Wear Characteristics of Multilayer-Coated Cutting Tools when Milling Particleboard

Wayan Darmawan Hiroshi Usuki Istie S. Rahayu
Christian Gottlöber Rémy Marchal

Abstract

This article presents the characteristics of delamination wear on the clearance face of newly coated K10 cutting tools when milling particleboard. The K10 cutting tools were multilayer coated with titanium aluminum nitride (TiAlN)/titanium silicon nitride (TiSiN), TiAlN/titanium boron nitride (TiBN), and TiAlN/chromium aluminum nitride (CrAlN). Particleboard with a density of 0.61 g/cm^3 was cut using the multilayer-coated tools and a monolayer-coated (TiAlN) tool. Cutting tests were performed at a high cutting speed of 41.8 m/s and a feed rate of 0.2 mm/rev to investigate the delamination wear on the clearance face of these coated tools. Experimental results showed that the newly multilayer-coated tools experienced a smaller amount of delamination wear than the monolayer-coated tool when milling the particleboard. The best multilayer coating was TiAlN/CrAlN; that tool only suffered a slight chipping on the cutting edge at a cutting length of 1 km. The high hardness, low coefficient of friction, high resistance to oxidation, and high resistance to delamination wear of the multilayer-coated TiAlN/CrAlN tool indicate a very promising applicability of this coating for high-speed cutting of abrasive wood-based materials.

Particleboard is made in large and increasing quantities in many countries. Recently, the use of particleboard has been increasing for building construction and decorative purposes. In the secondary wood manufacturing industry, where wood-based material such as particleboard is machined extensively, tool wear is an important economic parameter. Therefore, investigating wear characteristics will lead to making better choices of cutting tool materials used to cut wood-based material.

Machining of particleboard causes cutting tools to wear out much faster than machining of solid woods. Rapid dulling of the steel cutting edge of router bits, saw teeth, or other knives/blades when machining particleboard is a well-known phenomenon. The use of tungsten carbide tools for cutting particleboard has been limited because of the relatively high rate of wear caused by high-temperature oxidation and abrasion (Stewart 1992, Sheikh-Ahmad and Bailey 1999). Thus, an effort to coat the surfaces of the carbide cutting tool with a hard material has been made to increase the wear resistance of the carbide tool.

Some coatings that have been commercially produced consist of a monolayer of titanium carbide (TiC), titanium nitride (TiN), titanium aluminum nitride (TiAlN), titanium carbonitride (TiCN), chromium nitride (CrN), chromium carbide (CrC), or diamond-like carbon. These coatings have been commercially used in the metal-working industry with good results (Banh et al. 2004). However, their applications for wood-based material machining, which involves high-speed cutting, are limited because of the occurrence of coating film delamination.

In a previous study (Salje and Stuehmeier 1988), K10 tungsten carbide inserts were coated with TiN and TiC films by the chemical vapor deposition method and then used for cutting particleboard. Those authors noted that the TiN coating brought no advantages in the milling of particleboard; in other words, the edge life attained or the total tool paths were not longer than those attained using uncoated cutting edges. A TiC-coated tungsten carbide tool was also reported to show large edge fractures after a short time of operation. In a study by Sheikh-Ahmad and Stewart (1995), K grades of tungsten carbide tools were coated with TiN, TiN/TiCN, and TiAlN by the physical vapor deposition

The authors are, respectively, Associate Professor, Bogor Agric. Univ., Bogor, Indonesia (wayandar@indo.net.id); Professor, Shimane Univ., Matsue, Japan (usuki@riko.shimane-u.ac.jp); Assistant Professor, Bogor Agric. Univ., Bogor, Indonesia (istiesr@yahoo.com); Associate Professor, Technische Univ. Dresden, Dresden, Germany (christian.gottloeber@tu-dresden.de); and Professor, ParisTech, Cluny, France (remy.marchal@cluny.ensam.fr). This paper was received for publication in November 2010. Article no. 10-00059.
©Forest Products Society 2010.
Forest Prod. J. 60(7/8):615–621.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

(PVD) method for continuous milling of particleboard, and those authors noted that a slight improvement in wear resistance was provided by coatings that were synthesized to carbide grade with fine grain size (0.8 μm) and low cobalt content (3%). In contrast, coatings applied to carbide grade with higher cobalt content and coarse grain size decreased the wear resistance of the tools. The primary failure mode for the PVD coatings tested in that work was chipping of coatings on the rake face. This was caused by inadequate adhesion of coating over the tool surfaces because of improper substrate and coating combination.

