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RESEARCH

Wear Characteristics of Multilayer-Coated Cutting Tools in Milling Wood and Wood-Based Composites

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A B S T R A C T

This article presents the characteristic of wear on the clearance face of newly multilayer-coated K10 cutting tools when cutting mersawa wood, fiberboard, particleboard, and glass reinforced concrete (GRC). The K10 cutting tools were coated with monolayer titanium aluminum nitride (TiAlN), multilayer TiAlN/titanium silicon nitride (TiSiN), and TiAlN/titanium boron oxide nitride (TiBON). Cutting tests were performed on computer numeric control router at a high cutting speed of 17 m/s and a feed rate of 0.2 mm/rev to investigate the wear characteristics on the clearance face of these coated tools. Experimental results show that the coated tools experienced a smaller amount of clearance wear than the uncoated tool in cutting the mersawa wood, fiberboard, particleboard, and GRC. The GRC compared to the other work materials caused higher amount of clearance wear for both the uncoated and coated cutting tools. High content of silica and density were the reason for this phenomenon. The best coating among other coated cutting tools in this study was multilayer TiAlN/TiBON. The high hardness, low coefficient of friction, high resistance to oxidation, and high resistance to delamination wear of the multilayer-coated TiAlN/TiBON tool indicate a very promising applicability of this coating for high-speed cutting of abrasive woods and wood-based materials.

1. INTRODUCTION

Recently, the use of abrasive wood (wood with high silica) and wood-based materials has been increasingly used for building construction and decorative purposes. In the secondary wood manufacturing industry, where the abrasive wood and wood-based materials are machined extensively, tool wear would be an important economic parameter. Tool wear affects not only tool life, but also additional power consumption, surface finish, and production rates. In order to enhance productivity and reduce operating cost, it is necessary to use advanced cutting tools that can provide longer tool life, less unscheduled stops, and better surface quality. Tool's material that is currently used widely in wood machining is tungsten carbide-type. Otherwise, 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 [1-2]. An innovative technology that had been developed to improve the wear resistance is by depositioning of hard coating film on the surface of tungsten carbides.

Previous studies reported that the application of coating materials on the surface of tungsten carbide does not always generate more wear resistance than uncoated tools. It was reported in a study that K10 tungsten carbide inserts were coated with Titanium Nitride (TiN) and Titanium Carbide (TiC) films by the chemical vapor deposition (CVD) method and then used for cutting particleboard [3]. Those authors noted that the TiN coating brings no advantages in the milling of particleboard; in other words, the edge life attained or the total tool paths are not longer than those attained using uncoated cutting edges. It was reported that, 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/NbC)) by plasma-assisted chemical vapor deposition (PACVD) for milling laminated particleboard [4]. Those authors noted that TiN and TiAlON coated carbide tools do not provide any improvement in wear resistance compared with the uncoated carbide tool and that the TiC coated carbide tool provides only a slight improvement. It was noted in another study that the wear of TiN, Chromium Nitride (CrN), Chromium Carbide (CrC), Titanium Carbon Nitride (TiCN), and TiAlN coatings when cutting wood-chip cement board was produced 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 [5]. For high-speed cutting, delamination of these coating films was caused by oxidation, which was accelerated by the 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 oxide nitride (TiBON), and titanium silicon nitride (TiSiN), which have been noted to keep excellent properties (high hardness, low friction coefficient, and high oxidation and corrosion resistances [6-9].

The multi-layer of TiSiN/CrN generates lower rate of wear of 0.6 μm^2/min compared to single layer TiSiN of 2.87 μm^2/min [10]. Another study also reported that, multilayer-coated of TiSiN/TiAlN has higher hardness and resistance of corrosion [7]. Cutting tool with a multilayer CrN/CrCN (Chromium Carbon Nitride) coating was reported to improve the quality of treated wood surface in comparison with uncoated knives [11]. The combination of multilayer coating in those study provides the tools with high hardness and low coefficient of friction.

In this study, innovative multilayer coatings of TiAlN/TiBON, and TiAlN/TiSiN were synthesized onto the surface of K10 tungsten carbide using the arc-ion plating method, and the multilayer-coated tools were experimentally investigated for their possible use in the machining of mersawa wood, fiberboard, particleboard and glass reinforced concrete (GRC). The purpose of this study was to investigate the clearance wear characteristics of the multilayer-coated tools in high-speed cutting of mersawa wood, fiberboard, particleboard, and glass reinforced concrete (GRC).

