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PERFORMANCE OF COATED TUNGSTEN CARBIDE IN MILLING COMPOSITE BOARDS

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ABSTRACT

The purpose of this research was to analyze the performance (wear resistance, surface roughness, chip formation, and noise level) of AlCrN, TiN, and TiAlN coated tungsten carbides in cutting composite boards. The composite boards of wood plastic composite, laminated veneer lumber, and oriented strand board were cut by the coated tungsten carbide tools in a computer numerical control router. The results show that the differences in structure among the composite boards resulted in the difference in clearance wear, chip formation, surface roughness, and noise level phenomenon. The abrasive materials in wood plastic composite generated the highest clearance wear on the coated carbide tools tested. TiAlN coated carbide tool provided better wear resistance, smoother composite boards surfaces, and lower noise levels.

KEYWORDS: Chip formation, clearance wear, coated tungsten carbide tool, composite board, noise level, surface roughness.

INTRODUCTION

Composite board industries manufacturing wood plastic composite (WPC), laminated veneer lumber (LVL), and oriented strand board (OSB) are developing rapidly in various countries (Antov et al. 2020). They have high ratio of the tensile strength of the material to its density (Kulman et al. 2019). These composite boards have been widely used for decorative and building construction purposes (Ribeiro and del Menezzi 2019). In the secondary wood manufacturing industry, where the composite boards are machined using a cutting tool, the wear of cutting tool edge, in addition to the cutting force (Koleda et al. 2019, Kopecký et al. 2019) and friction coefficient (Li and Zhang 2019), is one of the imperative productivity parameters in the machining. Darmawan and Tanaka (2004), Darmawan et al. (2009, 2011) reported that the wear of cutting tool affects the noise level and the surface quality. The high heterogeneity in structure of composite board compared to metal and wood would be predicted to result in the complexity of cutting tool wear problem. Therefore, the elucidation of the wear phenomenon of cutting tools is considered to be necessary in an effort to find better choices of cutting tool materials used in cutting composite boards.

At present, a cutting tool material that dominates in the wood working industry is tungsten carbide. Tungsten carbide is a good selection for many wood machining processes because of its toughness and hardness. Darmawan et al. (2012) reported that the wear resistance of tungsten carbide tool was much higher than high speed steel tools for cutting tapi-tapi wood and composite boards (cement board, particle board, and fiber board) in the same cutting condition, as a result of the higher hardness of tungsten carbide tool (1450 HV) compared to high speed steel tool (815 HV). Though tungsten carbide tool has been widely used for machining solid wood, however previous studies reported that machining of composite boards using tungsten carbide tools has been limited due to relatively high rate of wear caused by combination of abrasion, high-temperature oxidation, and inorganic content such as silica in composite boards (Darmawan et al. 2012). In addition, Ratnasingam et al. (2010) noted that machining of particleboard caused carbide cutting tool to wear out much faster than cutting of solid woods. Therefore, a need for cutting tool with longer life and better performance exists especially for cutting composite boards.

Other cutting tool materials that were produced for the secondary wood manufacturing industry are ceramic, cubic boron nitride, and polycrystalline diamond cutting tool. However, the cost of these cutting tools seems to very high, and the difficulty in creating cutting tools of complex shapes and tool size limits for the composite board machining application (Darmawan 2017). An alternative, deposition of hard coating materials onto the surface of tungsten carbide tools has been recently promoted for cutting composite boards. The effects on cutting tool wear of adding hard coating materials onto the surface of tungsten carbide tools are reported in the literatures. Titanium nitride (TiN), titanium carbon nitride (TiCN), and chromium nitride (CrN) coating films were deposited on tungsten carbide tools by physical vapor deposition (PVD) method (Darmawan et al. 2001). It was noted in the work that these coated carbide tools were advantageous in reducing the progression of wear, in retaining lower noise level and normal force in cutting hardboard and wood-chip cement board compared to uncoated carbide tool. TiCN coating thin film deposited on tungsten carbide tools has increased microhardness, reduced the coefficient of friction, and subsequently improved cutting tool life as compared to uncoated carbide tool (Talib et al. 2013). In addition, depositioning TiCN coating film on tungsten carbide tools has reduced the thermal conductivity of cutting tool from 80.20 $kW \cdot m^{-1} \cdot K^{-1}$ to 0.10 $kW \cdot m^{-1} \cdot K^{-1}$. This reduction results in the prevention of cobalt oxidation during cutting at high temperature (Talib et al. 2013). In contrast, Sheikh-Ahmad and Stewart (1995) noted that TiN and titanium aluminium oxide nitride (TiAlON) coated carbide tools did not provide any improvement in wear resistance compared to uncoated carbide tool when cutting particleboard, and the titanium carbide (TiC) coated carbide tool provided only a slight improvement.

Depositions of a newly coating material of aluminium chromium nitride (AlCrN) and commercially coatings of TiN and titanium aluminium nitride (TiAlN) onto tungsten carbide tools in the field of composite boards machining are little known concerning their performance. These coating materials have high hardness, better oxidation resistance, and lower friction coefficient. The ongoing research was proposed to achieve better performance of the AlCrN, TiN, and TiAlN coated tungsten carbide tools in cutting composite boards of WPC, LVL, and OSB. The performance investigated were wear resistance, surface roughness, chip formation, and noise level.

