ORIGINAL ARTICLE

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Performance of coated carbide tools in turning wood-based materials: Effect of cutting speeds and coating materials on the wear characteristics of coated carbide tools in turning wood-chip cement board

Received: May 24, 2000 / Accepted: October 10, 2000

Abstract This paper reports on the performance of coated carbide tools in turning wood-chip cement board. The coating materials studied were titanium carbonitride (TiCN), titanium nitride (TiN), chromium nitride (CrN), and titanium nitride/aluminum nitride (TiN/AlN), which were synthesized on the P30 carbide substrate. The aim is to investigate the effect of coating materials and cutting speeds on the wear characteristics of the coated carbide tools. Cutting tests were performed when turning wood-chip cement board at cutting speeds of 30, 40, 50 and 60 m/s, a depth of cut of 1 mm, and a feed of 0.05 mm/rev. The results of the study show that the coated carbide tools provided better performance than the P30 carbide tool, especially in terms of reducing the progression of the wear rate and clearance wear. The TiN/AlN-coated carbide tool showed the smallest increase in both wear rate and clearance wear with an increase in cutting speed and had the longest tool life among the coated carbide tools investigated. Though the TiCN-coated carbide tool was observed to have a low wear rate and low clearance wear for cutting speeds of 30 and 40 m/s, when the cutting speeds were >50 m/s its wear rate and clearance wear were almost the same as those of CrN- and TiN-coated carbide tools, which had high values for these parameters.

Key words Coated carbide tool · Tool wear · Wear rate · Cutting speed · Wood-chip cement board

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Part of this paper was presented at the 21st IUFRO World Congress, August 2000, Kuala Lumpur, Malaysia

Introduction

Machining wood-based materials such as particleboard or wood-chip cement board causes cutting tools to wear out much faster than when machining solid wood. Rapid dulling of the cutting edge of the steel router bits, saw teeth, or other cutting tools when machining particleboard is a well-known occurrence. Furthermore, the use of tungsten carbide tools (widely used in the secondary wood-working industry) for cutting wood-based materials is also limited because of the relatively high rate of wear.

Coating the surfaces of carbide tools with a hard material has been tried to increase the life of the carbide tool. Coating materials widely synthesized on the surfaces of the carbide tool are titanium carbonitride (TiCN), titanium nitride (TiN), chromium nitride (CrN), titanium nitride/aluminum nitride (TiN/AlN), hafnium nitride (HfN), titanium carbide (TiC), chromium carbide (CrC), diamond-like carbon (DLC), and diamond.[1,2] Up to now, researching suitable coating materials and substrate combinations, especially for machining wood-based materials, has been important work.

The superiority of P30 carbides coated with TiN, TiCN, and CrN by a physical vapor deposition (PVD) method was reported for cutting hardboards and wood-chip cement boards at low cutting speed.[3,4] It was also noted that the coated carbide tools were found to suffer more delamination and wear when cutting wood-chip cement board than when cutting hardboard. When considering that the wood-based materials such as wood-chip cement board are machined using a circular saw at high cutting speed, investigation of the machining behaviors of the coated carbide tools for high speed cutting of the wood-chip cement board is important to study. Therefore, TiN, CrN, TiCN, and TiN/AlN coating materials synthesized on the P30 carbide tool by the PVD method were evaluated for high speed turning of wood-chip cement board of high density to investigate the effect of coating materials and cutting speeds on the wear characteristics of the coated carbide tools.

Table 1. Specifications of the coated carbide tools

Tool and coating material	Thickness of film (μm)	Hardness (HV)	Resistance to oxidation temperature (°C)	Rate of heat conduction[5] ($Ws^{1/2}/m^2K$)
P30 carbide				
Coated carbide				
–	–	1450	NA	NA
TiN	3–4	2000	750	8 100
CrN	3–4	1800	800	NA
TiCN	3–4	3000	450	13 900
TiN/AlN	3–4	4000	930	6 300

NA, not available; TiN, titanium nitride; CrN, chromium nitride; TiCN, titanium carbonitride; TiN/AlN, TiN/aluminum nitride

Table 2. Specifications of the work material (high-density) wood-chip cement board

Thickness	25 mm
Density	1.20 g/cm^3
Moisture content	11.6%
Hardness	50.6 N/mm^2
Composition	
Wood chips	25 wt%
Cement	75 wt%

Table 3. Cutting conditions for the carbide tools

Cutting speed (V)	30, 40, 50, 60 m/s
Feed (F)	0.05 mm/rev
Depth of cut (D)	1.0 mm
Tool geometry	
Wedge angle	90°
Corner radius	0.8 mm