2. MATERIALS AND METHOD

Multilayer-coated cutting tools and work materials

General specifications of the multilayer-coated cutting tools tested and the materials machined are shown in Tables 1 and 2, respectively. The K10 carbide tool (90 % WC, 10 % Co) that was selected as a substrate was 7 mm long, 4 mm width, and 2 mm thick. The hardness of the K10 was measured to be 1450 HV. The 13° rake and 5° clearance angles used in this experiment are now being commercially produced especially for cutting wood and wood-based materials. The K10 carbides were coated with a monolayer coating of TiAlN and multilayer coatings of TiAlN/TiBON, and TiAlN/TiSiN by the arc-ion plating 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 TiBON, or TiSiN above the TiAlN layer).

Table 1. Specifications of the coated carbide tools tested.

Coating material	Film thickness (μm)[a]	Hardness (HV)	Oxidation temperature start at (°C)	Friction coefficient
Uncoated	-	1450	700	0.8
TiAlN	3	2800	800	0.8
TiAlN/TiBON	3	2700	800	0.6
TiAlN/TiSiN	3	3600	1100	0.9

[a]Film thickness was targeted. Hardness, oxidation temperature, and friction coefficient values were measured according to ASTM E2546 [24], ASTM G111 [25], and ASTM G99 [26], respectively.

Table 2. Specifications of the cutting material.

Characteristic	Particle board	Mersawa wood	Fiber board	GRC
Thickness (mm)	12	50	12	12
Moisture content (%)	8	12	10	13
Density (g/cm^3)	0.61	0.80	0.67	1.42
Silicate content (%)[a]	1.86	1.00	0.29	46.1

[a]Silicate contents were measured according to TAPPI T211 om-85 [27].

Experimental setup

The cutting test was set up on the numerical controlled (NC) router with the condition as shown in Table 3. The board samples were prepared in rectangular form. A piece of sample was placed on the table of the NC router and locked by vacuum from compressor machine. A cutting tool edge was held rigidly in a tool holder with a cutting circle diameter of 12 mm. Cutting was performed along the edge of the board and with spindle rotation set in the clockwise direction (Fig. 1). The movement of the board during the cutting was controlled by feeding directions of the NC table in such a way that caused the board to be edged in a down-milling movement, and then to be edged in an up-milling movement.

Table 3. Milling condition on CNC router.

Variable	Condition
Cutting speed (m/s)	17
Feed (mm/rev)	0.2
Spindle speed (rpm)	10000
Feed speed (mm/min)	2000
Width of cut (mm)	2
Depth of cut (mm)	3

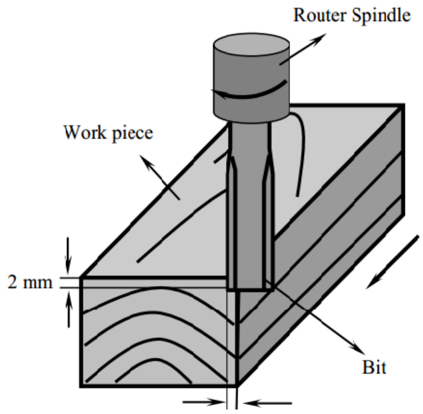

Fig. 1. Schematic diagram of routing on the edge of the work pieces.

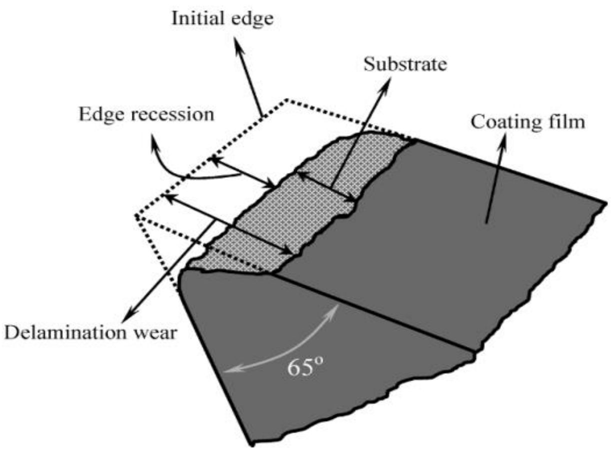

Fig. 2. Schematic wear delamination measurement on the clearance face of the cutting tool.

Measurement

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 edge recession and delamination wear were measured along the clearance faces of the tools (Fig. 2). Measurements of wear on the clearance faces were made using an optical video microscope. The tools were also inspected after the final cut (1000 m) using scanning electron microscopy

(SEM) for identification of the mode of cutting-edge failure.