MATERIAL AND METHODS

General specification of the tungsten carbide tools tested and the composite boards machined are shown in Tab. 1 and Tab. 2, respectively.

Tab. 1: Specification of tungsten carbide tools tested.

Coatings	Film thickness (μm)	Hardness (HV)	Oxidation temperature (^{o}C)	Friction coefficient
Uncoated	-	1400	Start at 700	0.8
AlCrN	3	2800	Start at 1000	0.6
TiN	3	2200	Start at 600	0.7
TiAlN	3	2800	Start at 800	0.8

Film thickness, hardness, oxidation temperature, and friction coefficient values were measured according to ASTM B568, ASTM E2546, ASTM G111, and ASTM G99, respectively.

Tab. 2: Specification of composite boards machined.

Composite boards	Moisture content (%)	Density ($kg\ m^{-3}$)	Modulus of rupture (MPa)	Hardness ($N\ m^{-2}$)	Silica content (%)
WPC	2.1	135	28	3.64	5.09
LVL	10.4	83	80	5.23	0.73
OSB	11.2	59	20	1.41	0.01

Moisture content and density values were measured according to BS 373, Modulus of rupture and hardness values were measured according to ASTM D143, silica content was measured according to TAPPI T211 om-02.

The K10 carbide tool (90% WC and 10% Co) used as a substrate was in 6.40 mm long, 4.30 mm wide, and 2.45 mm thick with a clearance angle of 5^{o} and a rake angle of 13^{o}. This geometry is now being commercially produced to prevent chipping of the cutting edge when using in abrasive work materials machining. The tungsten carbide tools were coated with monolayer coatings of AlCrN, TiN, and TiAlN by the arc-ion plating method on both clearance and rake faces.

Cutting test was set up on the computer numerical control (CNC) router with condition as shown in Tab. 3. The composite board samples were prepared in rectangular form. A piece of work material was placed on the table of the CNC router and locked by vacuum machine. Cutting tool edge was held rigidly in a cutting tool holder with diameter of cutting circle of 12 mm. Cutting test was performed along the edge of the board with spindle rotation set in the clockwise direction. The coated carbide tools were inspected with an optical video microscope before cutting test for any surface defects and cracks of the coating film on both clearance and rake faces. The cutting was stopped at every specified linear cutting length of 100 m, at which the cutting tool wear, surface roughness, chip formation, and noise level were investigated. The cutting tools wear was inspected using an optical video microscope to obtain the amount of edge recession and delamination wear (Fig. 1).

Tab. 3: Specification of cutting conditions.

Variable	Condition
Cutting speed (m s^{-1})	6.3
Feed rev (mm rev^{-1})	0.2
Spindle speed (rev min^{-1})	10000
Feed speed (mm min^{-1})	2000
Cutting width (mm)	1
Cutting depth (mm)	2

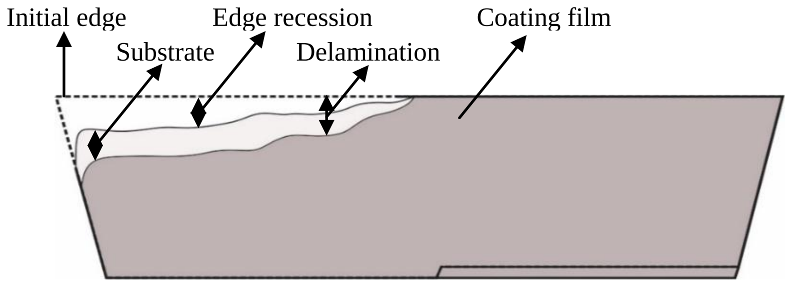

Fig. 1: Schematic wear measurement on the clearance face of coated carbide tools.

The machined surface was evaluated in the Ra value of surface roughness. The surface roughness tester SJ-210 was used to measure the roughness on the surface of the machined composite boards. The Ra was measured across the cutting direction of samples with a diamond tip radius of 5 µm. The tracing length was 15 mm and the cut off was 2.5 mm. Five points for roughness measurement were diagonally marked on the surface of the samples. Investigation of the chips was carried out by mesh analysis of the formed chips. The deposited chips on the table. of the machine were collected and documented. The chip shapes in this work were classified according to the method suggested by Su et al. (2003). The collected chips were sieved by steel screens of 10 mesh (diameter of holes 2.0 mm), 20 mesh (diameter of holes 0.8 mm), 40 mesh (diameter of holes 0.4 mm), and 80 mesh (diameter of holes 0.2 mm). The sieved chips were analyzed according to the type of chip and the weight percentage of each screened chip. A precision sound level meter Sanfix 356 was used for measurement of the sound level of the audible cutting noise on the A scale, which is usually used for measuring the peak of sound pressure level. The sound level meter was set up at the height of the cutting tool edge (about 1 m above ground level) and at a distance of about 1 m along a straight line extending from the cutting tool edge. The noise level was recorded per 5 second at every cutting test, and the values was transferred to a computer for analysis.

