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Performance of coated carbide tools when grooving wood-based materials: effect of work materials and coating materials on the wear resistance of coated carbide tools

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Abstract This paper presents the performance of coated carbide tools when grooving various density hardboards and wood-chip cement boards. Work materials of low density (about 0.8 g/cm^3) and high density (about 1.2 g/cm^3) were tested. The coating materials studied were chromium carbide, titanium carbonitride, and titanium carbide, which were synthesized on P30 carbide substrate using a chemical vapor deposition method; titanium nitride, chromium nitride, and titanium carbonitride were synthesized using the physical vapor deposition method. Cutting tests were performed during grooving at a cutting speed of 1000 m/min and a feed rate of 0.1 mm/rev. The results of the study show that the coated carbide tools are more advantageous in reducing the progression of tool wear and retaining lower normal force and noise level when cutting both hardboard and wood-chip cement board of high density than was the uncoated carbide tool. The wear rate of the coated carbide tools for the wood-chip cement board increased more rapidly than that of the hardboard with increasing densities. Though the coated carbide tools suffered more wear with the low-density wood-chip cement board than with hardboard, their normal force and noise level were always lower for the low-density wood-chip cement board.

Key words Coated carbide tool · Tool wear · Grooving · Hardboard · Wood-chip cement board

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Introduction

Fiberboard and particleboard are now made in large and increasing quantities in many countries. About 1.04 million and 0.76 million cubic meters of fiberboard and particleboard, respectively, were produced in Asian in 1997.[1] Recently, the use of the two materials has been increasing for building construction and for decorative purposes.

These materials are generally machined before being placed in service. In the woodworking industry, the cutting tools used for machining wood-based materials are usually cemented carbide tools, although use of these tools in some applications involving particleboard and fiberboard is limited because of their relatively high rate of wear.

A method to coat the surfaces of the carbide tool with a hard material has been developed to increase its resistance to wear. The coating materials presently available consist of titanium carbide (TiC), titanium nitride (TiN), titanium aluminum nitride (TiAlN), titanium carbonitride (TiCN), chromium nitride (CrN), chromium carbide (CrC), hafnium nitride (HfN), and diamond and diamond-like carbon (DLC).[2] The use of these coatings in metal machining has been successful, but their application to wood machining has provided mixed results.

Borided tungsten carbide (WC-6%Co) had lower cutting forces and less edge recession than untreated tungsten carbide during machining of medium-density fiberboard (MDF).[3] Another study showed that a slight improvement in resistance to wear of a commercial carbide tool coated with TiN, Ti(N,CN), or $TiAlN_2$ by a physical vapor deposition (PVD) method during machining of particleboard was limited to carbide grades of fine grain size with low cobalt content.[4] Furthermore, TiN coating synthesized on carbide substrate using a chemical vapor deposition (CVD) method did not improve the wear resistance during milling of particleboard, and TiC coating has shown only a slight improvement.[5]

Seemingly, these data indicate that the use of commercial carbide for wood cutting (K-grade carbide) as a substrate in coating materials with both PVD and CVD

Table 1. Specifications of tools

Tool	Coating method	Coating material	Deposition temperature (°C)	Hardness (HV)	Thickness of film (μm)
Carbide tool[a]	–	–	–	1450	–
	CVD	CrC	1000	1600	3–4
Coated carbide tool	CVD	TiC	1000	3800	3–4
	CVD	TiCN	1000	2600	3–4
Coated carbide tool	PVD	TiN	500	2000	3–4
	PVD	TiCN	500	3000	3–4
	PVD	CrN	500	1800	3–4

[a] Used only for cutting high density work materials

Table 2. Specification of work materials

Work material	Thickness (mm)	Density (g/cm^3)	Moisture content (%)	Compressive strength (N/mm^2)	Shear strength (N/mm^2)	Hardness (N/mm^2)
LD cement board	25	0.79	10.5	3.4	0.6	10.0
HD cement board	25	1.20	11.6	23.4	3.5	50.6
LD hardboard	25	0.81	8.1	110.8	0.7	33.8
HD hardboard	25	1.18	7.4	118.8	4.7	70.0

LD: low density; HD: high density

methods brings no advantage especially for machining particleboard. Therefore, searching for another grade of carbide compatible with the coating materials is important.

A P-grade carbide was studied here as a substrate by considering that P-grade carbides are better in terms of hardness and strength at high temperatures than are the high speed steel tools (SKH) and K-grade carbides.[2] Therefore, P-grade carbides are more resistant to substrate degradation caused by high temperatures during the coating process, which causes the coated P-grade carbides to become more resistant during delamination or chipping of the coating (or both) during the application.