3. RESULTS AND DISCUSSION

Edge recession behaviours on clearance face of the coated tools are provided in Fig. 3. The results show that the amount of edge recession increased with increasing in cutting length. The results in Fig. 3 indicated that the highest amount of edge recession was contributed by cutting GRC both on coated tools and uncoated tools. This phenomenon is considered to be caused by the two following reasons. First, GRC contained high abrasive materials such as silica which reached 46.1 % (Table 2). In addition, the cement as a binder of fiber glass on GRC board lead to exert higher abrasion on the cutting tools compared to other work materials. The cement in GRC generally consist of limestone, alumina, and silica [12] which have harmful effect as silica contain in wood or that of cured formaldehyde resin in particleboard which caused the cutting tools wear out rapidly. Second, GRC board has a high density of 1.42 g/cm^3 which will make more materials are machined at a given cutting volume.

The amount of edge recession resulted from cutting the mersawa and particleboard was higher than that in cutting fiberboard because the silica content in mersawa wood and particleboard was higher than in fiberboard (Table 2). This is in agreement with the fact that wood and particleboard are an extraneous and non-homogenous material with a high amount of inclusions of high-hardness particle [13,14]. The results in Figure 4 indicate the presence of hard abrasives in the work materials tested. Silica compound in wood have the form of silicon dioxide (SiO_2) which is located at the inter-layer of tracheids and ray parenchymas. It was noted that silica in tapi-tapi wood has the hardness of about 1200 HV [15]. SEM micrographs under high magnification showed that surface of the silica crystals appeared corrugated, which imposed high mechanical abrasion during the cutting (Fig. 4). The lower amount of edge recession in cutting the fiberboard was caused by not only the lower silica content and density but also by the characteristic of fiberboard that consisted of a group of individual fiber which resulted in a low friction during the cutting process.

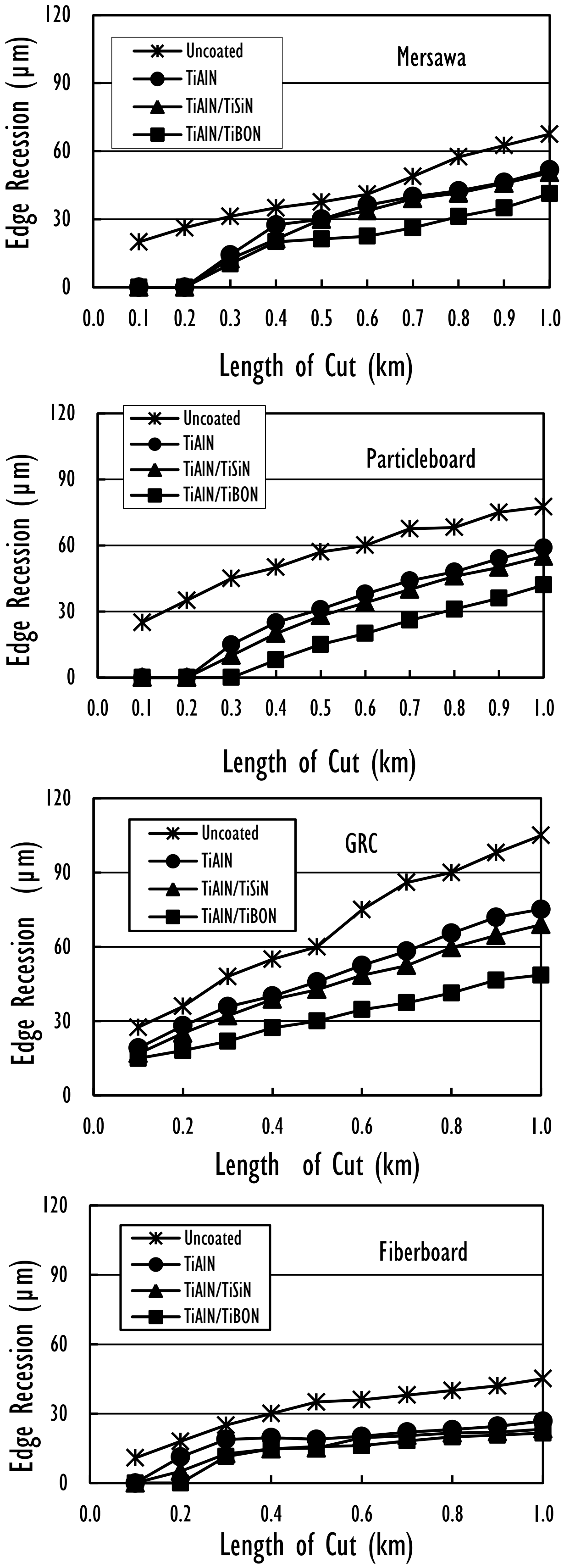

Fig. 3. Edge recession behaviors of coated tools with cutting length when milling mersawa wood, GRC, fiberboard, and particleboard.