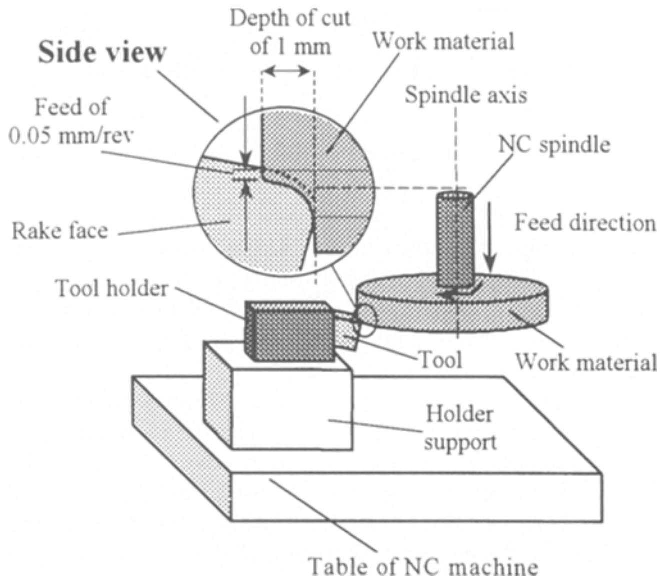

Fig. 1. Experimental setup. *NC*, numerically controlled

Experimental procedure

Coated tools and work materials

Specifications of the coated tools tested, the work material machined, and the cutting conditions applied are shown in Tables 1–3. The P30 carbide tool [81%WC, 9%(Ti,Ta)C, 10%Co] was 12.7 mm long, 12.7 mm wide, and 4.8 mm thick with a wedge angle of 90° and a rake angle of −5°. This geometry, which provides a strong edge, is now being commercially produced especially to prevent chipping of the cutting edge when performing high-speed machining of high-density wood-chip cement board, which consists of about 75 wt% of hard particles of cement (Table 2). The P30 carbide tools were coated with the single layer of TiN, CrN, or TiCN and alternating multiple layers of TiN/AlN coatings by the PVD method on the rake and clearance faces. All the coated carbide tools for this experiment were produced in a standard production line for coated cutting tools.

Experimental setup

Cutting tests were performed in turning as shown in Fig. 1. The work material, with a diameter of 300 mm, was held on the router spindle of a numerically controlled (NC) machine. A tool with its holder was placed on the holder support, which was held on the table of the NC machine. The holder support was positioned in such way that the corner of the cutting edge was right to the axis of the router spindle.

Turning was performed by the corner of the cutting edge along the edge of the disk with a 1 mm deep cut. The disk was fed down into the corner of the cutting edge with a feed of 0.05 mm per revolution (Fig. 1). When the corner of the cutting edge finished one pass of cutting (cutting from the bottom to the top face of the disk with a cutting length of about 500 m), the amount of tool wear was measured on the clearance face of the corner of the tool. Turning of the work material was then continued, increasing the disk rotational speed and feed speed to maintain a constant cutting speed. Testing was stopped after 10 passes of cutting (cutting length of about 5000 m).

Measurements

All tools were inspected before testing to ensure that there were no surface cracks or chipping of the coating materials on the rake and clearance faces using an optical video microscope. The clearance wear was measured using a