RESULTS AND DISCUSSION

Edge recession and delamination

The amount of edge recession increased with increasing in cutting length (Fig. 2). The gradual progression of wear on the surface of cutting tool was reported to be resulted from the cutting heat friction between the cutting tool and workpiece (Wei et al. 2018). The coated carbide tools provided better performance, especially in reducing the progression of edge recession than the uncoated carbide tool when cutting WPC, LVL, and OSB. The phenomenon was caused by a remarkable enhancement in hardness of coated carbide tools after coated with a coating film (Tab. 1).

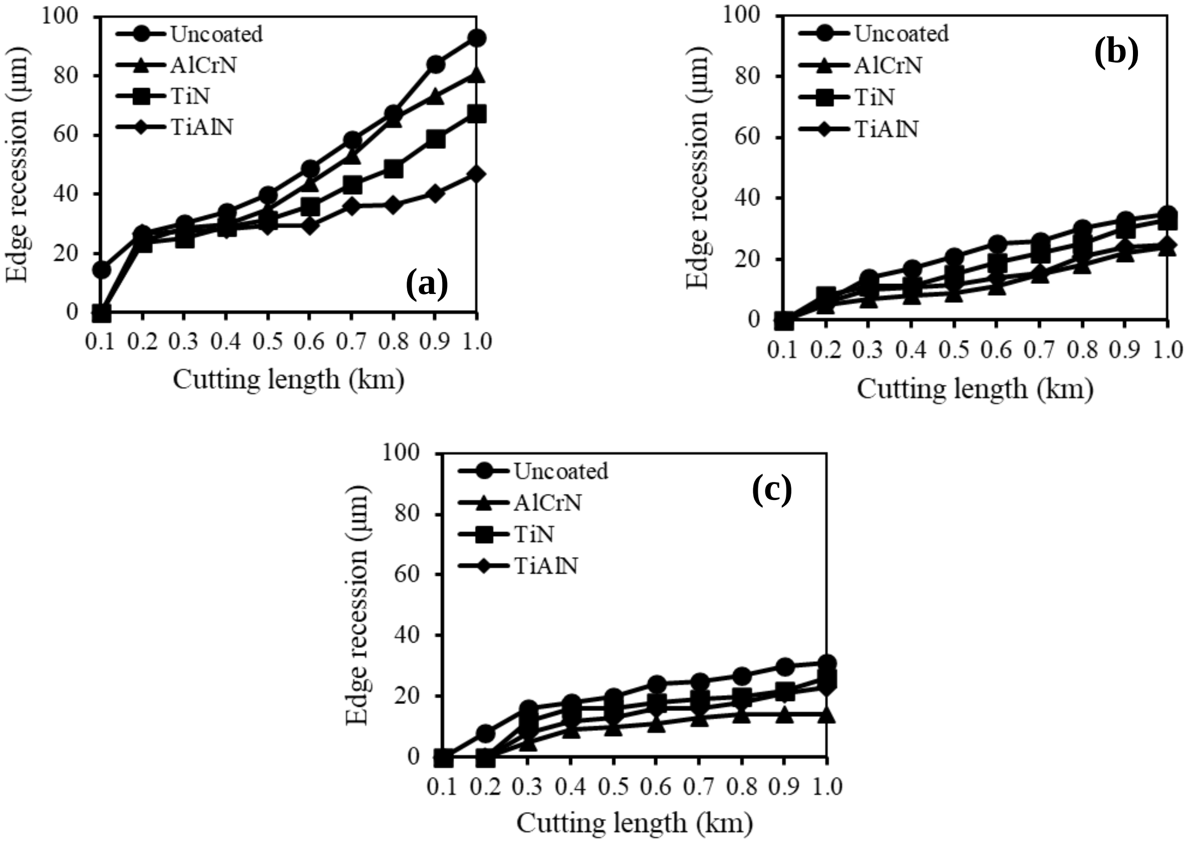

Fig. 2: Edge recession behaviours of tungsten carbide tools in cutting: (a) WPC, (b) LVL, (c) OSB.

The AlCrN, TiN, and TiAlN coated carbide tools showed similar edge recession progress near the beginning of cutting the composite boards, however the progression was gradually different among these coated carbide tools at the end of cutting. The AlCrN coated carbide tools generated the lowest edge recession in cutting LVL and OSB, however it generated the highest edge recession among the coated carbide tools tested when cutting WPC. Though the AlCrN coated carbide tool had a superior specification compared to the other coated carbide tools (Tab. 1), however it could not be superior for cutting abrasive material of WPC. WPC was higher in density and silica content compared to LVL and OSB (Tab. 2). The TiAlN coated carbide tool provided a lower edge recession than AlCrN coated carbide tool when cutting WPC. Moreover, the AlCrN coated carbide tool provided only a slight difference in edge recession compared to TiAlN coated carbide tool when cutting LVL and OSB. It was also noted in other studies that AlCrN coated carbide tool with high hardness, low friction coefficient, and high oxidation temperature generate lower amount of coating film delamination and lower edge wear in cutting metal compared to the TiAlN coated carbide tool (Kumar et al. 2014, Chandrashekhar et al. 2016, Mo et al. 2007).