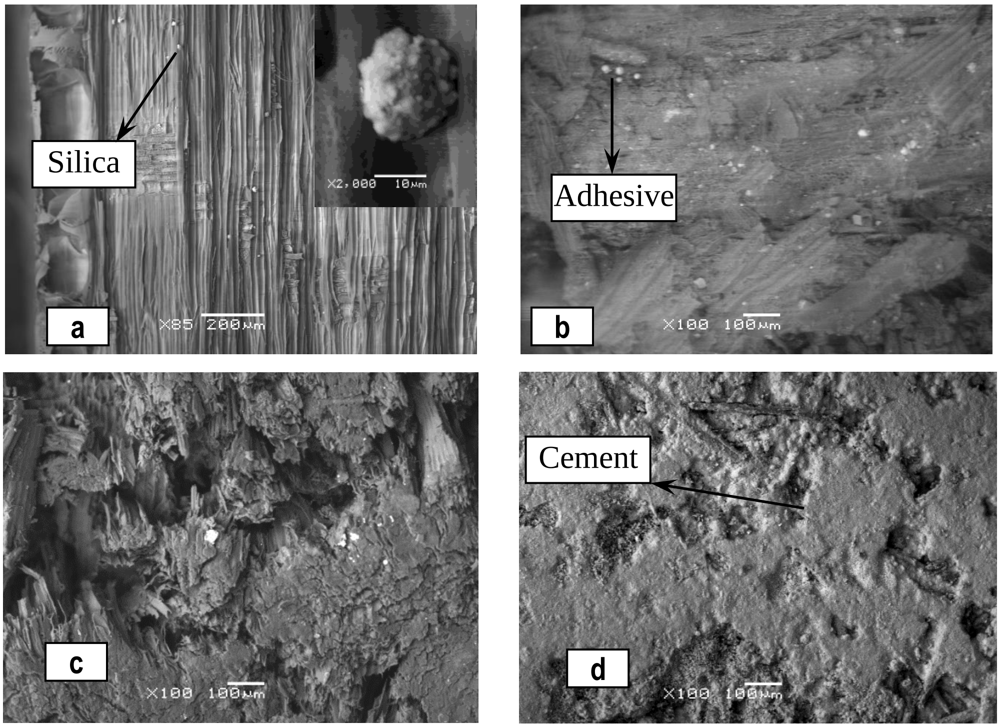

Fig. 4. SEM micrograph of the work materials showing the abrasives on the mersawa wood (a); particleboard (b); fiberboard (c); and GRC (d).

The results in Fig. 3 shows that the coated tools provided better performance, especially in reducing the progression of edge recession, than the uncoated tool when cutting mersawa wood, particleboard, fiberboard, and GRC. Lower hardness of the uncoated tungsten K10 (1450 HV) compared to single layer TiAlN, multilayer TiAlN/TiSiN, and TiAlN/TiBON coated tools (Table 1) could be the reason for this phenomenon. In the other way, thin film formed by hard materials on surface of tungsten carbide substrate dampens the thermal conductivity during the cutting. The thermal conductivity of a single layer of TiN and TiAlN was 11 W/mK and 5 W/mK, respectively, and in multilayer TiN/TiAlN, it was lower to be 4.7 W/mK [16], while the thermal conductivity of uncoated tungsten carbide was reported to be 80.2 W/mK [17]. High conductivity of the tungsten carbide will lead to the oxidation of cobalt (Co) binder during the cutting process [18]. Oxidation of the Co binder caused the bonding between tungsten carbide grains to be weak and susceptible to mechanical abrasion during the cutting process.