In a study by Fuch and Raatz (1997), TiN, titanium aluminum oxide nitride (TiAlON), and TiC coatings were synthesized on the surface of tungsten carbide (93.5% tungsten carbide [WC], 5% Co, 1.5% tantalum carbide and niobium carbide [TaC/TaB]) by plasma-assisted chemical vapor deposition for milling laminated particleboard. Those authors noted that TiN- and TiAlON-coated carbide tools did not provide any improvement in wear resistance compared with the uncoated carbide tool and that the TiC-coated carbide tool provided only a slight improvement. Darmawan et al. (2001) reported that the wear of TiN, CrN, CrC, TiCN, and TiAlN coatings when cutting wood-chip cement board resulted from delamination of the coating film at both low- and high-cutting speeds. Among the coatings tested in that study, TiAlN exhibited the lowest occurrence of delamination. For high-speed cutting, delamination of these coating films was caused by oxidation, which was accelerated by an increase in cutting temperature.

The findings of the studies discussed above indicate that the monolayer coatings did not provide significant improvement in the cutting tool life for high-speed cutting of wood-based materials. Therefore, ongoing research is proposed to achieve better performance of the coated carbide tools when cutting these materials. Multilayer coatings would be a promising technique to improve the performance of monolayer coatings. Therefore, TiAlN coating, which is high in hardness, good in oxidation resistance, and better in wear resistance than the other monolayer coatings, was multilayered in the present study with the newest-generation coatings of titanium boron nitride (TiBN), titanium silicon nitride (TiSiN), and chromium aluminum nitride (CrAlN), which have been noted to keep excellent properties (high hardness, low friction coefficient, and high oxidation and corrosion resistances; Ding et al. 2006, Chang et al. 2007). These multilayer coatings were applied to the surface of K10 tungsten carbide using the PVD method, and the newly coated (TiAlN/TiBN, TiAlN/TiSiN, and TiAlN/CrAlN) tools were experimentally investigated for their possible use in machining particleboard. The purpose of this study was to investigate the clearance wear characteristics of these tools in the high-speed cutting of particleboard.

Materials and Methods

Multilayer-coated cutting tools and work materials

General specifications of the multilayer-coated cutting tools tested and the particleboard machined are shown in Tables 1 and 2, respectively. The K10 carbide tool (94% WC, 6% Co) that was selected as a substrate was 16 mm long, 16 mm wide, and 6.2 mm thick. The hardness of the K10 was measured to be 1,400 HV. The 65° wedge angle used in this experiment is now being commercially produced especially for cutting wood-based materials. The K10 carbides were coated with a monolayer coating of TiAlN and multilayer coatings of TiAlN/TiBN, TiAlN/TiSiN, and TiAlN/CrAlN by the PVD method on both rake and clearance faces. The multilayer coatings were deposited onto the surface of K10 in a thickness of 3 μm (1.5 μm of TiAlN coating above the substrate and 1.5 μm of TiBN, TiSiN, or CrAlN above the TiAlN layer; Table 1).

Table 1.—Specifications of the coated carbide tools tested.[a]

Coating material	Film thickness (μm)	Hardness (GPa)	Oxidation temperature	Friction coefficient
TiAlN	3	28	Start at 600°C	0.91
TiAlN/TiBN	3	44	Start at 700°C	0.56
TiAlN/TiSiN	3	35	Start at 700°C	0.61
TiAlN/CrAlN	3	38	Start at 800°C	0.45

[a] Film thickness, hardness, oxidation temperature, and friction coefficient values were measured according to ASTM B568 (ASTM International 2009b), ASTM E2546 (ASTM International 2009a), ASTM G111 (ASTM International 2006), and ASTM G99 (ASTM International 2010), respectively.

Table 2.—Specifications of the particleboard machined.

Characteristic[a]	Value
Thickness (mm)	12
Moisture content (%)	8
Density (g/cm^3)	
Average	0.61
Outer part	0.73
Inner part	0.51
Ash content (%)	
Average	12.15
Outer part	16.5
Inner part	8.61
Silicate content (%)	
Average	1.86
Outer part	2.65
Inner part	1.24

[a] Ash and silicate contents were measured according to TAPPI T211 om-85 (TAPPI 1991).

Experimental setup

The cutting test was set up on the numerical controlled (NC) router as shown in Figure 1. The particleboard samples were prepared in rectangular form (12 by 100 by 150 mm). A piece of particleboard was placed on the table of the NC router and locked by screws. A cutting tool edge was held rigidly in a tool holder with a cutting circle diameter of 32 mm. The milling conditions are shown in Table 3.

