THE IMPORTANCE OF EXTRACTIVES AND ABRASIVES IN WOOD MATERIALS ON THE WEARING OF CUTTING TOOLS

Wayan Darmawan,[a,]* Istie Rahayu,[a] Dodi Nandika,[a] and Remy Marchal [b]

For many wood cutting processes, the interest of high-speed tool steels and tungsten carbides remains very important because of their good tool edge accuracy and easy grinding. The wear of high-speed steel and tungsten carbide is an important economic parameter. Wood extractives and silica have a potential adverse effect on tool wear. Rapid chemical wearing due to corrosion and mechanical wearing has been attributed to the presence of extractives and silica in wood and wood composites. This paper presents the wear characteristics of SKH51 high-speed steel and K10 tungsten carbide caused by extractive and abrasive materials present in the lesser-known Tapi-Tapi wood and wood composites of wood cement board, particleboard, MDF, and oriented strand board (OSB). Experimental results showed that wearing of the cutting tools tested was determined by extractives and silica contained in the wood and wood composites. Wood cement board, which is high in silica content, caused severe damage to the cutting edge of the high-speed steel. A corrosion/oxidation mechanism was found to contribute to the wear of SKH51 and K10 when cutting the Tapi-Tapi wood, MDF, particleboard, wood cement board, and OSB. The silica and extractives determined the abrasion and corrosion wear mechanism to a varying degree.

Keywords: Wear resistance; high-speed steel; Tungsten carbide; Silica; Extractive; Wood composite

Contact information: a: Department of Forest Products, Faculty of Forestry, Bogor Agricultural University (IPB), Bogor (16680) Indonesia; b: Arts et Metiers ParisTech, Cluny, France.
** Corresponding author: wayandar@indo.net.id*

INTRODUCTION

Tropical woods and wood composites are being machined in large and increasing quantities in many countries for building construction and decorative purposes. As the tropical woods and wood composites are machined extensively into useful products, cutting tool wear is becoming an important economic parameter. Despite the extensive use of the tropical woods and wood composites in the wood industry, knowledge of wearing characteristics of cutting tools used for machining the tropical woods and wood composites is limited. Therefore, investigating the wear characteristics of cutting tools will lead to making better choices of cutting tool materials used to cut the tropical woods and wood composites.

High-speed steel and tungsten carbide cutting tools are widely used in the woodworking industry throughout Indonesia for machining tropical woods and wood composites. Such products generally are high in extractives and abrasive materials. Few studies been done to extensively explore chemical components of the commercial wood species. It has been noted that their extractives range from 1.4% to 13.8%, and their ash-contents range from 0.1% to 5.0% (Martawijaya *et al.* 1989).

It is known that chemical components of the woods may play an important role in determining cutting tool wear rates. To adequately describe the wear mechanisms, wood and cutting tool interactions must be considered. This is not a simple problem due to the large number of possible interactions, as well as difficulties in characterizing each of these interactions. There is evidence that the extractives in wood act as lubricants and effectively decrease the coefficient of friction during wood cutting (McKenzie and Karpovich 1968); however, many studies indicate that the extractives in wood adversely affect wearing of cutting tools. Hillis and McKenzie (1964) postulate a chelation reaction between polyphenolic extractives and the iron in steel cutting tools as a wear mechanism. McKenzie and Hillis (1965) produced etching on steel knives by exposing them to chemical solutions typical of those found in wood. Their results showed that a measurable amount of tool wear was due to chemical reaction between the cutter and the wood being cut. Kirbach and Chow (1976) emphasized the complexity of tool wear problems inherent in the multi-component nature of the work and tool materials. It was noted in their study that the wear of carbide tools was due to a chemical attack of the tool material binder and a mechanical failure of the exposed carbide grains.