The results in Fig. 3 also indicate that the multilayer-coated TiAlN/TiBON had the highest resistance to edge recession wear compared to the multilayer-coated TiAlN/TiSiN and monolayer-coated TiAlN when cutting the mersawa wood, fiberboard, GRC, and particleboard. The high wear resistance of the TiAlN/TiBON cutting tool is considered as a result from the following reasons. First, the friction coefficient of the multilayered TiAlN/TiBON coating was lower than that of TiAlN, and TiAlN/TiSiN coatings, which led to less abrasion against the hard abrasive materials contained in the cutting materials. Rizzo et al. [19] reported that multilayer of TiAlN/AlN has lower friction coefficient than single layer TiAlN that indicating a smooth surface and suggesting a gradual exfoliation typical of the laminated structure. Other studies reported that a coating material with the highest coefficient of friction shows the highest surface roughness, and further affect life time of cutting tools [20-21]. Second, it was reported in another study [22] that the TiBON film provides lubrication effect at high temperatures.

Figure 3 also shows that high edge recession was contributed by TiAlN monolayer and TiAlN/TiSiN multilayer coated. This fact could confirm the results noted by Bouzakis et al. [23] that the deterioration of the adhesion of TiSiN coating on the substrate can be attributed to a potential superficial decomposition of the tungsten carbides during the Si deposition and to the formation of silicon carbides SixC.

Hereafter a superficial brittleness on the tungsten carbide surfaces could develop, leading to local fractures and coating detachment from the tungsten carbides under load due to an adhesion reduction.

The amount of edge recession wear that occurs on coated tools seems to depend on the amount of delamination wear. It was explained that the wear of coated tools is preceded by chipping of the coating film which is caused by mechanical abrasion [12]. A higher delamination of coating films will generate a higher edge recession wear during cutting process. Table 4 illustrates a linear relationship between amount of delamination with the amount of edge recession wear when cutting mersawa wood, fiberboard, GRC, and particleboard.

Table 4. Edge recession wear and delamination relationship for the coated tools in cutting GRC, fiberboard, mersawa wood, and particleboard.

Work material	Coating tools	Linear equation	R
GRC	TiAlN/TiBON	Y = 18.572+0.0402X	0.87
	TiAlN/TiSiN	Y = 17.965+0.0518X	0.93
	TiAlN	Y = 12.13+0.0578X	0.91
Fiber-board	TiAlN/TiBON	Y = 19.196+0.0544X	0.92
	TiAlN/TiSiN	Y = -3.567+0.0427X	0.99
	TiAlN	Y = 7.735+0.0868X	0.98
Mersawa wood	TiAlN/TiBON	Y = 8.616. +0.0792X	0.97
	TiAlN/TiSiN	Y = 18.461+0.0617X	0.89
	TiAlN	Y = -8.450+0.516X	0.98
Particle-board	TiAlN/TiBON	Y = -5.547 +0.606X	0.99
	TiAlN/TiSiN	Y = 17.289+0.641X	0.99
	TiAlN	Y = -3.597+0.569X	0.98

Y = amount of edge recession wear, X = amount of delamination wear, R = correlation of coefficient

The worn edges of the coated tools under an optical video microscope showed similar delamination mechanisms of coating films in the cutting of mersawa wood, GRC, fiberboard and particleboard. Figure 5 depicts the mechanism of delamination of the TiAlN/TiBON coating, which is selected for discussion in this article. Delamination of the TiAlN/TiBON coating was preceded by premature chipping of 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/TiBON 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/TiBON films were removed from the substrate. The SEM micrographs of the worn edges of the TiAlN/TiBON coated tool in cutting the mersawa wood and particleboard after 1 km cutting length are shown in Figure 6. A characteristic feature of both monolayer and multilayer coatings is the presence of interlayer boundaries affecting a change in the mechanism of its destruction during the operation. In recent review of such coatings, Wacholinski and Gilewicz [14] reported that all the coatings tested are characterized by relatively high values of critical forces (>80N) which weaken the toughness and fracture of the coatings, and the coherence between the layers in the coating.