The reason for the above phenomenon could be due to the higher brittleness of the AlCrN coating, which caused the coating film to crack and to detach (Fig. 3) from the surface of the tungsten carbide substrate, especially when cutting abrasive composite board (WPC). The AlCrN coated tool micrograph (Fig. 3a) shows a crack on the coating film near the cutting edge without any friction marks on the AlCrN coating film. Though the AlCrN coated carbide tool was the lowest in friction coefficient (0.6) among the coated carbide tools tested, however its high brittleness could promote the presence of the cracks followed by delamination of the coating film without abrasion. TiN coating film shows friction marks on the coating film near the cutting edge with a small cracking. Otherwise, TiAlN coating film shows friction marks without any cracks along the coating film near the cutting edge because of its highest friction coefficient (0.8) among the coated carbide tools.

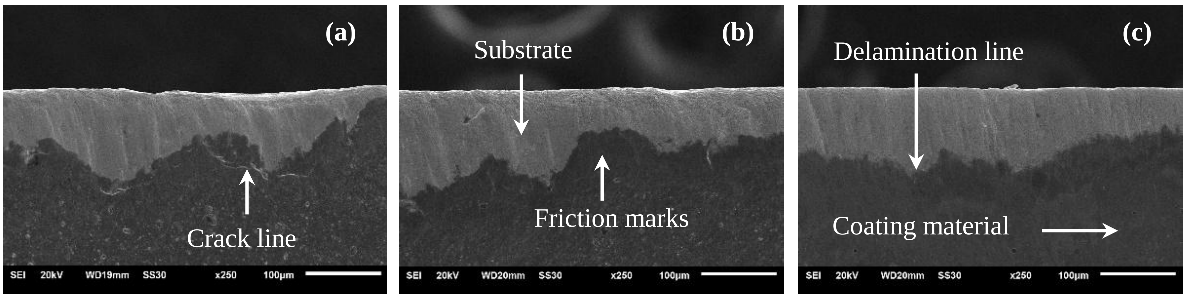

Fig. 3: SEM micrograph of the worn clearance face of (a) AlCrN, (b) TiN, and (c) TiAlN coated carbide tools at the end of cutting WPC.

It also appears in Fig. 2 that there was a considerable difference in amount of edge recession of coated carbide tools among the composite boards machined. The result shows that the coated carbide tools suffered more wear when cutting WPC compared to LVL and OSB. The higher density, MOR, hardness, silica content (Tab. 2), and a high amount of inorganic matters in WPC could be the reason for this phenomenon. The presences of abrasive and additives materials in the WPC led to severe mechanical wearing on the cutting tool edge tested. The main components of WPC were plastic polymer, lignocellulose materials, fillers (mostly crystalline silicates, titanium dioxide, and other heavy metals), stabilizers, pigments, and other additives (Niska and Sain 2008, Saloni et al. 2011). It was confirmed in previous studies that the high amount of inorganic matters contained in the composite boards, combined with plastic polymer cause severe abrasive wear to the cutting tool (Saloni et al. 2011). On the other hand, the lowest density, hardness, MOR, and silica content of the OSB compared to other composite boards generated the lowest edge recession wear on the coated carbide cutting tools tested. The edge recession wear on coated carbide tools could be attributed by the amount of delamination of coating films. It was reported by Fahrussiam et al. (2016) that there was a strong linear relationship between delamination and edge recession wear when cutting composite boards using coated carbide tools. The result shows the progression of coating films delamination of the coated carbide tools, in which delamination increased with the increase in cutting length (Fig. 4). The higher delamination of the coating films resulted in the higher edge recession wear during the cutting. It could be considered that the cutting edge would be more susceptible to wearing, since the coating film had been delaminated from the surfaces of the cutting edge. AlCrN coated carbide tool generated the highest delamination wear when cutting the WPC, whereas TiAlN coated carbide tool generated lowest delamination wear when cutting the WPC.