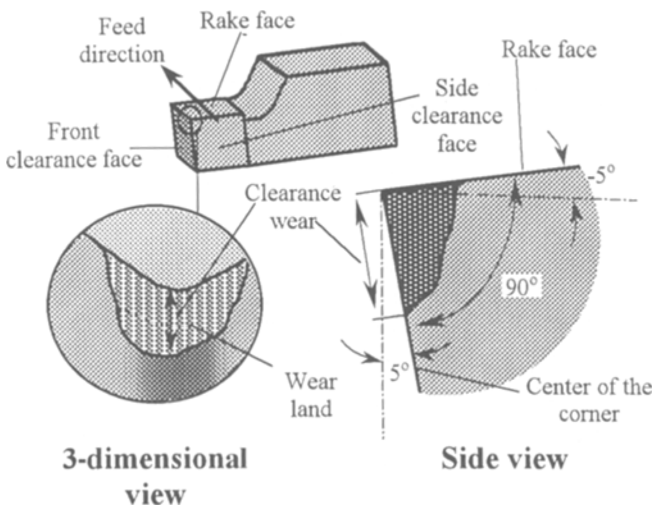

Fig. 2. Clearance wear measurement

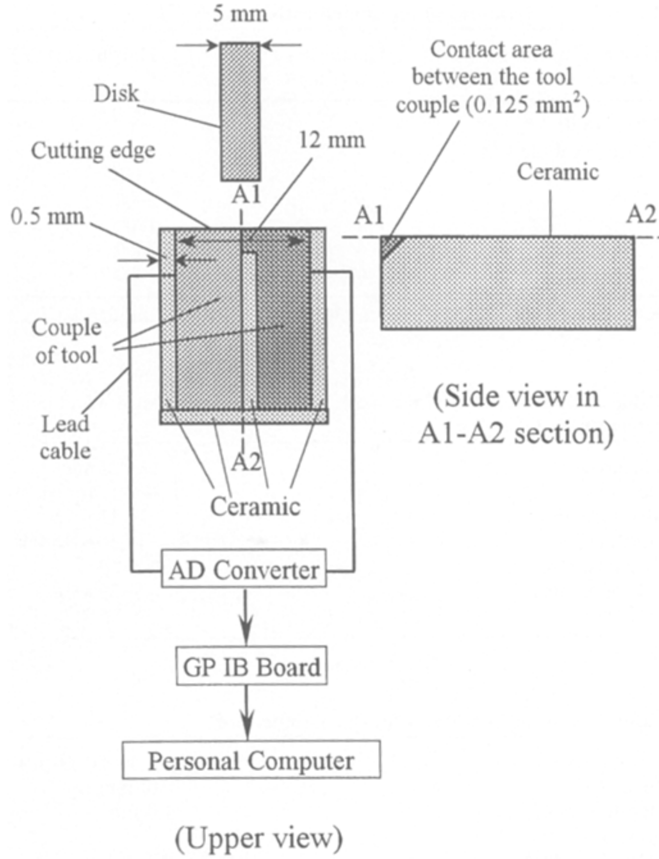

Fig. 3. Thermal electromotive force (EMF) measurement. *AD*, Aanalog to digital; *GP IB*, General purpose interface bus

measurescope, as shown in Fig. 2. The tools were also inspected at the final cut using scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS) to identify the mode of the cutting edge failure and to map the residual elements of the worn surfaces.

Cutting tool temperatures were determined by measuring the thermal electromotive force (EMF) between a pair of cutting tools. The couple used in this experiment was the K10 and cermet cutting tools. Considering that the tool temperature increases with decreasing contact area, and any fracture during the preparation of the couple is easy to generate especially when the contact area is small, a contact area of about 0.125 mm^2 (Fig. 3) was prepared between the couple. Each was connected to an AD converter using a lead cable, and a GP IB board was used to display the thermal EMF on a personal computer. To measure the thermal EMF, orthogonal cutting of some work materials was performed using the couple. Work materials were prepared in a disk with a diameter of 300 mm and thickness of 5 mm. The orthogonal cutting was performed on the edge of the disk. The conditions of the cutting are shown in Tables 4 and 5. To obtain a stable EMF to measure the cutting tool temperature, a sharp edge of the couple was maintained during the testing; and to minimize the effect of heat conducted from the couple on the lead cables 3 s of cutting was performed using the couple. A new couple was used for each cutting speed and work material combination. Furthermore, the values of the thermal EMF were converted to temperature values using the thermal EMF temperature calibration chart derived from the couple.

The work material is one of the important factors that affect the temperature of the cutting tool, leading to wear. Cutting tool temperatures were observed to vary among the work materials tested, as presented in Fig. 4. It appears that the difference in cutting tool temperature among the work materials was small at low cutting speeds and was higher when the cutting speed was increased.

Comparing the work materials in Fig. 4, high-density wood-chip cement board generated the highest cutting tool

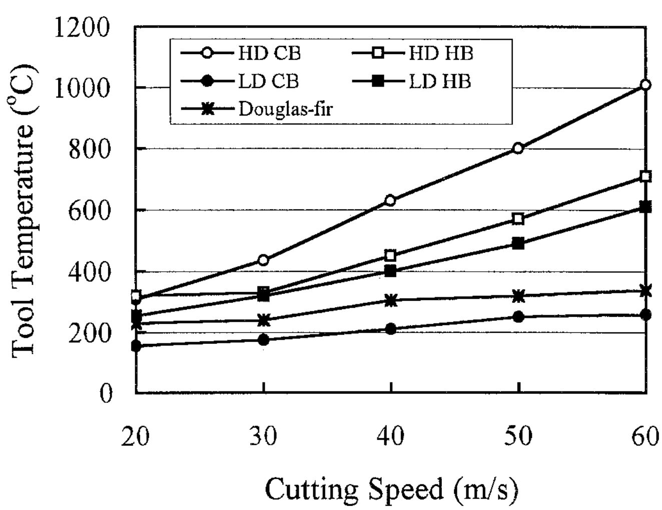

Fig. 4. Cutting tool temperatures as a function of the cutting speeds and work materials. HDCB, high-density wood-chip/cement board; *HDHB*, high-density hardboard; *LDCB*, low-density wood-chip/cement board; LDHB, low-density hardboard. Conditions: depth of cut (D) 0.05 mm; width of cut (W) 5 mm; cutting period 3 s. tools were K10 and cermet