Up to now the performance of coated carbide tools had been investigated separately when cutting work materials such as MDF,[3] particleboard,[4,5] wood-chip cement board,[6] or hardboard.[7] To evaluate application of coated carbide tools in the field of wood and wood-based material machining, it was thought necessary to study them with various work materials, including these with variations in density. Throughout this study, the carbide tools coated with TiN, CrN, and TiCN by the PVD method and with CrC, TiC, and TiCN by the CVD method were studied when grooving hardboard and wood-chip cement board. The purpose was to investigate the effect of coating materials, coating methods, work materials, and density of the work material on the wear characteristics of the coated carbide tools.

Materials and methods

Tools and work materials

General specifications of the tools tested, the wood-based materials machined, and the cutting conditions applied are shown in Tables 1–3. The carbide tools [81%WC, 9%(Ti,Ta)C, 10%Co] were 25 mm long, 5.2 mm wide, and 6.2 mm thick. A 72° wedge angle used in this experiment is now being commercially produced especially for cutting wood-chip cement board or hardboard. The carbide tools were coated with CrC, TiC, and TiCN by the CVD method and with TiN, CrN, and TiCN by the PVD method on both rake and clearance faces. All coated carbide tools were produced in a standard production line that coats cutting tools.

Table 3. Specification of cutting conditions

Cutting speed	1000 m/min
Feed	0.1 mm/rev
Width of cut	5.2 mm
Rake angle	10.0°
Side rake angle	2.5°
Clearance angle	8.0°
Side clearance angle	7.5°

Experimental setup

Cutting tests were performed during grooving, as shown in Fig. 1. A motor was placed on the table of the numerical controlled (NC) machine. A work material with a diameter of 300 mm was held on the faceplate of the motor and locked by screws. The axis of the faceplate was adjusted to a height 200 mm above the table. A tool was held rigidly in a tool holder, and the cutting tool edge was set at the height of the faceplate axis.

Cutting was started at a disk diameter of 290 mm. To minimize the effect of density along the thickness of the

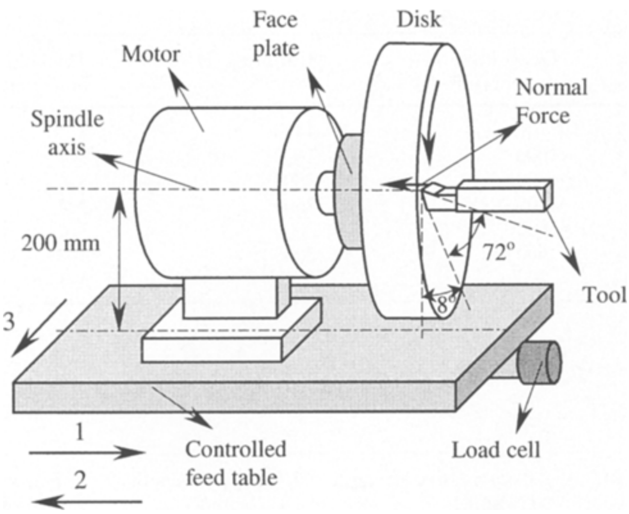

Fig. 1. Experimental setup. *1*, *2*, and *3* determine the feed orders of the table, respectively

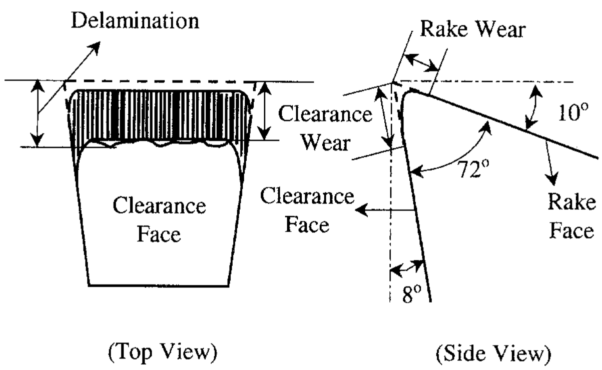

Fig. 2. Wear and delamination measurement

board, a 3 mm deep cut was made. When the cutting edge of the tool reached a depth of 3 mm, cutting was continued with a new cutting path at a distance of 5.2 mm inside the former, and the disk rotational speed was increased to maintain a constant cutting speed. Because the cutting length of one disk was about 300 m, the previous disk was replaced with a new disk to complete the required cutting length of 2 km.