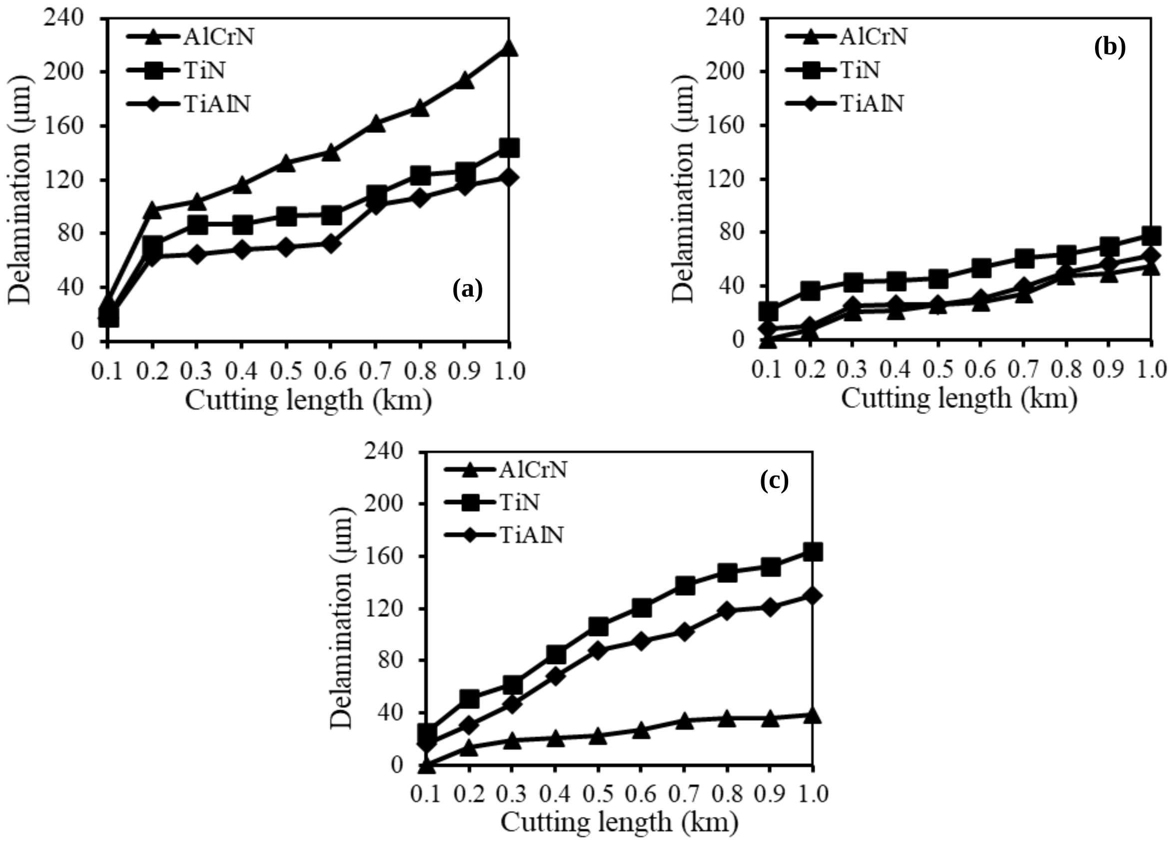

Fig. 4: Delamination behaviours of coated carbide tools in cutting (a) WPC, (b) LVL, and (c) OSB.

The reason for above phenomenon could be due to weak adhesion between AlCrN coating film and tungsten carbide substrate. The formation of weak adhesion bond is considered as a result from the following reasons. First, high residual stress on AlCrN coating film results in the formation of weak adhesion bond between the coating film and the tungsten carbide substrate, which cause the higher delamination (Yang et al. 2008, Zhu et al. 2015). Zhu et al. (2015) and Pham et al. (2010) noted that the lower chromium (Cr) and the higher aluminum (Al) content of the coating film will cause the higher residual stress on the cutting edge of the coated carbide tool. Kumar et al. (2014) and Adesina et al. (2019) found a low Cr content (18.6% - 22.2%) in AlCrN coating film. Higher Al content (38.1%) in AlCrN coating film compared to Al content (20.4%) in TiAlN coating film was also reported in these studies. Second, AlCrN coating film was found to be poor in adhesion with the tungsten carbide substrate because of the poor thermal conductivity (Dumkum et al. 2018). In addition, Lee et al. (2009) noted that the low thermal conductivity of AlCrN coating film may be a reason to raise the cutting temperature at the cutting tool interface, and causes the delamination wear as well as the built-up edge formation. It also appears in Fig. 4 that TiN and TiAlN coated carbide tool generated a higher delamination in cutting OSB than in cutting LVL. This fact could be attributed to the rigid behavior of the strands on the OSB. The strands were incompletely severed from the board. The strands led to rub against the coated carbide tools continuously, and in turn generated a higher delamination of TiN and TiAlN coating film.

Chip formation

Investigation of chips generated during cutting of the WPC, LVL, and OSB shows that both uncoated and coated carbide tools produced similar type and size of chips. The chip shapes were determined as spiral chip, splinter chip, flow chip, thin chip, and granule chip (Fig. 5). The spiral and splinter chips were netted on 10 mesh sieve, flow and thin chips were netted on 20 mesh sieve, and granule chips passed through 20 mesh sieves.

It also appears in Fig. 5 that the composite boards generated different chip shapes. The difference in chip shapes was caused by the difference in structure among the composite boards. WPC and LVL chips were classified as spiral chip, splinter chip, and flow chips (Fig. 5.1a-c and Fig. 5.3a-c, resp.). The OSB chips were classified as spiral chip, splinter chip, thin chip, and granule chip (Fig. 5.4a and 5.4c-e, resp.).