Cutting was performed along the edge of the board and with spindle rotation set in the clockwise direction. The movement of the board during cutting was controlled by feeding directions of the table as shown in Figure 1. The first feeding direction caused the board to be edged in a down-milling action, and the third feeding direction caused the board to be edged in an up-milling action. To understand the effect of density along the thickness of the board, a 6-mm-cut depth (3 mm for the outer part and 3 mm for the inner

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

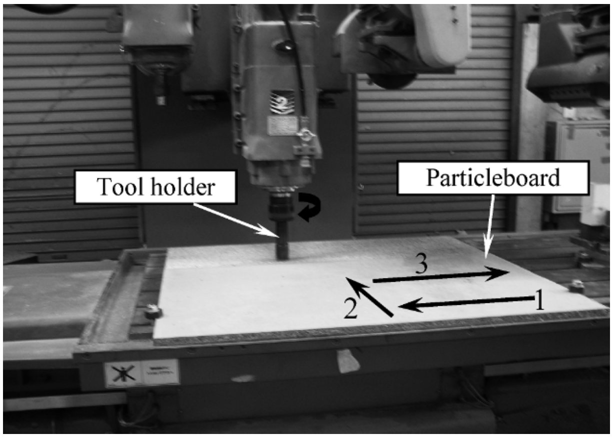

Figure 1.—Photograph of milling on the edge of the particleboard. The values of 1, 2, and 3 determine the feed order of the NC table.

Table 3.—Milling conditions.

Variable	Condition
Cutting speed (m/s)	41.8
Feed (mm/rev)	0.2
Spindle speed (rpm)	25,000
Feed speed (mm/min)	4,000
Width of cut (mm)	2
Depth of cut (mm)	6
Diameter of cutting circle (mm)	32
Rake angle (°)	8
Clearance angle (°)	7

part) was used. Density of the inner part of the board was 0.51 g/cm^3, and that of the outer part of the board was 0.73 g/cm^3.

Measurements

The coated tools were inspected with an optical video microscope before testing to ensure that no surface cracks and defects of coating film were on the rake and clearance faces. The cutting was stopped at every specified length of cut (100 m), at which point delamination of the coating film was measured along the clearance faces of the tools. Measurements of delamination wear on the clearance faces were made using an optical video microscope as shown in Figure 2. The tools were also inspected after the final cut using scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS) for identification of the mode of cutting-edge failure and occurrence of oxidation.

Results and Discussion

Delamination wear behaviors on clearance faces of the coated tools are provided in Figure 3. The results indicate that the amount of delamination wear increased with increasing cutting length. The multilayer-coated tools provided better performance, especially in reducing the progression of delamination wear, than the monolayer-coated (TiAlN) tool when cutting particleboard. Though the monolayer- and multilayer-coated tools showed almost the same delamination progress near the beginning of cutting, the delamination wear of the monolayer-coated tool

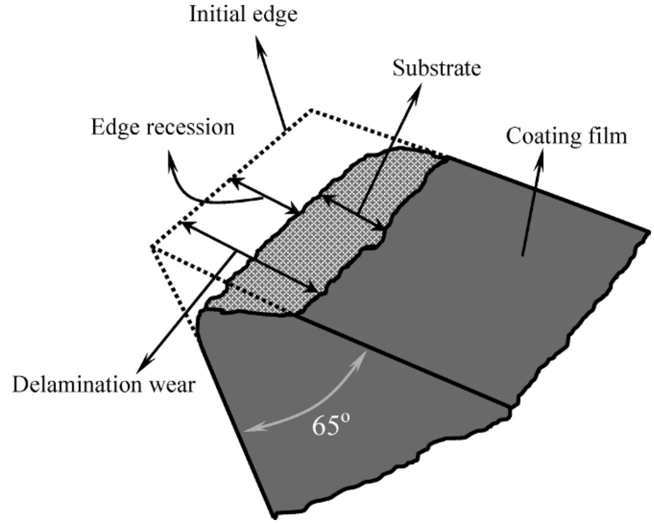

Figure 2.—Schematic diagram of delamination wear measurement on the clearance face of the cutting tool.

increased markedly and exceeded the delamination wear of the multilayer-coated tools, which showed only gradual progression of delamination during cutting of the particleboard. The monolayer-coated cutting tool suffered delamination wear of about 122 μm for cutting the outer part of the particleboard and about 60 μm for the inner part of the particleboard at the 1-km cutting length. On the other hand, the delamination wear of the multilayer-coated tools was less than 100 μm for the outer part of the particleboard and less than 50 μm for the inner part of the particleboard at the 1-km cutting length. The lower hardness, lower oxidation resistance, and higher friction coefficient of the monolayer-coated tool compared with the multilayer-coated tools (Table 1) would be the reason for this phenomenon.

It also appears from the results shown in Figure 3 that the outer part of the board (Fig. 3b) caused a higher amount of delamination wear compared with the inner part of the board (Fig. 3a). The progress of delamination wear shown in Figure 3 can be described as a linear function (Table 4). Regression coefficients for the linear functions determine the rate of the delamination wear (micrometers per kilometer) of the coated tools. The outer part of the particleboard caused delamination of TiAlN, TiAlN/TiBN, and TiAlN/TiSiN coatings 1.8 times faster than the inner part of the board (Table 4). The outer part of the particleboard usually contains a higher dosage of thermosetting resin (resolcinol or urea formaldehyde, in most cases) than the inner part. This is one of the main reasons for the increased tool wear when milling the outer part of particleboard. Furthermore, as depicted in Figure 4, the structure of the inner part of the board was more porous than that of the outer part. This could be considered as another reason that more materials are machined at a given cutting volume for the outer part of the board. The ash and silicate contents of the outer part were larger than those of the inner part of the board (Table 2), and the higher silicate content in the outer part imposed higher abrasion during the cutting. However, no delamination wear was observed for the multilayer-coated TiAlN/CrAlN tool in cutting both the outer and inner parts of the particleboard.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