Measurements

All tools were inspected before testing for any surface crack or defect of the coating on both the rake and clearance faces using an optical video microscope. The cutting was stopped at every specified length of cut, after which the delamination of the coating materials and the wear of the carbide substrate were measured along the rake and clearance faces of the tools. Wear and delamination were measured using the setup shown in Fig. 2. The tools were also inspected at the final cut using an optical video microscope and a scanning electron microscope (SEM) to identify the mode of the cutting edge failure.

A precision Sound Level Meter was used to measure the noise level of the cutting sound on the C scale. A microphone was placed at the height of the faceplate axis (about 1000 mm above ground level) and at a distance of about 200 mm along a straight line extending from the cutting tool edge.

The cutting force recorded was the normal (thrust) force component (Fig. 1). The cutting force was measured with a load cell attached on the table of the NC machine in such way that any pressure on the table would be detected by the load cell. The load cell was connected to a strain amplifier, and a GP-IB board was then used to record and display the force during cutting on a personal computer.

Results and discussion

Effect of coating materials on the wear resistance, normal force, and noise level of the coated carbide tools

The amount of tool wear and delamination, the normal force, and the noise level of the cutting sound were measured intermittently. From the results in Table 4, it appears that the amount of tool wear was greater along the clearance face than along the rake face while cutting 2 km of the work materials for almost all tools investigated. Though these was no major difference in performance among the coated carbide tools investigated while cutting the work materials of each density at the investigated cutting length, the amount of clearance wear of both PVD- and CVD-coated carbide tools tested was much lower than that of uncoated carbide tools while cutting high-density materials. However, the rake wear of the uncoated carbide tool was relatively the same as that of the CVD-coated carbide tools and slightly higher than that of the PVD-coated carbide tools.

By investigating the worn edges of the coated carbide tools under SEM, a relatively same pattern of tool wear was observed when cutting hardboards and wood-chip cement boards. For this discussion, SEM micrographs (Fig. 3) of the worn edge of the uncoated carbide tool, the CrC- and TiCN-coated carbide tools by the PVD method (P-TiCN), and the TiCN-coated carbide tool by the CVD method (C-TiCN) are shown after cutting 2 km of high-density hardboard. Figure 3a indicates that the wear of the uncoated carbide tool was mainly due to the abrasion (Ab) and ploughing (Pl) of carbide, which resulted in a rounded cutting edge. In Figs. 3b, 3c, and 3d delamination is least in the P-TiCN-coated carbide tool and is less in the C-TiCN-coated carbide tool than in the CrC-coated carbide tool. This fact and the fact that the wear is least in the P-TiCN-coated carbide tool and less in the C-TiCN-coated carbide tool than in the CrC-coated carbide tool suggest that the substrate (Sb) would be exposed to abrasion or ploughing (or both) during cutting after the coating material (CM) had disappeared.

The results in Table 4 indicate that PVD-coated carbide tools suffered less delamination than the CVD-coated car-

Table 4. Summary of tool wear and delamination, normal cutting force, and noise level at final cutting length (2000m)

Tools	Hardboard				Wood-chip cement board			
	Low density		High density		Low density		High density	
	Rake	Clearance	Rake	Clearance	Rake	Clearance	Rake	Clearance
CVD								
CrC	48/66[a]	62/105[a]	53/75	67/98	53/77	82/156	65/105	117/200
	34.2[b]	**107.5**[c]	*43.7*	**109.8**	*16.8*	**104.6**	*50.1*	**109.9**
TiC	43/68	58/106	52/84	65/89	47/97	67/89	52/86	97/124
	34.2	**107.4**	*43.9*	**109.4**	*14.6*	**103.6**	*49.7*	**109.6**
TiCN	43/61	57/75	48/69	61/101	45/75	59/83	49/80	89/135
	32.0	**105.1**	*42.6*	**108.1**	*13.1*	**102.7**	*44.0*	**108.8**
PVD								
TiN	41/60	54/62	45/65	59/95	42/56	61/77	50/67	90/107
	32.2	**106.3**	*42.8*	**108.2**	*13.2*	**103.4**	*43.7*	**109.2**
TiCN	40/50	50/61	40/56	52/78	41/44	56/70	45/67	88/94
	31.4	**106.8**	*42.1*	**109.8**	*13.3*	**104.4**	*44.1*	**109.3**
CrN	42/71	56/63	45/67	60/73	46/58	63/86	47/72	93/112
	33.7	**106.9**	*43.1*	**109.2**	*14.0*	**104.5**	*48.5*	**109.1**
Carbide	–	–	49	101	–	–	58	160
	–	–	*50.7*	**111.5**	–	–	*52.3*	**112.4**