Table 4. Conditions for the thermal electromotive force measurement

Work material	Thickness (mm)	Density (g/cm^3)	Moisture content (%)
HD cement board	5	1.20	11.6
HD hardboard	5	1.18	8.1
LD cement board	5	0.79	10.5
LD hardboard	5	0.81	7.4
Douglas fir	5	0.32	11.0

HD, high density; LD, low density
Tool couple: K10 carbide and cermet (−5° rake angle, 5° clearance angle, 90° wedge angle)

Table 5. Cutting conditions for thermal electromotive force measurement

Cutting speed (V)	20, 30, 40, 50, 60 m/s
Depth of cut (D)	0.05 mm
Width of cut (W)	5 mm
Contact area between the couple	0.125 mm^2
Cutting period (S)	3

Table 6. Wear rate of the tools investigated at four cutting speeds

Tool	Wear rate (μm/min) at cutting speeds 30–60 m/s			
	30	40	50	60
P30 carbide	47.8	118.0	167.9	276.5
CrN-coated carbide	37.3	112.9	159.8	241.5
TiN-coated carbide	35.0	76.6	163.3	242.7
TiCN-coated carbide	24.2	61.6	164.5	276.1
TiN/AlN-coated carbide	25.7	33.4	47.4	52.2

Conditions: F, 0.05 mm/rev; D, 1 mm; work material (WM), high-density cement board (HDCB)

Table 7. Exponent n and constant C of the Taylor tool life equation ($VT^n = C$)

Tools	Exponent n	Constant C
P30 carbide	0.33	47.3
CrN-coated carbide	0.34	49.6
TiN-coated carbide	0.36	54.6
TiCN-coated carbide	0.29	54.7
TiN/AlN-coated carbide	0.73	132.0

Conditions: F, 0.05 mm/rev; D, 1 mm; criterion, 200 μm; WM, HDCB; V, 30, 40, 50, 60 m/s

temperature. Therefore, it was chosen as the work material for investigating the wear characteristics of the coated carbide tools in this study.

Results and discussion

Behavior of clearance wear

The results of the turning experiment are presented in Tables 6 and 7, and in Figs. 5–8. Figure 5 shows the progression of the clearance wear with cutting time at four cutting speeds for all the tools investigated. Almost the same clearance wear behavior was observed for all the tools investigated. It appears that the differences in the clearance wear among the cutting speeds were not marked at the beginning of cutting; greater differences in clearance wear developed, however, and followed an approximately linear increase in wear with cutting time. Therefore, clearance wear rates, which were characterized by the coefficients of the linear regression equation, were calculated using Fig. 5; the results are summarized in Table 6. Behaviors of clearance wear of the tools investigated with cutting speeds at 1.3 min of cutting time, which were also calculated from the linear regression equations in Fig. 5, are presented in Fig. 6.

The results in Table 6 and Fig. 6 indicate that the higher wear rate and greater clearance wear, respectively, were seen with almost all tools investigated when higher cutting speeds were used. Comparable differences in these values were observed for all the tools investigated. The values for the coated carbide tools were better than those for the P30 carbide tool. This fact is thought to be due to the coated carbide tools being harder than the P30 carbide tool, which resulted in their being more resistant to mechanical abrasion than the P30 carbide tool.

SEM/EDS indications of wear patterns of coated carbide tools

Although the TiCN-coated carbide tool had the lowest wear rate and clearance wear for a cutting speed of 30 m/s (Table 6, Fig. 6), its values increased drastically and matched those of the CrN- and TiN-coated carbide tools when the cutting speed was >50 m/s. Therefore, the TiCN-coated carbide tool is suitable at low cutting speeds. This phenomenon is thought to depend on the TiCN-coated carbide tool being able to retain its hardness at low cutting speeds, and that it probably escapes oxidation, as indicated by the EDS image in Fig. 7e (left) when there is no oxygen observed in its coating film, because the cutting tool temperature (Fig. 6, right) was observed to be still under its oxidation temperature (Table 1). The same phenomenon was observed for the CrN- and TiN/AlN-coated carbide tools for the 30 m/s cutting speed, as shown in Fig. 7d (left) and 7f (left), respectively.