In the period after 1980, chemical wear due to extractives in the woods, such as gums, fats, resins, sugars, oils, starches, alkaloids, and tannins, has also been reported as an important factor in determining the overall wear of woodworking cutting tools (Fukuda *et al.* 1992; Krilov 1986; Morita *et al.* 1999; Murase 1984; and Darmawan and Tanaka 2006). Extractives vary in chemical composition, amount, and reactivity among tropical wood species, which might affect their degree of chemical impact on cutting tool materials.

Rapid mechanical wearing of cutting tools has often been attributed to the presence of silica and other abrasive agents in the woods (Hayashi and Suzuki 1983; Huber 1985; Porankiewicz and Gronlund 1991; Darmawan *et al.* 2011). It was noted in these studies that woods with high silica content caused high wear rate of high-speed steel cutting tool. However, the authors did not explain in detail the importance of silica content and its distribution on the wearing phenomenon of the high-speed steel cutting tool.

The Indonesian industry is now about to utilize lesser known species and fast growing wood species for construction, furniture, and wood composite products (wood cement board, particleboard, medium density fibreboard (MDF), and oriented strand board (OSB)). These wood composites are made of a mixture of fast growing wood species. Investigation of chemical and mechanical wearing of cutting tools, which are used to machine lesser known wood and wood composites made of fast growing species, have received little attention. The focus of this study was to investigate the effect of extractives and silica contained in a lesser known species (Tapi-Tapi wood) and wood composites (wood cement board, particleboard, MDF, and OSB) on chemical and mechanical wear characteristics of high-speed steel and tungsten carbide cutting tools. This paper indicates that progress has been made toward a better understanding of the wearing phenomenon of high-speed steel and tungsten carbide cutting tools in cutting the Indonesian tropical woods and wood composites. It is hoped that the knowledge obtained in this study will be used to produce improved cutting tools, which will lower the processing cost for wood manufacturers.

EXPERIMENTAL

In the first phase of this research, experiments were performed to study the interaction between wood and wood composite extractives and cutting tools materials. The acidity (pH) of wood and wood composite tested (Table 1) was determined by dissolving 10 g of 50 mesh wood and wood composite powders in 50 mL of distilled water. The solution was heated in a water bath for about 30 minutes at 80°C. Afterwards, the solution was cooled and filtered with filter paper. The pH of the solution was measured using a pH meter.

Table 1. Specification of Wood Materials

Properties	Wood Materials				
	Tapi-Tapi wood	Wood cement board	Particleboard	MDF	OSB
Density (g/cm^3)	0.48	1.10	0.65	0.62	0.61
Moisture (%)	13.9	12.2	14.4	14.4	10.6

The extractive content of wood was determined by using the ethanol/benzene extraction method. Extractions were performed on 10 g of 50 mesh wood powder of Tapi-Tapi (*Santiria laevigata*), wood cement board, particleboard, MDF, and OSB using TAPPI T204 om-88 procedures (TAPPI 1991a). The extractive contents were calculated based on the percentage of extract dry weight to powder dry weight.

TAPPI T211 om-85 procedures were used to determine the ash and silica content of these wood materials (TAPPI 1991b). Ash and silica determinations were performed on 10 g of 50 mesh wood powder, which was heated in a furnace at 600°C for 6 hours. Ash content was calculated based on the percentage of ash weight to powder dry weight. The resultant ash was added to 20 mL of 4N HCl and heated in a water bath at 80°C. The ash solution was diluted with distilled water. Then $AgNO_3$ was used to indicate that the diluted ash solution was free of Cl. The solid sediment was heated at 105 ± 3°C to obtain the constant weight of silica. Silica content was calculated based on the percentage of silica weight to powder dry weight. In order to determine the abrasive material distribution in the wood and wood composites, wood sample of 2 x 2 x 2 cm and wood composites sample of 1.2 x 2 x 2 cm were analyzed by scanning electron microscope/energy dispersive spectroscopy (SEM/EDS). A sample was precisely placed inside an opened-metal box with the dimensions of 2.1 x 2.1 x 2.1 cm. The box was held rigidly inside the vacuum chamber of the SEM machine for the EDS analysis on the surface of the sample.