[a] wear/delamination, in micrometers
[b] Normal cutting force, in Newton (in italics)
[c] Noise level, in decibels on the C scale (in boldface)

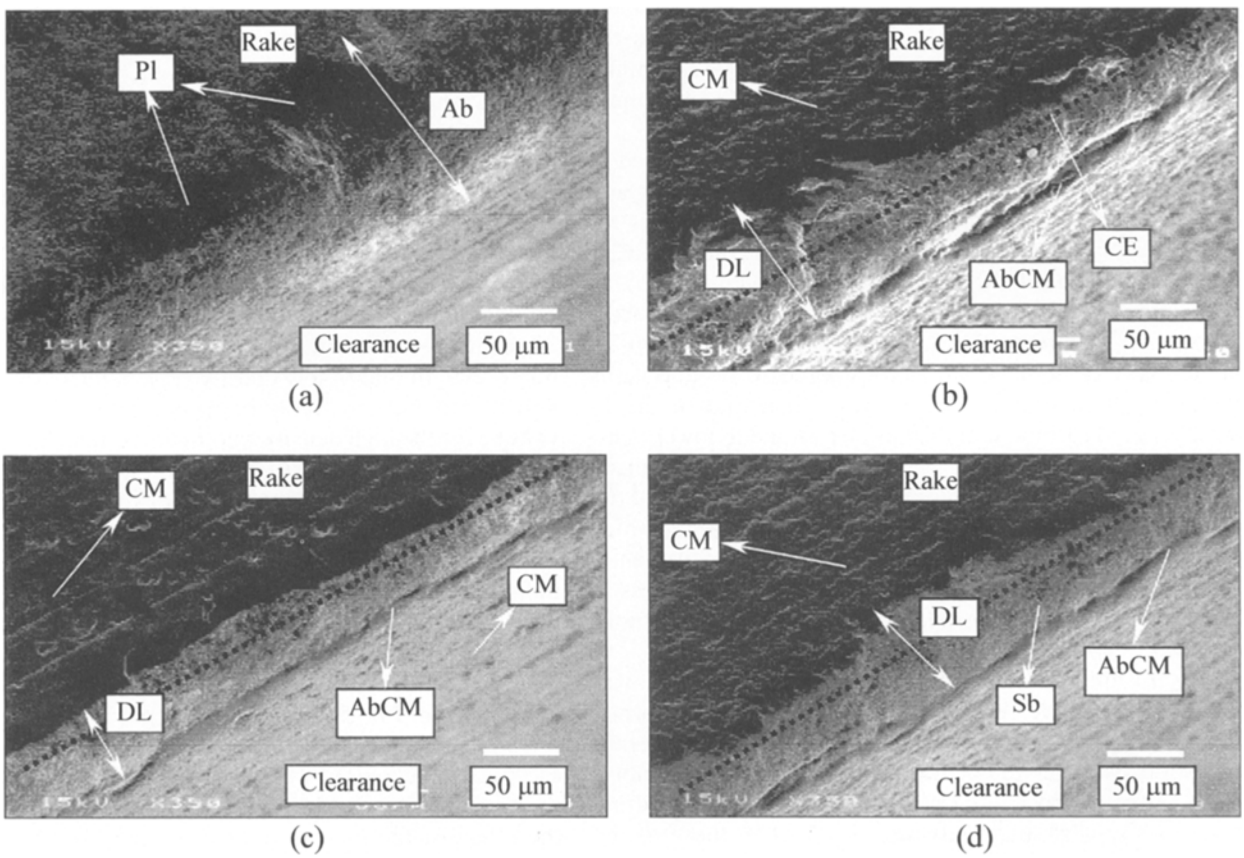

Fig. 3. Scanning electron microscopy micrograph of the worn edges of uncoated carbide tool (**a**) and CrC-coated (**b**), P-TiCN-coated (**c**), and C-TiCN-coated carbide (**d**) tools when cutting high-density hardboard at the final cutting length. *CE*, cutting edge; *Ab*, abrasion; *Pl*, ploughing; *DL*, delamination; *CM*, coating material; *Sb*, substrate; *AbCM*, abrasion of coating material