The drastic increase in these values for the TiCN-coated carbide tool at >50 m/s cutting speed is thought to be due to the fact that the cutting tool temperature (Fig. 6, right) exceeded its oxidation temperature (Table 1). This high temperature was observed to cause severe oxidation of the TiCN coating, which can be seen in the EDS image in Fig. 7e (right). It can be seen in Fig. 7e that plentiful oxygen is present on the coating film near the delamination line of the TiCN-coated carbide tool. This leads us to believe that the TiCN-coated carbide tool suffered thermal degradation. As the result, severe delamination of the TiCN coating occurred at high cutting speeds, indicated by the narrower abrasion band of coating material (Fig. 7b) compared to that of the TiN/AlN-coated carbide tool (Fig. 7c). Further-

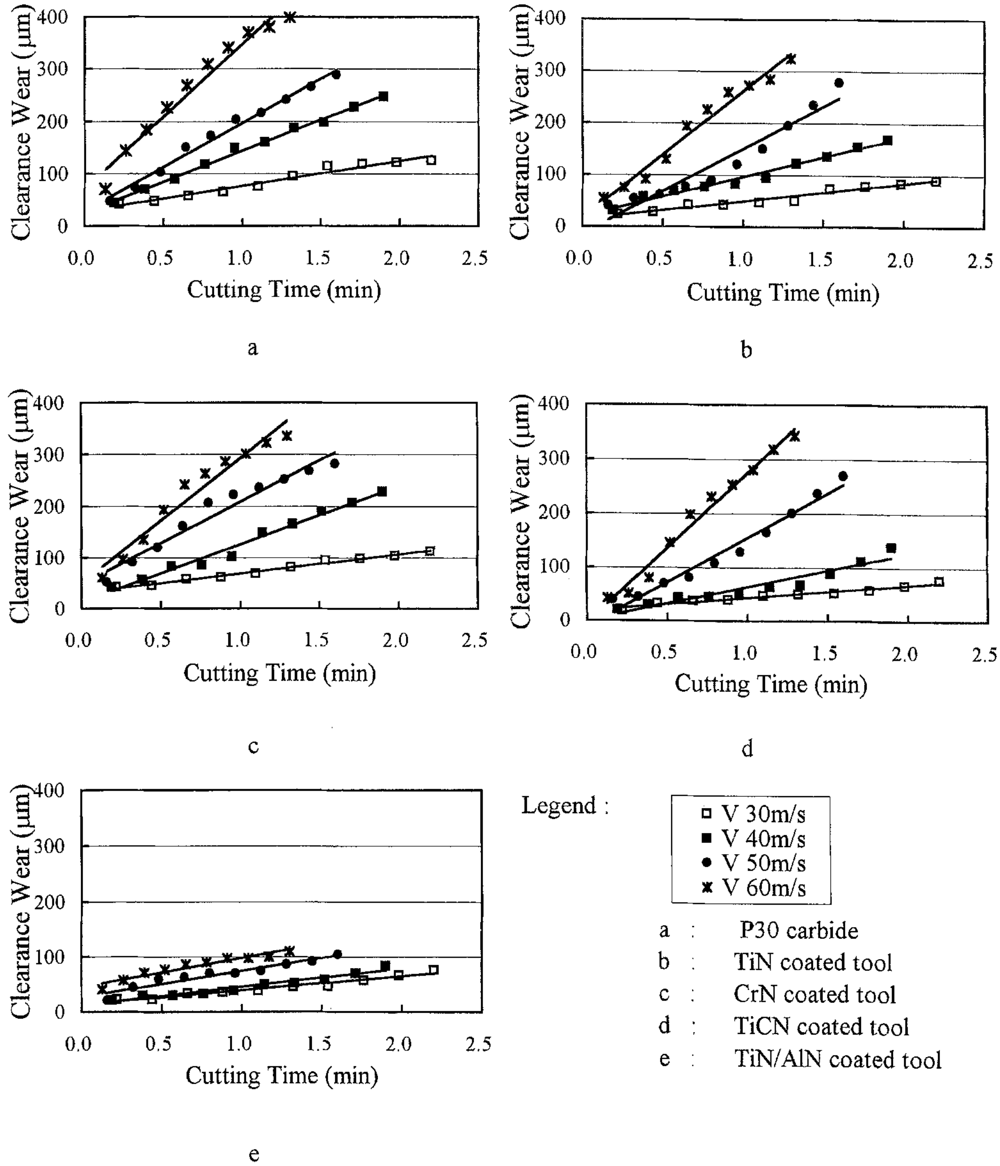

Fig. 5. Clearance wear progress curves with cutting time for all tools investigated at four cutting speeds. Conditions: feed (F) 0.05 mm/rev; D 1 mm; work material (WM), HDCB