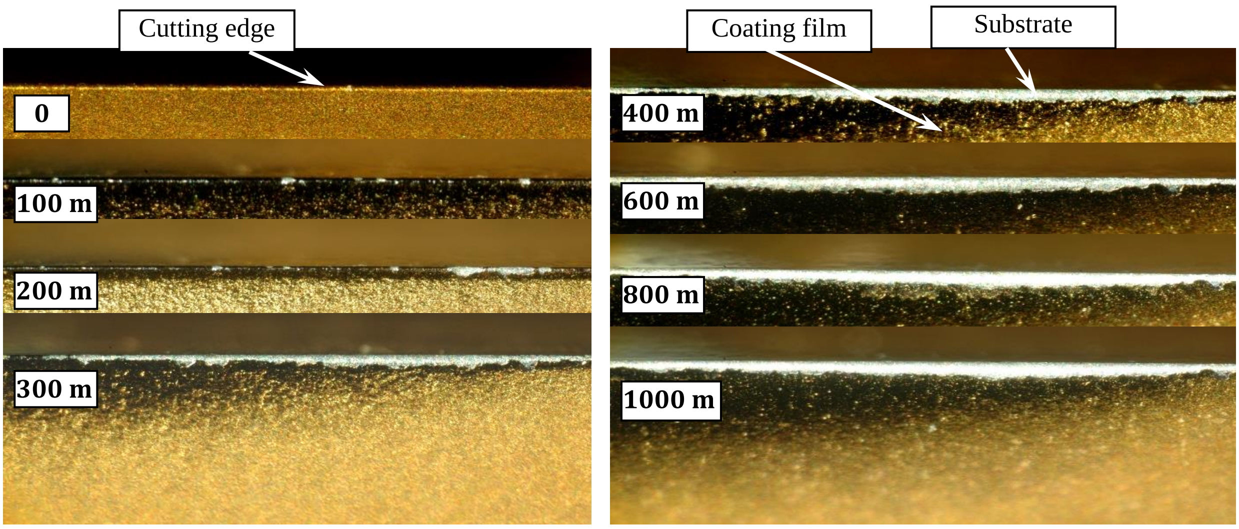

Fig.5. Wear mechanism of the TiAlN/TiBON multilayer coating when cutting particleboard.

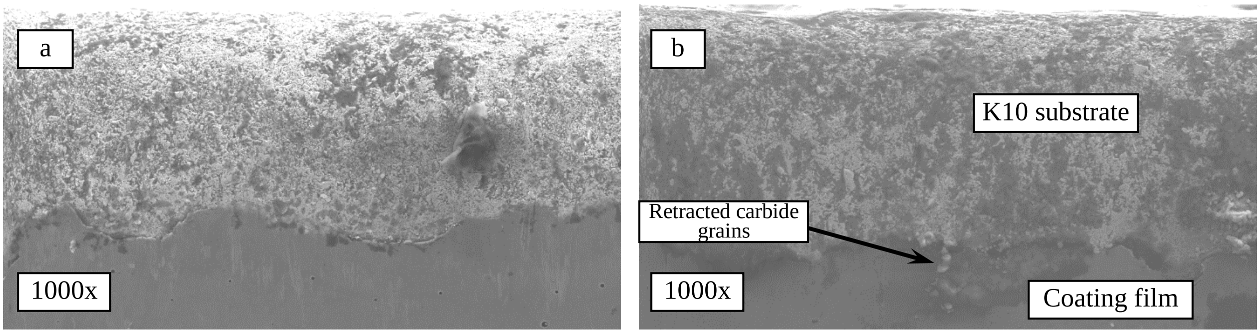

Fig.6. SEM micrographs of the worn edges of the TiAlN/TiBON multilayer coating when cutting particleboard (a) and mersawa wood (b) at the final cutting length of 1 km.

The SEM micrographs in Figure 6 reveal that the patterns of edge wear generated by TiAlN/TiBON in cutting the two materials were relatively the same. Delaminations of coating film were generated by the TiAlN/TiBON coated carbide tools. This suggests that the substrate of the TiAlN/TiBON coated tools would be exposed to any possible mechanical abrasion, which caused retraction of tungsten carbide grains from the substrate during cutting. The retraction of carbide grains was reported to cause a corrugated cutting edge, which tends to produce rough board surfaces during cutting [12].

4. CONCLUSION

The following conclusions can be noted based on the findings of this study. Monolayer and multilayer coatings are superior in reducing the progression of tool wear compared to uncoated tungsten carbide K10. Cutting the GRC material causes the highest amount edge recession wear due to the high content of silica. The delamination of the TiAlN, TiAlN/TiSiN, and TiAlN/TiBON coating films is preceded by chipping of the coating films, which is caused mainly by mechanical abrasion.

The wear patterns of the coated carbide tools when cutting mersawa wood, particleboard, fiberboard and GRC are almost the same. The wear of the carbide substrate occurs after the coating films have disappeared from the carbide substrate. The high hardness, low coefficient of friction, and high resistance to delamination wear of the TiAlN/TiBON coating indicate a very promising applicability for high-speed cutting of abrasive wood-based material.

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