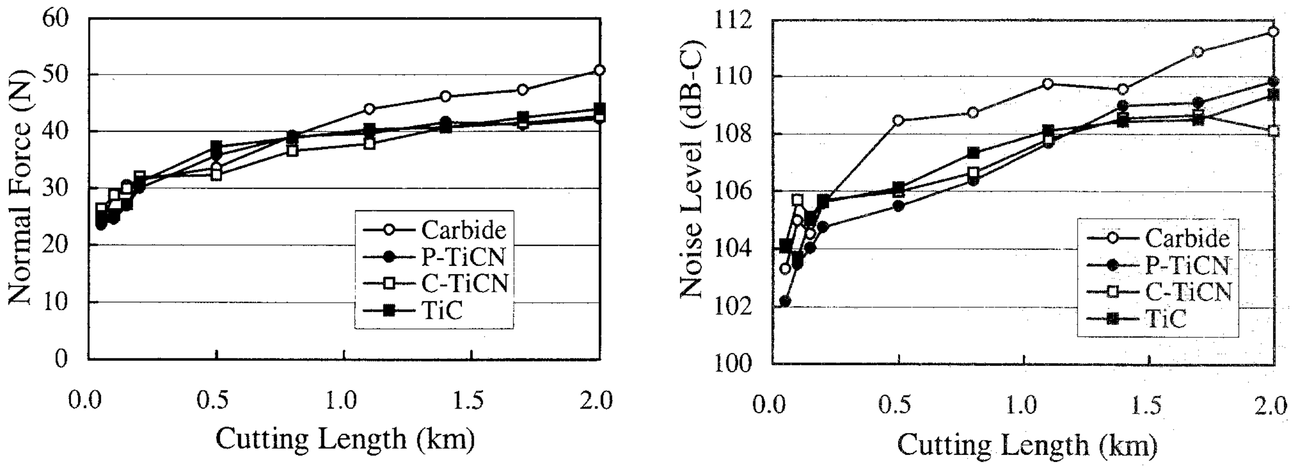

Fig. 4. Variation in normal force (**left**) and noise level (**right**) of the uncoated carbide and three of the coated carbide tools with cutting length when cutting hardboard of high density

bide tools while cutting the work materials, except for the clearance face of the TiN- and CrN-coated carbide tools while cutting high-density hardboard and low-density wood-chip cement board, respectively. However, when the amount of delamination along the rake face and along the clearance face in each coated carbide tool is combined, clearly the PVD-coated carbide tools are better than the CVD-coated carbide tools for protecting against delamination while cutting both hardboard and wood-chip cement board.

When the P-TiCN-coated carbide tool was compared to the C-TiCN-coated carbide tool, the amount of wear and delamination for all work materials machined was less for the P-TiCN-coated carbide tool than for the C-TiCN-coated tool (Table 4; Figs. 3c, 3d). This behavior is probably due to the differences in hardness and the coating process of the two materials. The lesser hardness of the C-TiCN-coated carbide tool, which is considered to be due to its deposition temperature being higher than that of the P-TiCN-coated carbide tool (Table 1), resulted in lower resistance to abrasion. This high temperature was also reported to cause more degradation of the carbide substrate and the formation of brittle phases in the interface layer,[8,9] which decreases the tool's toughness and causes detrimental effects. Therefore, selecting a proper coating process is important for minimizing delamination to prolong the tool's life.

The results in Table 4 indicate that although there was not a considerable difference in noise level and normal force among the coated carbide tools investigated in regard to various work materials, the normal force and the noise level generated by the coated carbide tools while cutting high-density work materials were lower than those of the uncoated carbide tool. Furthermore, the normal force and the noise level generated by the tools increased in proportion with an increase in cutting length, and the uncoated carbide tool showed the highest levels especially near the end of the cutting (Fig. 4). Therefore, the coated carbide tools are considered to be more advantageous than uncoated carbide tools, not only in terms of wear resistance but also in the noise level and normal force with increasing cutting length for high-density work materials.