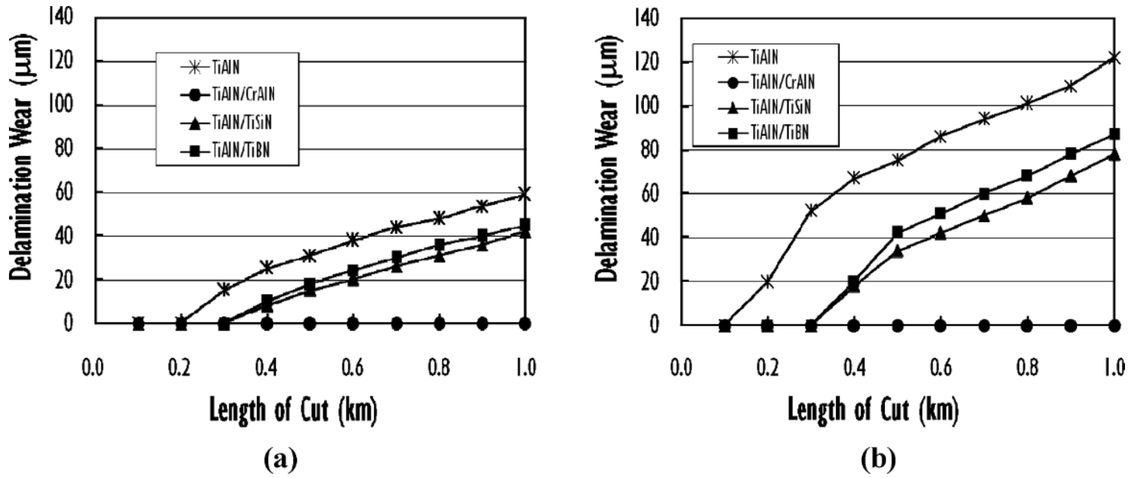

Figure 3.—Delamination wear behaviors of the newly coated tools with cutting length when milling the (a) inner part of the particleboard and the (b) outer part of the particleboard.

Table 4.—Linear regression equations and correlation coefficients for determining the rate of delamination wear according to Figure 3.[a]

Coated tool	Linear equation	r
In milling inner part of particleboard		
TiAlN	$y = 68.97x - 6.53$	0.98
TiAlN/TiBN	$y = 56.42x - 10.73$	0.98
TiAlN/TiSiN	$y = 51.15x - 10.33$	0.98
TiAlN/CrAlN	—	—
In milling outer part of particleboard		
TiAlN	$y = 124.73x + 4.00$	0.96
TiAlN/TiBN	$y = 102.90x - 19.33$	0.97
TiAlN/TiSiN	$y = 92.27x - 17.60$	0.98
TiAlN/CrAlN	—	—

[a] r = correlation coefficient; y = delamination wear; x = cutting length.

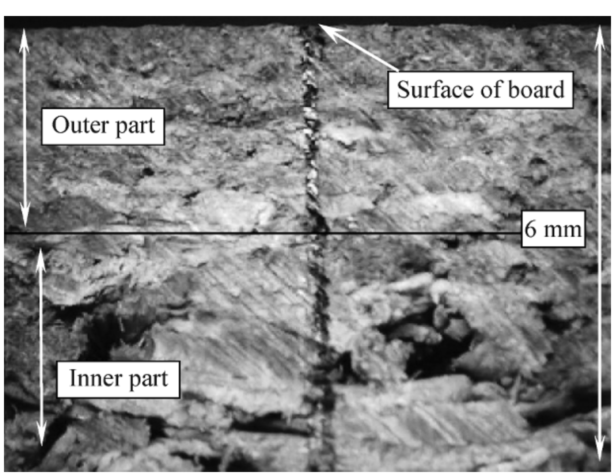

Figure 4.—Photograph showing the structure of the particleboard along the thickness.