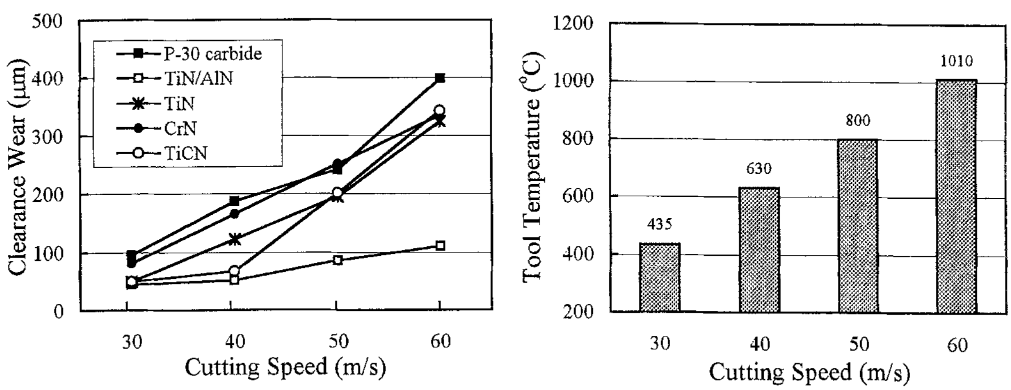

Fig. 6. Behaviors of the clearance wear of the tools tested with cutting speed at 1.3-min cutting time. **Left** Conditions: F 0.05 mm/rev; D 1 mm; T 1.3 min; WM, HDCB. **Right** Conditions: D 0.05 mm; W 5 mm; cutting period 3 s; WM, HDCB. Tools were K10 and cermet

more, the hardness decreased at 800°C. The hardness of the TiCN coating was reported to be about 1100 HV at 800°C.[6] These data suggest that the wear rate and clearance wear of the TiCN-coated carbide tool were accelerated by oxidation of its coating film and the decreased hardness due to the high temperature.

It is thought, moreover, that the hardness of the substrate underneath decreases rapidly at temperatures as low as 600°C,[7] and that the TiCN coating has a high rate of heat conduction (Table 1), which allows much heat to conduct and concentrate in the substrate. Therefore, cutting temperatures of about 800° and 1010°C determined at 50