Effect of density of work materials on wear resistance, noise level, and normal force of coated carbide tools

Figure 5 shows the effect of density on the amount of wear, normal force, and noise level of P-TiCN-coated carbide tools while cutting 2km of hardboards and wood-chip cement boards. It appears that both the rake and the clearance wear tend to increase with an increase in the density of the work materials. This behavior was found to be more marked on the clearance face than on the rake face. The clearance wear of the P-TiCN-coated carbide tool was 32μm greater when cutting high-density wood-chip cement board than in that of low density (Fig. 5, left). This is probably due to more materials being present in a given cutting volume for the high density wood-chip cement board; moreover, the mechanical strengths are higher in the high-density wood-chip cement board (Table 2). It may also relate to the fact that the higher the density in the work materials the more is the abrasiveness,[10] which leads to more abrasion while cutting. However, only a slight difference in clearance wear, which could be caused by almost the same compressive strength (Table 2), was observed when cutting hardboard of low and high density (Fig. 5, right).

As seen in Fig. 5 (left), it also appears that the normal force and the noise level generated by the P-TiCN-coated carbide tool increased with an increase in the density of the wood-chip cement board. This result is thought to be due to the effect of the increased wear attained by the P-TiCN-coated carbide tool when cutting high-density wood-chip cement board than that of low density and to the higher strength of the high-density wood-chip cement board (Table 2). Though there was not a considerable difference in wear when cutting hardboards of low and high density using the coated carbide tool, slight differences in normal

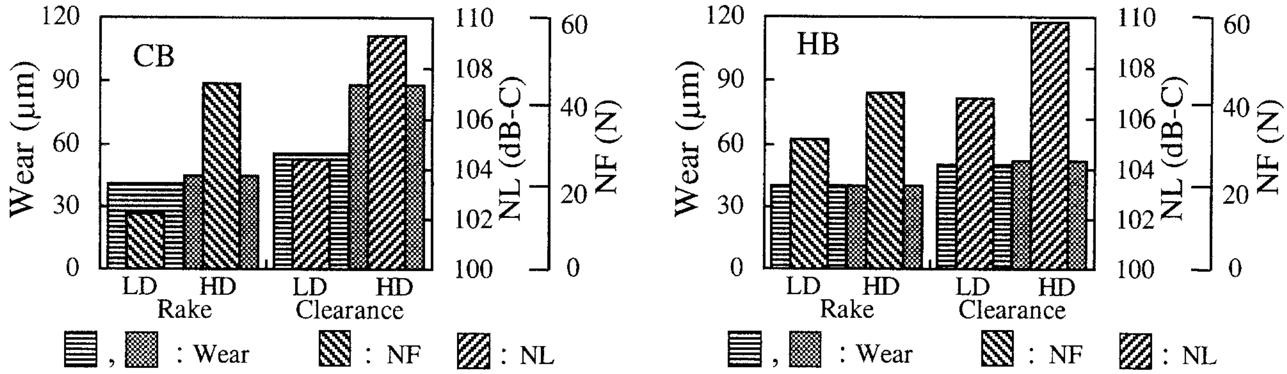

Fig. 5. Wear of the P-TiCN-coated carbide tool and its variation in normal force and noise level when cutting wood-chip cement board (**left**) and hardboard (**right**) of low and high density, respectively, at the final cutting length. *NF*, normal force; *NL*, noise level; *LD*, low density; *HD*, high density; *HB*, hardboard; *CB*, wood-chip cement board

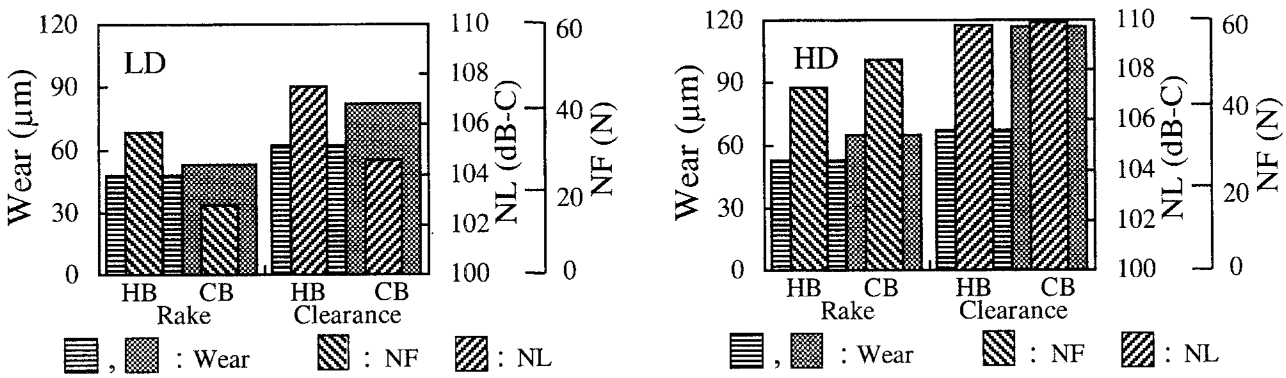

Fig. 6. Wear of the CrC-coated carbide tool and its variation in normal force and noise level when cutting the work materials of low-density board (**left**) and high-density board (**right**), respectively, at the final cutting length. *NF*, normal force; *NL*, noise level; *LD*, low density; *HD*, high density; *HB*, hardboard; *CB*, wood-chip cement board