The results shown in Figures 3 and 5 indicate that the multilayer-coated TiAlN/CrAlN tool had the highest resistance to delamination wear compared with the multilayer-coated TiAlN/TiSiN and TiAlN/TiBN tools when cutting particleboard. The TiAlN/CrAlN tool did not suffer any delamination of the coating film up to a cutting length of 1,000 m. The cutting edge of the TiAlN/CrAlN tool suffered slight chipping of the coating film at a cutting length of 800 m, and it retained the slight chipping up to the final cutting length of 1 km without any delamination of coating film (Fig. 5). The high delamination wear resistance of the TiAlN/CrAlN tool is considered to result from the following reasons. First, the friction coefficient of the multilayered TiAlN/CrAlN coating was lower than that of TiAlN, TiAlN/TiBN, and TiAlN/TiSiN coatings, which led to less abrasion against the hard abrasive materials contained in the particleboard. The hard abrasive materials in the particleboard consisted mainly of cured resin and silicate (Table 2), which generate harmful effects on the edge of the coated cutting tool. Second, oxidation temperature data shown in Table 1 and EDS results shown in Figure 6, which were produced by mapping the oxygen element from SEM micrographs of the edges of the coated tools before and after cutting, suggest a better oxidation resistance by the multilayered TiAlN/CrAlN coating compared with the TiAlN, TiAlN/TiBN, and TiAlN/TiSiN coatings. Higher peaks of oxygen profiles depicted by TiAlN, TiAlN/TiBN, and TiAlN/TiSiN on the EDS analysis in Figure 6b indicate the occurrence of more severe oxidation on these coatings. This phenomenon could be confirmed by a previous result in which delamination of monolayer coatings (TiN, TiAlN, TiCN, and CrN) in high-speed cutting of wood-chip cement board was caused by a higher contribution of oxidation (Darmawan et al. 2001). The oxidation was reported to be accelerated by the increase in cutting temperature up to 800°C as a result of an increase in cutting speed above 30 m/s. A possible high temperature generated during high-speed cutting of particleboard in the present study would oxidize the TiAlN-, TiAlN/TiBN-, and TiAlN/TiSiN-coated carbide tools, which in turn would lead to the severe delamination of coating films as a result of thermal degradation.

Investigating worn edges of the coated tools under an optical video microscope showed similar delamination mechanisms of coating films when cutting particleboard. Figure 7 depicts the mechanism of delamination of the TiAlN/TiSiN coating, which is selected for discussion in