The spiral chip was found in all composite boards machined. The spiral chip was formed from incompletely severed chips through compression. Flow chips were only found in cutting WPC and LVL. Su et al. (2003) noted that the flow chips match to the theoretical shape of milling model. The absent of flow chips in cutting OSB was caused by its frangible structures. It was reported that the frangible structure allows chip separation through tension perpendicular to the grain (Darmawan et al. 2019). The instantaneous impact between cutting tool edge and the frangible structure of OSB resulted in the formation of splinter, thin, and granule chips during cutting OSB. Splinter chips were block chips torn along the grain. Thin chips were almost the same as the flow chip but a little smaller. Granule chips were generated from broken pieces. Granule chip was generated in all composite boards machined.

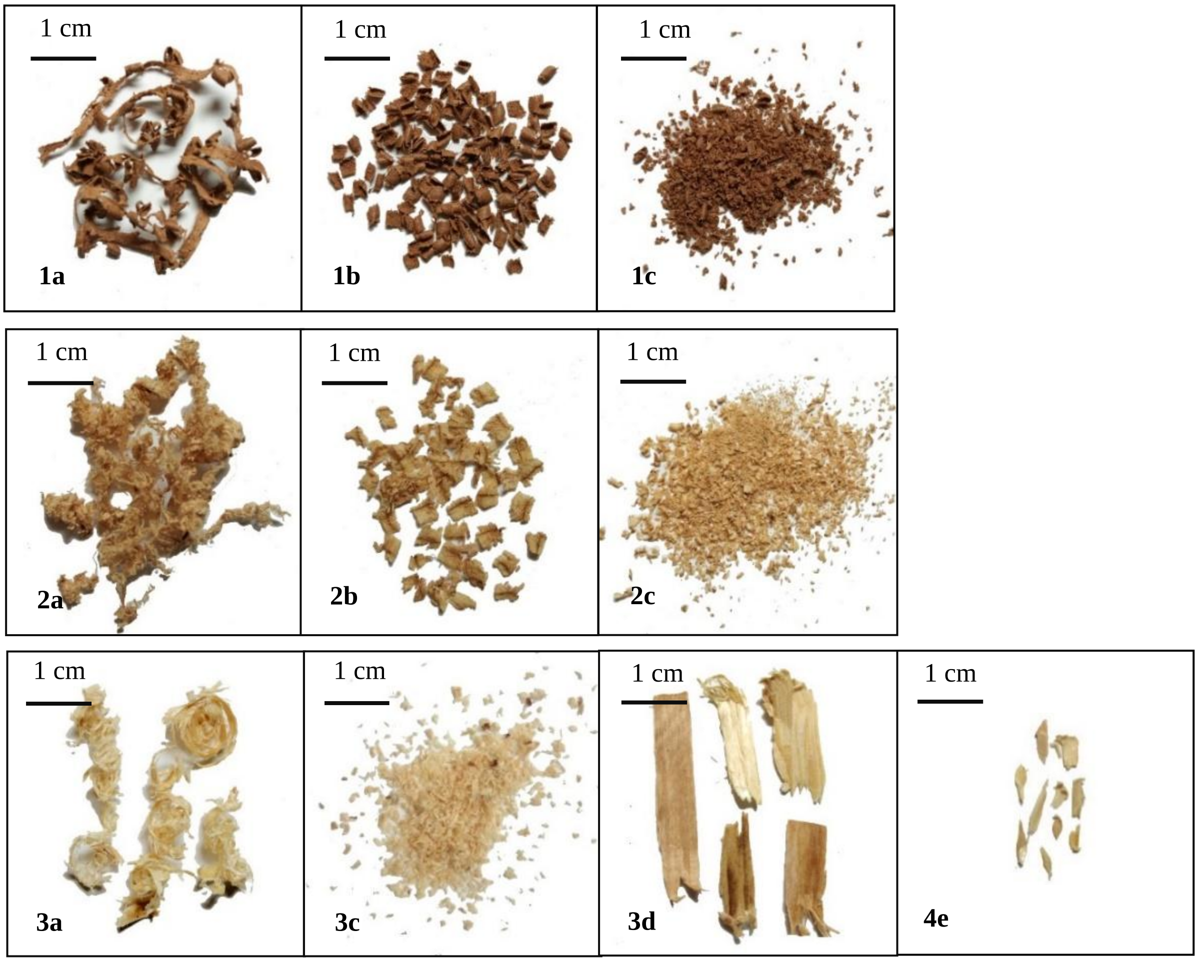

Fig. 5: Classification of chips in five shapes: (a) spiral, (b) flow, (c) granule, (d) splinter, and (e) thin, generated during cutting (1) WPC, (2) LVL, and (3) OSB.

The chip distributions were similar among the tungsten carbide tools tested for all composite boards machined (Tab. 4).

Tab. 4: Weight percentage of chips generated during cutting composite boards.