force and noise level were observed, probably due to the difference in shear strength and hardness (Table 2) between the low- and high-density hardboard. Based on the results in Table 4, almost the same phenomenon as was shown for the P-TiCN-coated carbide tool would be seen with the other coated carbide tools.

Effect of work materials on wear resistance, noise level, and normal force of the coated carbide tools

The results in Table 4 and Fig. 6 indicate that although the two work materials that were grooved had almost the same density their amount of wear, normal force, and noise level were different. The amount of wear attained by the CrC-coated carbide tool was observed to be greater for the wood-chip cement board than for the hardboard of the same density. The difference was more prominent on the clearance face than on the rake face. The differences in clearance wear were about 20μm and 50μm for cutting work materials of low density (Fig. 6, left) and high density (Fig. 6, right), respectively. These differences are thought to be due to two factors: First, the wood-chip cement boards of low or high density (Figs. 7a, 7a1, respectively) contain a large amount of hard-particle cement (PC), which means they cause more abrasion of the cutting tool than does

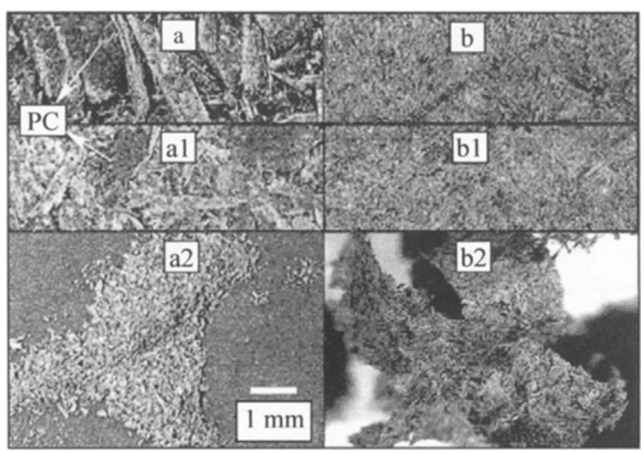

Fig. 7. Photomicrograph of the work materials and their chip formations. **a** Low-density wood-chip cement board. **a1** High-density wood-chip cement board. **a2** Chips of wood-chip cement board. **b** Low-density hardboard. **b1** High-density hardboard. **b2** Chip of hardboard. *PC*, hard particle of cement

hardboard during the cutting process. The harmful effect of the hard particles of cement is considered to be same as that of silica found in wood[11] or that of cured formaldehyde resin in particleboard,[12] which causes the cutting tool to wear out