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

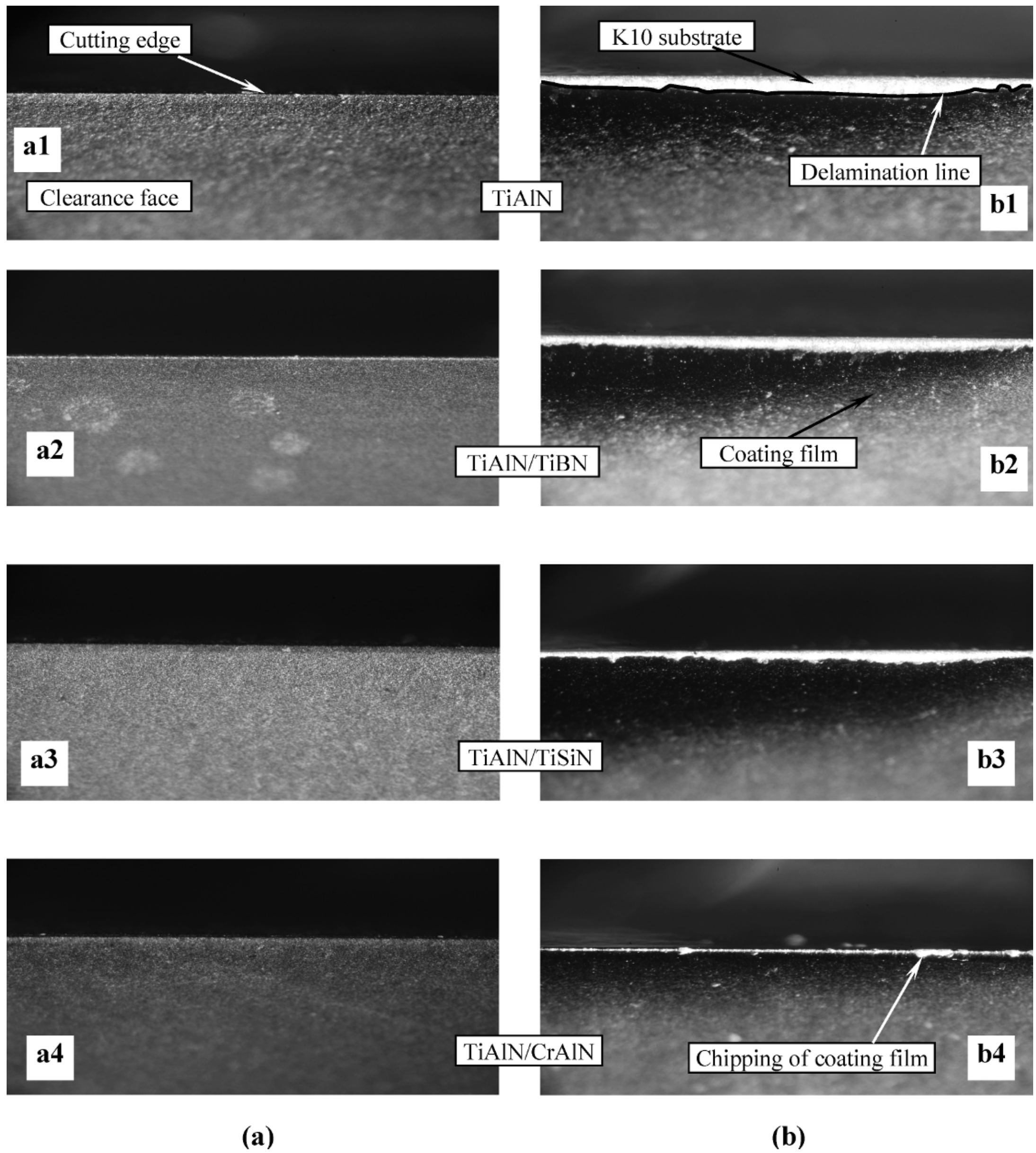

Figure 5.—Wear patterns of the coated cutting tools (a) before cutting and (b) after a cutting length of 1 km.

this article. Delamination of the TiAlN/TiSiN coating was preceded by slight chipping of the coating film at the cutting edge. The extent of chipping was found to increase at a cutting length of 200 m. As the cutting continued up to a length of 300 m, the cutting edge underwent more prominent chipping of the coating film. Chipping of the coating film occurred on the whole cutting edge as the cutting length reached 400 m. Furthermore, the TiAlN/TiSiN coating gradually delaminated in proportion along the cutting edge as the cutting action continued beyond 400 m. We consider that the wear of the K10 substrate occurred as the TiAlN/TiSiN films were removed from the substrate.

The SEM micrographs of the worn edges of the TiAlN-, TiAlN/TiSiN-, TiAlN/TiBiN-, and TiAlN/CrAlN-coated tools when cutting the particleboard for a 1-km cutting length are shown in Figure 8. These micrographs reveal that the patterns of edge wear generated by TiAlN, TiAlN/TiSiN, and TiAlN/TiBiN were relatively the same. Though severe delaminations were generated by the TiAlN-, TiAlN/TiSiN-, and TiAlN/TiBiN-coated carbide tools, delamination did not occur in the TiAlN/CrAlN-coated carbide tool. This suggests that the substrate of the TiAlN-, TiAlN/TiSiN-, and TiAlN/TiBiN-coated tools would be exposed to any possible mechanical abrasion, which causes retraction of tungsten carbide grains from the substrate during cutting (Figs. 8a through 8c). Retraction of carbide grains was reported to cause a corrugated cutting edge, which tends to produce rough board surfaces during cutting (Darmawan et al. 2009). Otherwise, the TiAlN/CrAlN coating strongly covered and protected the K10 carbide substrate from wearing and maintained a sharp cutting edge (Fig. 8d).

Conclusions

The following conclusions can be made based on the findings of this study.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

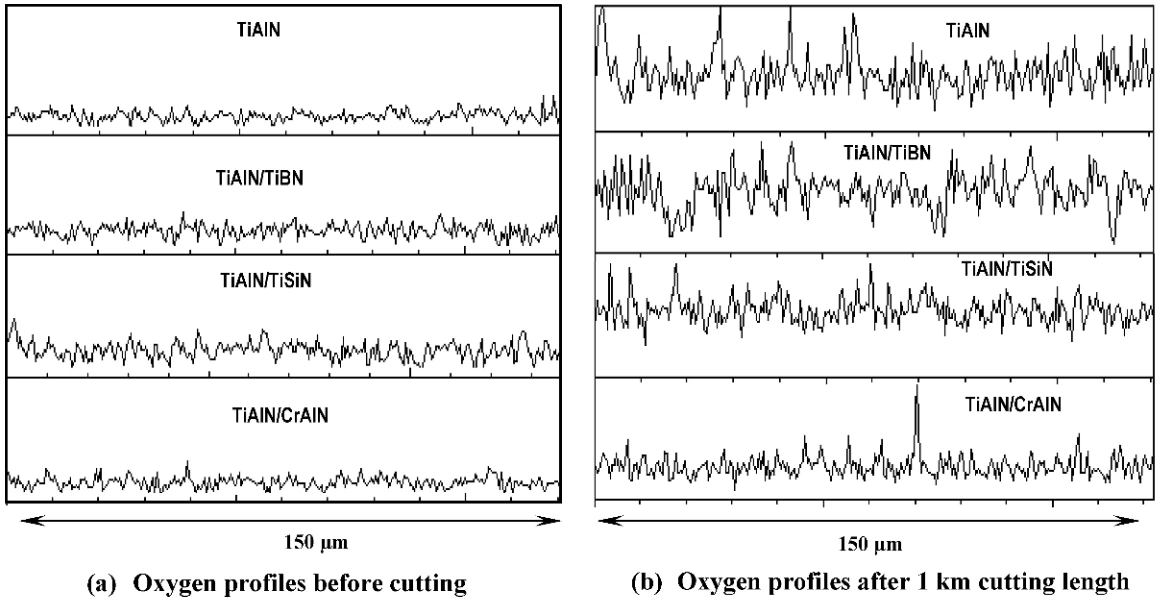

Figure 6.—SEM/EDS analysis showing indications of oxidation on the cutting edge of the coated tools (a) before cutting and (b) after a cutting length of 1 km.