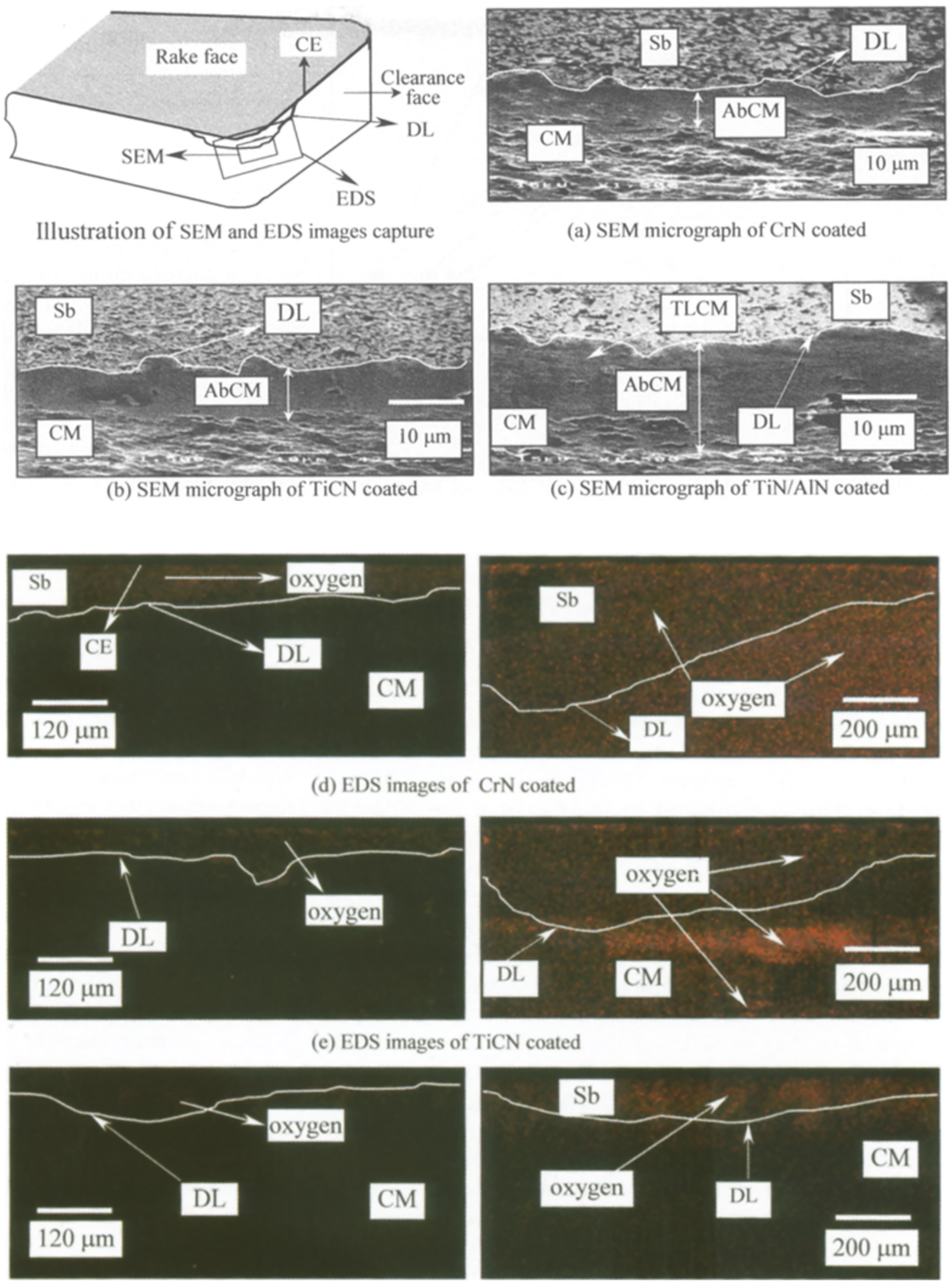

Fig. 7. Scanning electron microscopic (*SEM*) micrographs (**a–c**) of the chromium nitride (CrN)-, titanium carboritride (TiCN)-, and titanium nitride/aluminum nitride (TiN/AlN)-coated carbide tools for 60 m/s cutting speed and their emergy dispersive spectroscopy (EDS) images for 30 m/s (**d–f left**) and 60 m/s (**d–f right**) cutting speed. *Red dots* indicate the presence of oxygen. *AbCM*, abrasion band of coating material; *CM*, coating material; *Sb*, substrate; *DL*, delamination line; *CE*, cutting edge; *TLCM*, thin layer of coating film. Conditions: F 0.05 mm/rev; D 1 mm; WM, HDCB; cutting length 5 km

and 60 m/s cutting speeds, respectively (Fig. 6, right) are thought to be responsible for the damage to the substrate due to a severe loss of hardness. The hardness of P grade carbide (10% Co/84% WC) was reported to be about 600 HV at 800°C and 500 HV at 900°C.[7]

The same patterns of wear as seen with the TiCN-coated carbide tool were also observed in the CrN-coated (Fig. 7a,d, right) and TiN-coated carbide tools, which had a high wear rate and high clearance wear at 50 and 60 m/s cutting speeds (Table 3; Fig. 6, left). Therefore, the CrN- and TiN-coated carbide tools are believed to follow the behaviors of the TiCN-coated carbide tool explained above. The CrN- and TiN-coated carbide tools also had high values at cutting speeds of 40 m/s (Table 3; Fig. 6, left). Although the 630°C cutting tool temperature for the 40 m/s cutting speed (Fig. 6, right) was under the oxidation temperature (Table 1), this temperature is thought to decrease the hardness, which further weakens resistance to mechanical abrasion. This suggestion is confirmed by the fact that the hardness of the TiN-coated carbide tool decreased with an increase in temperature, and its hardness at 600° and 800°C was about 850 and 625 HV, respectively.[6]

In contrast, the TiN/AlN-coated carbide tool showed the smallest increase in these values with an increase in cutting

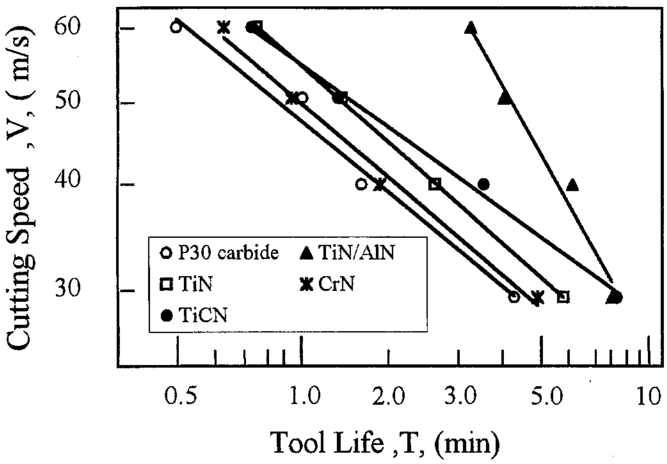

Fig. 8. Tool life and cutting speed relations for all tools investigated. Conditions: F 0.05 mm/rev; D 1 mm; WM, HDCB; tool life criterion 200 μm

speed among the tools investigated (Table 6; Fig. 6, left). Its values at a cutting speed of 60 m/s were almost equal to or lower than those at 40 m/s for the other tools investigated. This result suggests that the TiN/AlN-coated carbide tool allows a wider range of cutting speed during its application. Furthermore, in regard to the suitability of a substrate, the P30 carbide tool is probably a better choice for the TiN/AlN coating. This is attributed to the fact that the TiN/AlN coated on P30 carbide can resist delamination and chipping, as indicated by its wider abrasion band of coating material where a thin layer of coating film still covered the substrate (Fig. 7c), whereas the other coated carbide tools we investigated had narrower abrasion bands of the coating material without a thin layer of coating film, as shown in Fig. 7a,b.