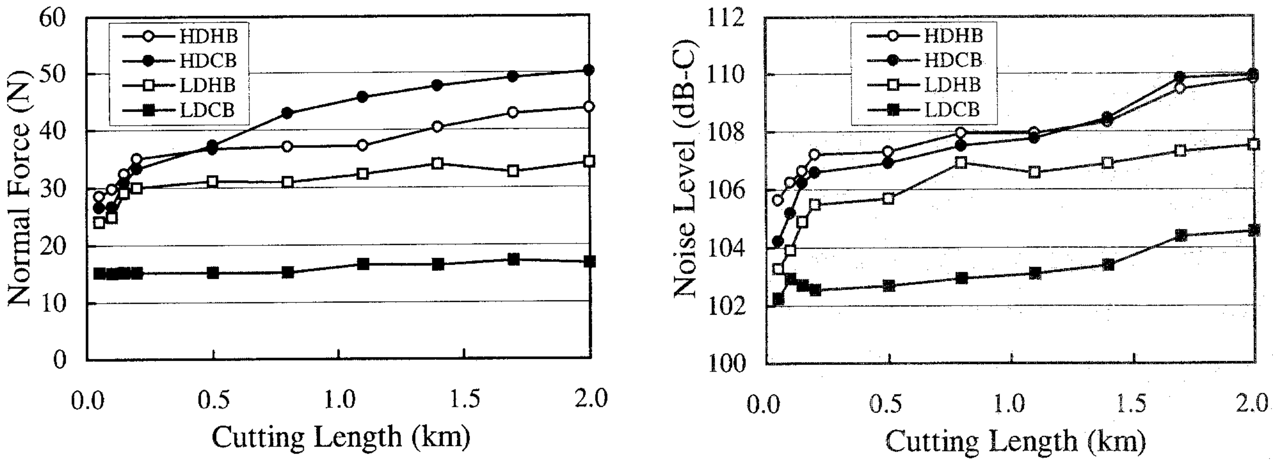

Fig. 8. Variation in normal force (**left**) and noise level (**right**) of the CrC-coated carbide tool with cutting length in different density hardboard and wood-chip cement board. *HDHB*, high-density hardboard; *HDCB*, high-density wood-chip cement board; *LDHB*, low-density hardboard; *LDCB*, low-density wood-chip cement board

rapidly. Second, the fine dust (Fig. 7a2) produced while cutting wood-chip cement board of both in low and high density is sometimes embedded and dragged onto the surfaces of the cutting tool, whereas the chips (Fig. 7b2) produced while cutting hardboard of both low (Fig. 7b) and high (Fig. 7b1) density escape freely up the rake face and cause less abrasion. Based on the results in Table 4, the same phenomenon seen with the CrC-coated carbide tool would seemingly be found with the other coated carbide tools investigated.

Based on the results in Fig. 6 (left), although the CrC-coated carbide tool exhibited more wear when cutting low-density wood-chip cement board than with low-density hardboard, the normal force and noise level generated while cutting low-density wood-chip cement board were much lower. At a cutting length of 2km, the CrC-coated carbide tool generated a normal force when cutting low-density wood-chip cement board that was almost half than seen when cutting low-density hardboard; moreover, the noise level generated by the CrC-coated carbide tool with low-density wood-chip cement board was lower by around 3 decibels on the C scale (dB-C) than when cutting low-density hardboard.

As seen in Fig. 8, the normal force and noise level of the CrC-coated carbide tool when cutting low-density wood-chip cement board were always lower than when cutting low-density hardboard, from the start of cutting up to a cutting length of 2km. This is thought to be due to the fact that the low-density wood-chip cement board (Fig. 7a) is much more porous, with lower compressive strength and hardness (Table 2), than low-density hardboard (Fig. 7b), which is more solid in structure, has higher compressive strength, and is harder. The results in Fig. 8 (left) indicate that the normal force of the CrC-coated carbide tool when cutting low-density wood-chip cement board appeared to be constant, though its wear and delamination increased with the cutting length. The reason of this phenomenon should be clarified in future research. Again, when the results in Table 4 are considered, this phenomenon should be also found in the other coated carbide tools.

Different normal forces and noise levels were observed when the CrC-coated carbide tool cut materials of high density: The CrC-coated carbide tool at a cutting length of 2km suffered not only more wear but also a slightly higher normal force (although relatively the same noise level) when cutting high-density wood-chip cement board than when cutting high-density hardboard (Fig. 6, right). However, as seen in Fig. 8, at or near the beginning of cutting the CrC-coated carbide tool generated slightly less normal force and a lower noise level when cutting high-density wood-chip cement board than when cutting high-density hardboard, probably because high-density wood-chip cement board is of lower strength than high-density hardboard (Table 2). Therefore, the normal force and noise level at a cutting length of 2km, as described above, is probably due to the larger amount of wear seen with the CrC-coated carbide tool when cutting high density wood-chip cement board than when cutting high-density hardboard at that cutting length.

Conclusions

Based on the results presented above, the following conclusions were reached.

1. Coated carbide tools, whose performances are almost the same, are superior to uncoated carbide tools for reducing the progression of tool wear, normal force, and noise level when cutting hardboard and wood-chip cement board of high density, based on our findings with the investigated tools and at the investigated cutting length.

2. Wear of the coated carbide tools depends largely on delamination of the coating materials, and the PVD-coated carbide tools are better than the CVD-coated carbide tools for protecting against delamination.

3. The tools tested suffer more wear when cutting wood-chip cement board than when cutting hardboard of the same density.

4. The rate of wear of the coated carbide tools increases more precipitously with the wood-chip cement board than with hardboard with an increase in their respective densities.

5. The normal force and noise level of the coated carbide tools are always lower for low-density wood-chip cement board than for low-density hardboard, though the wear is always more marked for the low-density wood-chip cement board.

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