Composite boards	Tungsten carbide tool	Weight percentage (%)				
		10 mesh (> 2 mm)	20 mesh (0.8-2 mm)	40 mesh (0.4-0.8 mm)	80 mesh (0.2-04 mm)	> 80 mesh (< 0.2 mm)
WPC	Uncoated	3.7	93.2	1.2	1.0	0.8
	AlCrN	4.5	92.6	1.1	1.0	0.8
	TiN	2.6	94.6	1.4	0.8	0.7
	TiAlN	5.9	92.3	0.6	0.7	0.5
LVL	Uncoated	1.3	31.4	34.6	23.6	9.1
	AlCrN	0.5	35.5	34.1	21.2	8.6
	TiN	0.5	33.7	36.5	20.8	8.5
	TiAlN	1.1	39.7	30.5	20.8	7.8
OSB	Uncoated	8.3	18.9	34.6	22.3	15.7
	AlCrN	11.6	19.1	34.0	24.5	10.8
	TiN	12.1	18.9	34.0	24.2	10.8
	TiAlN	12.4	18.9	35.0	23.5	10.2

The similar distribution was caused by the same geometry used for the cutting tool tested. The similarities in cutting tool geometry was reported to produce a similar chip type and distribution (Su et al. 2003, Wyeth et al. 2009, Darmawan et al. 2019). The results in Tab. 4 show that the chip distributions were different among the composite boards machined. It was found that the chips of WPC were more uniform in size compared to the chips of LVL and OSB, because of its fine structures. Cutting of WPC generated mostly flow chip (93%). A large amount of fine granule chips of OSB (through 80 mesh sieve) was observed to produce serious air pollution in the work area.

Surface roughness

The results show that the Ra value of composite boards tended to increase with increasing in cutting length (Fig. 6). The coated carbide tools generated smoother composite board surfaces than uncoated carbide tool. The AlCrN coated carbide tool tended to generate the smoothest surface in cutting LVL and OSB, whereas the TiAlN coated carbide tool tended to generate smoothest surface in cutting WPC. These facts could be attributed to the wear phenomenons. The mechanical abrasion occured during cutting resulted in an irregularity on the cutting edge of the cutting tools, which led to irregularities on the surface of the composite boards machined.

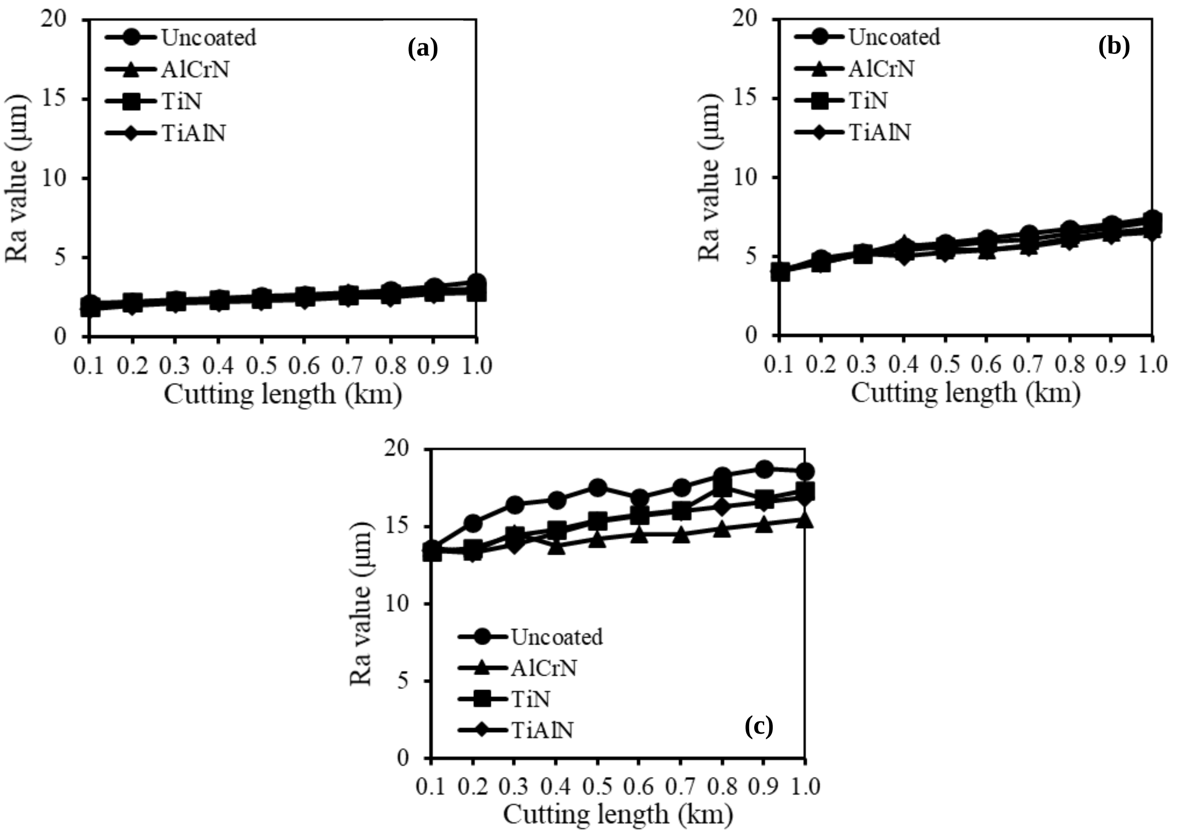

Fig. 6: Surface roughness behaviours of tungsten carbide tools in cutting: (a) WPC, (b) LVL, (c) OSB.