New tips of SKH51 high-speed steel and K10 tungsten carbide (Table 2), which were characterized by Japan Industrial Standard (JIS), were reacted with the prepared extractive solutions (10 g of 50 mesh wood powder in 100 ml ethanol/benzene) in a stirred slurry. The mixtures were allowed to react for 48 hours at 80°C by considering the fact that chemical wear due to oxidation or corrosion has started to occur at the initial stage of cutting and at temperatures 100°C for cutting a speed of 20 m/s. After the termination of reaction, the tips of the tool materials were dried and analyzed under SEM/EDS to characterize the possible corrosion that occurred on the surface of the tip of tool materials. Then the tips were cleaned with chloroform and dried, and their weight losses were determined.

Table 2. Specification of Cutting Tool Materials

Tool Materials	Specification			
	Dimension	Metal Components	Heat Treatment	Hardness
SKH51 high-speed steel	2x10x20 mm	C=0.88, Si=0.25, Mn=0.30, P=0.02, S=0.001Cr=4.04, W=6.13, Mo=4.92, V=1.85%wt	Hardened at 1220 ^{o}C followed by two times of one hour tempering at 560^{o}C with cooling in air	815 $HV_{0.5}$
K10 Tungsten carbide	2x10x20 mm	WC=94%, Co=6%wt	-	1450 $HV_{0.5}$

In the second phase of this research, the Tapi-Tapi wood and the wood composites in Table 1 were routed in up-milling direction on the Computer Numerical Control (CNC) Router using SKH51 high-speed steel, and K10 tungsten carbide bits, which are characterized according to Japan Industrial Standard (JIS). The Tapi-Tapi wood samples in the size of 6 x 12 x 100 cm were selected from the heartwood. The samples for the wood cement board, particleboard, MDF, and OSB were ordered and prepared in the size of 1.2 x 100 x 100 cm. The bits specification and routing conditions are summarized in Tables 3 and 4, respectively.

Table 3. Specification of Router Bits

Specification	Router Bits	
	SKH51 high-speed steel	K10 tungsten carbide
Bit diameter	16 mm	16 mm
Number of knife	1	1
Rake angle	10^{o}	10^{o}
Clearance angle	15^{o}	15^{o}
Hardness	815 $HV_{0.5}$	1450 $HV_{0.5}$

Table 4. Routing Conditions

Variable	Condition
Cutting speed	17 m/s
Feed	0.1 mm/rev
Spindle speed	20000 rpm
Feed speed	2000 mm/min
Width of cut	2 mm
Depth of cut	2 mm

A schematic diagram of the routing in the milling direction is presented in Fig. 1. The amount of wear on the clearance face of the bits was measured intermittently at every 200 m cutting length up to 2000 m cutting length. The schematic diagram of the wear measurement on the clearance face is described in Fig. 2. The wear measured was the amount of edge recession and edge abrasion. Their wear patterns were also characterized under an optical video microscope and scanning electron microscope (SEM).