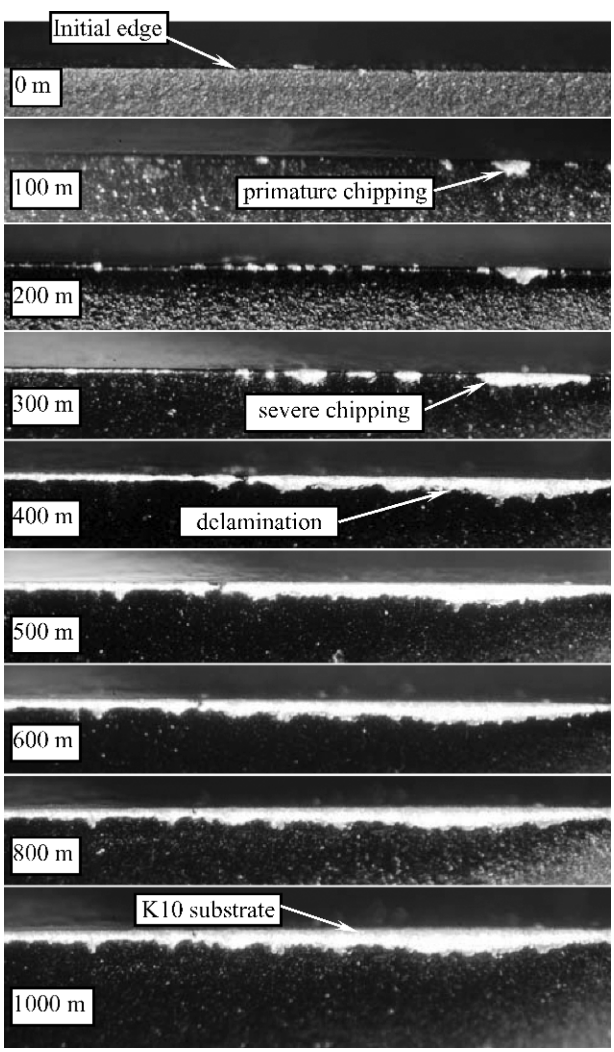

Figure 7.—Wear mechanism of the TiAlN/TiSiN multilayer coating when cutting particleboard.

1. The TiAlN/CrAlN multilayered coating is superior in reducing the progression of delamination wear when cutting particleboard.
2. Delamination of the TiAlN, TiAlN/TiSiN, and TiAlN/TiBiN coating films is preceded by chipping of the coating films, which is caused mainly by mechanical abrasion.
3. The wear patterns of the coated carbide tools when cutting particleboard is almost the same; the wear of the carbide substrate occurs after the coating film has disappeared from the carbide substrate.
4. The high hardness, low coefficient friction, high resistance to oxidation, and high resistance to delamination wear of the TiAlN/CrAlN coating indicate a very promising applicability for high-speed cutting of abrasive wood-based materials.

Literature Cited

ASTM International. 2006. Standard guide for corrosion tests in high temperature or high pressure environment. ASTM G111-97. *In:* Annual Book of ASTM Standards. Vol. 03.02. ASTM International, Philadelphia.

ASTM International. 2009a. Standard practice for instrumented indentation testing. ASTM E2546-07. *In:* Annual Book of ASTM Standards. Vol. 03.01. ASTM International, Philadelphia.

ASTM International. 2009b. Standard test method for measurement of coating thickness by x-ray spectrometry. ASTM B568-98. *In:* Annual Book of ASTM Standards. Vol. 02.05. ASTM International, Philadelphia.

ASTM International. 2010. Standard test method for wear testing with a pin-on-disk apparatus. ASTM G99-05. *In:* Annual Book of ASTM Standards. Vol. 03.02. ASTM International, Philadelphia.

Banh, T. L., Q. T. Phan, and D. B. Nguyen. 2004. Wear mechanisms of PVD coated HSS end-mills used to machine 1045 hardened steel. *Adv. Technol. Mater. Mater. Process*. 6(2):244–249.

Chang, C. L., W. C. Chen, P. C. Tsai, W. Y. Ho, and D. Y. Wang. 2007. Characteristics and performance of TiSiN/TiAlN multilayer coatings synthesized by cathodic arc plasma evaporation. *Surf. Coat. Technol*. 202(7):987–992.