It was confirmed in Fig. 3 that higher irregularity on the cutting edge of AlCrN coated carbide tool compared to TiAlN coated carbide tool caused the higher surface roughness of WPC machined by the AlCrN coated tool. The same phenomenon was also reported by Wei et al. (2018). It was reported that there was a noticeable and similar tendency between surface roughness and cutting tool wear, which explain that cutting tool wear provided great influence on machining quality.

There was a considerable difference in surface roughness among the composite boards machined. The highest and the lowest surface roughness were retained by OSB and WPC, respectively for all tungsten carbide tools tested. The difference in surface roughness among the composite boards was caused by their structures. The highest surface roughness of OSB was caused by the high porosity due to the irregular orientations and sizes of the strands in the board. Conversely, WPC was form by mechanical compaction of very fine matters structure which was led to smoothest surfaces. Moreover, the difference in moisture content of OSB and WPC (11.2% and 2.1%, respectively) would also affect the surface roughness of the board. It was reported by Cleverson et al. (2015) that the increase in the moisture content causes an increase in the surface roughness.

Noise level

There was not prominent difference in noise level between uncoated and coated carbide tools for all composite boards machined (Fig. 7). The average noise level in cutting the composite boards using uncoated carbide tool, AlCrN, TiN, and TiAlN coated carbide tool was observed to be 78.5 dB, 78.4 dB, 78.2, and 78.0 dB, respectively. It could be noticed that the uncoated carbide tool tended to produce slightly higher noise compared to the coated carbide tools. TiAlN coated carbide tool generated the lowest noise level among the coated carbide tools tested. This could be due to the lower amount of wear attained by the TiAlN cutting tool edge. Since the wear occurred on the cutting tool edge due to abrasion, it would expand the contact area between the worn cutting edge and the composite boards, which led to produce the higher noise during cutting. Though AlCrN coated tool showed the lowest wear among the tungsten carbide tools tested in cutting LVL and SB, it generated the highest noise level than other coated carbide tools because of its high in hardness.

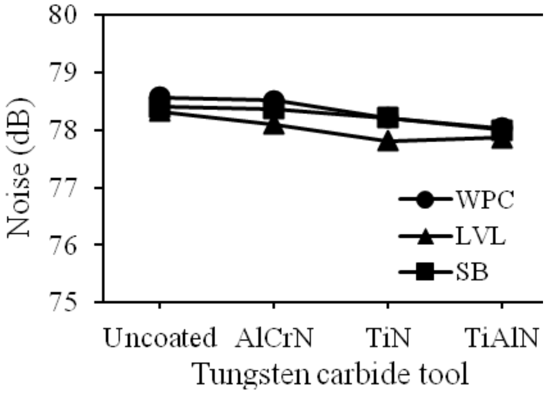

Fig. 7: Noise level in cutting composite boards using tungsten carbide tools.

The noise level was slightly different in cutting composite boards using the same tungsten carbide tools. The highest noise level was generated in cutting WPC (78.3 dB) and the lowest was in cutting LVL (78.0 dB). The difference in structure among the composite boards is considered to be the reason for this phenomenon. The high density, high hardness, high silica content, and low moisture content of WPC led to generate the highest noise during cutting compared to the other composite boards. In addition, Krilek et al. (2016) also reported the difference in structure between softwood and hardwood species generated different noise level, in which cutting of hardwood generated higher noise than softwood. Moreover, the higher moisture content of the samples was reported to reduce the emission of sound during machining (Cleverson et al. 2015).

Though LVL provided higher hardness and density compared to OSB, however cutting of OSB generated higher noise than in cutting of LVL. The noise in cutting OSB was observed to be generated from incompletely severed strands on the board. The same phenomenon was reported by Durcan and Burdurlu (2018) in cutting medium density fiberboard (MDF) of different densities. It was found that the noise level increased with decreasing of density. Decreasing density caused a reduction in elements of the cell wall or amount of substance that responding to the cutting force decreases and more breaking and crushing effect reveal.

The average noise level generated from cutting composite boards using tungsten carbide tools tested was 78.3 dB, with the maximum noise level was 81.2 dB. As recommended by ACGIH (2012), the maximum noise threshold limit value for workers is 85 dB for total duration of 8 hours per day. Therefore, cutting the composite boards using both uncoated and the coated tungsten carbide tools could be under control.

CONCLUSIONS

The coated carbide tools provide better wear resistance, smoother composite boards surfaces, and lower noise level compare to uncoated tungsten carbide tool in cutting WPC, LVL, and OSB. The difference in cutting tool tested does not provide significant difference in chip size and type. TiAlN coated carbide tool shows a better cutting performance and is suggested for machining the composite boards, especially in cutting an abrasive composite board. The abrasive materials contained in the composite boards are notable in wearing the tungsten carbide tools. The surface roughness of composite boards and the noise level increase due to increasing in the wear and could be a good indication for the wear of the tungsten carbide tools. The structure of the composite boards is observed more important than the wear of the tungsten carbide tools in determining the chip formation and surface roughness.

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