The thin layer of coating film found in the wider abrasion bands of coating material of the TiN/AlN-coated carbide tool for the 60 m/s cutting speed (Fig. 7c) suggests that the TiN/AlN coating film strongly binds with the carbide substrate underneath it and protects the substrate from wear. It is attributed to the alternating multiple layers of thin TiN and AlN (2.5 nm each) that produced the harder coatings, which in turn improved its resistance to mechanical abrasion. Although the cutting temperature for the 60 m/s cutting speed exceeded its oxidation temperature, it was observed that almost no oxidation occurred on its coating film (Fig. 7f, right), which would lead to thermal degradation. This is considered to be due to the alternating multiple layers in which the AlN coating provided a barrier that resisted chemical interaction.[6] Moreover, the TiN/AlN-coated carbide tool has a high degree of hardness and low rate of heat conduction (Table 1). Because of this superiority, it retains heat in the surfaces and retards conduction of heat to the substrate. This behavior leads to retention of the hardness of the substrate and so protects the substrate from wear. This pattern and the patterns of wear presented above suggest that delamination of the coating materials and wear of the substrate were caused primarily by mechanical abrasion due to loss of hardness and partly by high-temperature oxidation, which were accelerated by the increased cutting temperature. Therefore, coating materials synthesized on the substrate should have a high degree of hardness, high oxidation temperature, and low rate of heat conduction (low heat conductivity).

Tool life

Choosing a given tool life criterion of 200 μm clearance wear, a corresponding tool lifetime for each cutting speed can be found in Fig. 5 and is plotted in log scales in Fig. 8. The tool life exponent n and constant C in the Taylor tool life equation were calculated based on the log cutting time (T)/log cutting speed (V) plots. The results are shown in Table 7.

Experimental results presented in Table 7 show that values of n vary slightly among the tools investigated. It is well known that the Taylor tool life model is used to explain the differences in the wear mechanism. It is known that the tool life exponent n, with a value of unity, presents a relatively same wear mechanism, in which $n = 1$ determines the wear of the cutting tool due to mechanical abrasion. Therefore, the value of the tool life exponent for cutting wood-chip cement board shown in Table 7 gives an indication that the tools investigated had slightly different wear mechanisms. The values of n of the TiN/AlN-coated tool in Table 7, which is approximately 1, suggest that its wear was determined mainly by mechanical abrasion with only a small contribution by the chemical reaction (oxidation), as discussed above. It appears that the lives of the TiCN-, TiN-, and CrN-coated carbide tools and the P30 carbide tool well strongly affected by the cutting speeds or indirectly by the cutting tool temperature (Fig. 8). This phenomenon indicates that these tools suffered more severe chemical reaction than the TiN/AlN-coated carbide tool. The results in Table 7 indicate that the TiCN-coated tool suffered the most severe chemical reaction followed by the P30 carbide tool and the CrN- and TiN-coated carbide tools. Furthermore, comparison of the value of C in Table 7 indicates that the TiN/AlN-coated carbide tool has the longest life and the P30 carbide tool the shortest. Specifically, the cutting speed for 1 min of tool life for the TiN/AlN-coated carbide tool is predicted to be 132.0 m/s followed by those coated with TiCN (54.7 m/s), TiN (54.6 m/s), and CrN (49.6 m/s), and the P30 carbide tool (47.3 m/s).

Conclusions

The following conclusions can be drawn based on the findings of this study. (1) Coated carbide tools are superior because of their slower wear rate and their wear resistance compared to the P30 carbide tool. (2) The TiCN-coated carbide tool was excellent in terms of its wear rate and wear resistance for low-speed machining, whereas the TiN/AlN-coated carbide tool had a superior wear rate and wear resistance for both low- and high-speed machining and had the longest tool life among the coated carbide tools investigated. (3) Delamination of the coating film and wear of the substrate of the coated carbide tools were primarily caused by mechanical abrasion with a small contribution made by the chemical reaction at low cutting speeds. There was a much larger contribution by the chemical reaction at high cutting speeds except for the TiN/AlN-coated carbide tool.

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