Darmawan, W., J. Quesada, F. Rossi, R. Marchal, F. Machi, and H. Usuki. 2009. Performance of laser treated AISI-M2 cutting tool for peeling beech. *Eur. J. Wood Prod*. 67:247–255.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

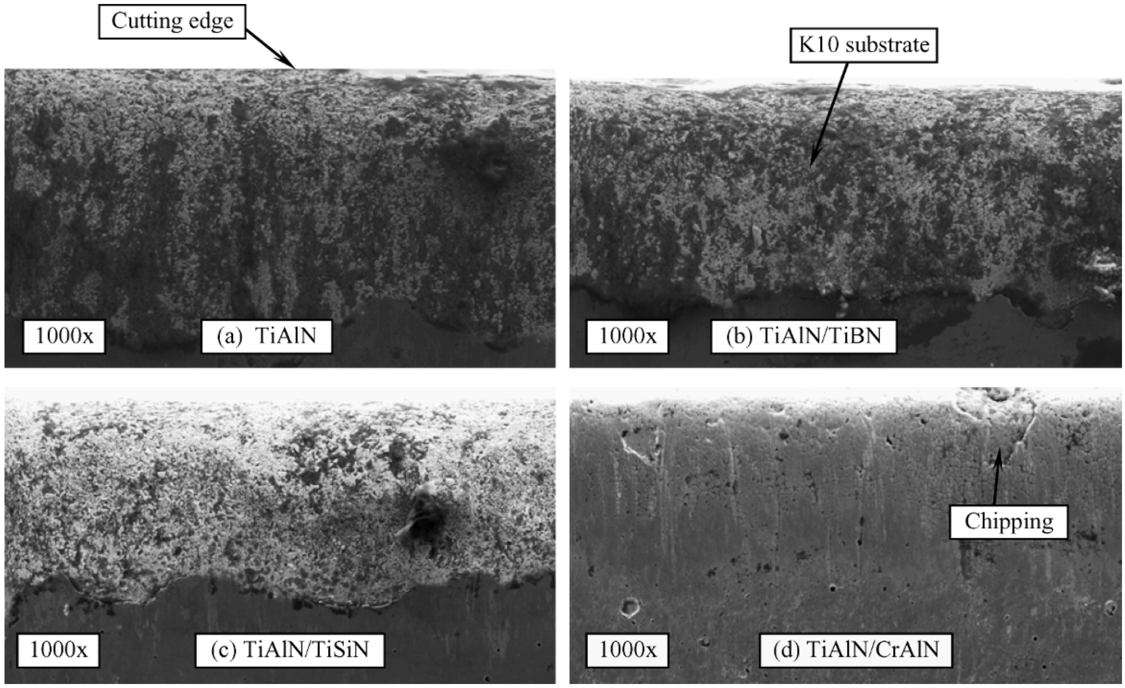

Figure 8.—Scanning electron micrographs of the worn edges of the newly coated cutting tools when cutting particleboard at the final cutting length of 1 km: (a) TiAlN, (b) TiAlN/TiBN, (c) TiAlN/TiSiN, and (d) TiAlN/CrAlN.

Darmawan, W., C. Tanaka, H. Usuki, and T. Ohtani. 2001. 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. *J. Wood Sci*. 47(5):342–349.

Ding, X. Z., A. L. K. Tan, X. T. Zeng, C. Wang, T. Yue, and C. Q. Sun. 2006. Corrosion resistance of CrAlN and TiAlN coatings deposited by lateral rotating cathode arc. *Thin Solid Films* 516:987–992.

Fuch, I. and C. Raatz. 1997. Study of wear behavior of specially coated (CVD, PACVD) cemented carbide tools while milling of wood-based materials. *In:* Proceedings of the 13th International Wood Machining Seminar, June 17–19, 1997, University of British Columbia, Vancouver, British Columbia, Canada. pp. 709–715.

Salje, E. and W. Stuehmeier. 1988. Milling particleboard with high hard cutting materials. *In:* Proceedings of the Ninth International Wood Machining Seminar, October 10–12, 1988, University of California Forest Products Laboratory, Richmond. pp. 211–228.

Sheikh-Ahmad, J. Y. and J. A. Bailey. 1999. High-temperature wear of cemented tungsten carbide tools while machining particleboard and fiberboard. *J. Wood Sci*. 45(6):445–455.

Sheikh-Ahmad, J. Y. and J. S. Stewart. 1995. Performance of different PVD coated tungsten carbide tools in the continuous machining of particleboard. *In:* Proceedings of the 12th International Wood Machining Seminar, October 2–4, 1995, Kyoto University, Kyoto, Japan. pp. 282–291.

Stewart, H. A. 1992. High-temperature halogenation of tungsten carbide cobalt tool material when machining medium density fiberboard. *Forest Prod. J*. 42(10):27–31.

TAPPI. 1991. TAPPI Test Methods: Ash in Wood and Pulp (T211 om-85). Vol. 1. TAPPI Press, Atlanta.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26