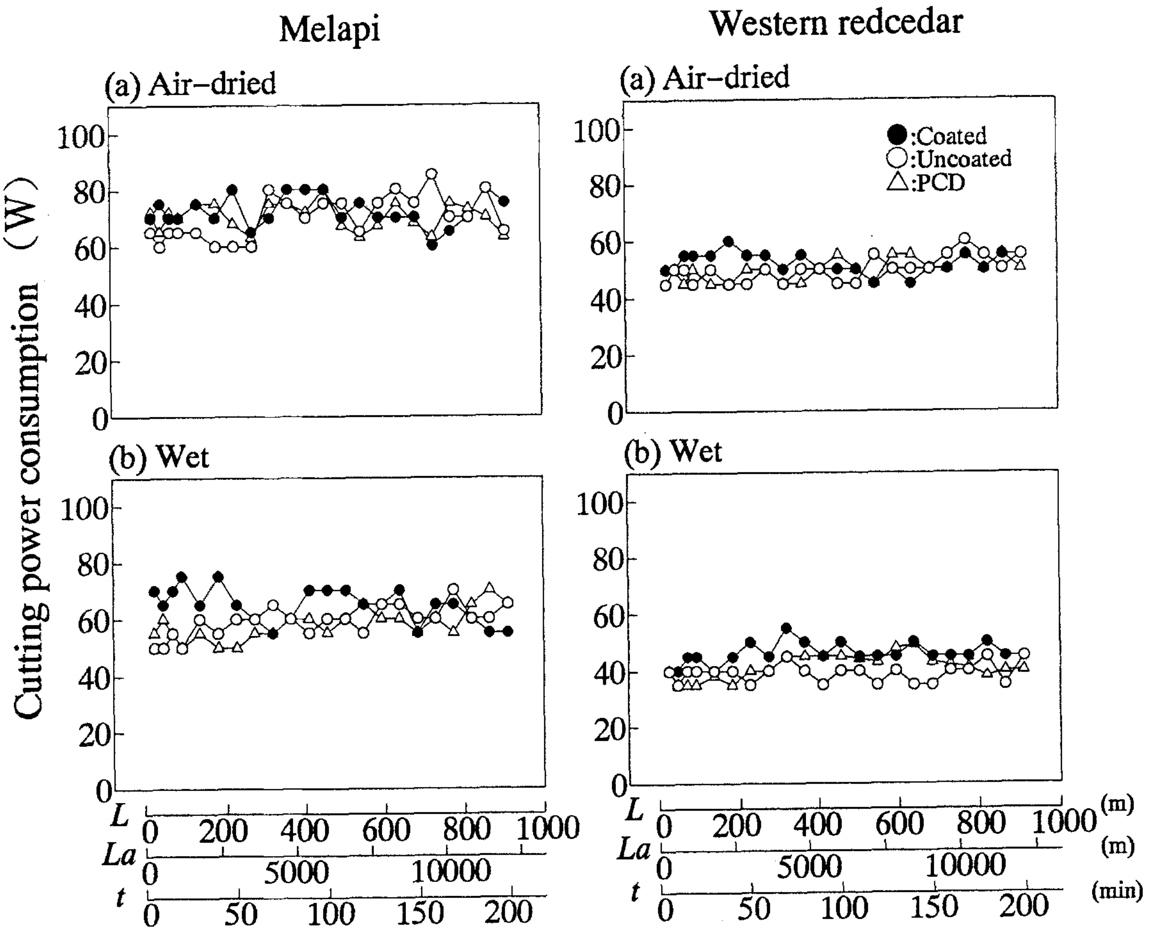

Fig. 6. Variation in cutting-power consumption for coated, uncoated, and PCD tools in relation to cutting length (*L*), cutting arc length (*La*), and cutting time (*t*)

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