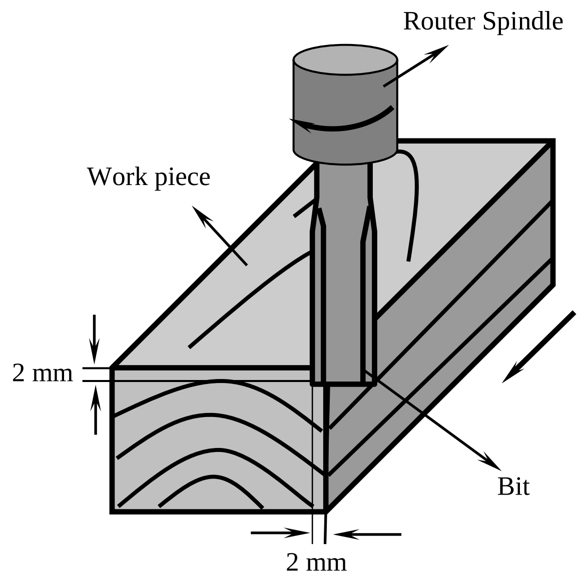

Fig. 1. Schematic diagram of routing on the edge of the work piece

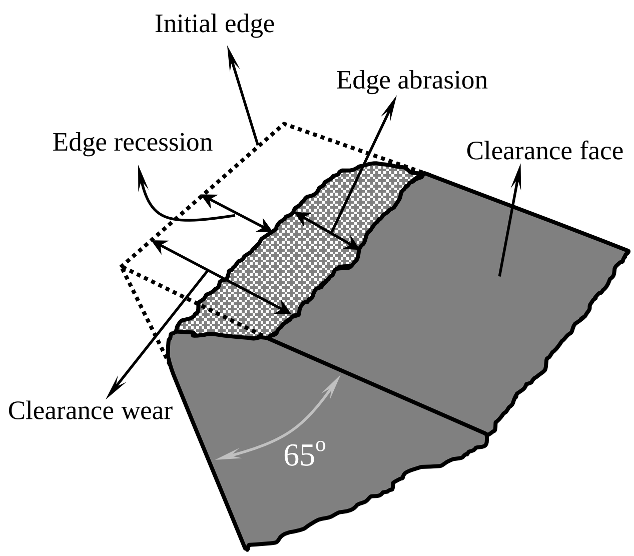

Fig. 2. Schematic diagram of wear measurement on clearance face of cutting tool

RESULTS AND DISCUSSION

Chemical Wear Caused by Extractives

Extractives and silica content in the wood materials, as well as the percentage of weight loss of tool materials after 48 hours of exposure to wood material extracts at 80^{o}C are presented in Tables 5 and 6, respectively. The amount of chemical wear in this work was determined by the percentage of weight loss of the tool materials. The results in Table 5 show that the Tapi-Tapi wood was acidic and the wood composites tested were nearly neutral in pH. The wood materials varied slightly in extractive content. Tapi-Tapi wood had the highest extractive content, and wood cement board had the highest silica content.

Table 5. Chemical Characteristics of the Experimented Wood Materials

Wood Materials	Ph	Extractive (%)	Ash (%)	Silica (%)
Tapi-Tapi	4.47	13.8	1.27	0.75
Wood cement board	7.78	9.6	94.2	55.1
Particleboard	6.61	11.6	2.87	1.20
MDF	7.05	10.9	6.0	0.95
OSB	6.16	8.8	2.41	0.47

Table 6. Percentage of Weight Loss of Tool Materials after 48 Hours Reaction at 80°C with Wood Materials Extract

Tool Materials	Wood Extract				
	Tapi-Tapi Wood	Wood Cement Board	Particleboard	MDF	OSB
SKH51	0.48	0.06	0.08	0.11	0.14
K10	0.11	0.01	0.02	0.02	0.05

The results in Table 6 indicate that SKH51 and K10 tool materials suffered weight losses for all wood materials. High extractives content of these wood materials could be the reason for the weight loss of the tool materials. High extractives and acidity of Western red cedar (Kirbach and Chow 1976) and of eucalypt (Krilov 1986) were noted to cause corrosion of steel cutting tools. The SKH51 and K10 tool materials suffered the highest percentage of weight loss when they were soaked in Tapi-Tapi wood extract. Though the amount of extractives per unit oven dry volume in the Tapi-Tapi wood was almost the same with the others, the extractives of Tapi-Tapi wood had the strongest acidity. This indicates that the strong acidity of chemical compounds in the Tapi-Tapi wood extract compared to the others is more reactive to elements of the tool materials. It was investigated that the surface of the tip of SKH51 after soaked in Tapi-Tapi extract was covered by a light brown compound. Under SEM/EDS analysis, the light brown compound revealed some chemical elements dominated by iron oxide (Fe and O) as shown in Fig. 3a. The presence of Fe and O indicated the occurrence of corrosion on the surface of the tip of tool materials. The corrosion could take place on certain parts of the surface of the tip, as indicated by high peaks of O profile in Fig. 3b.

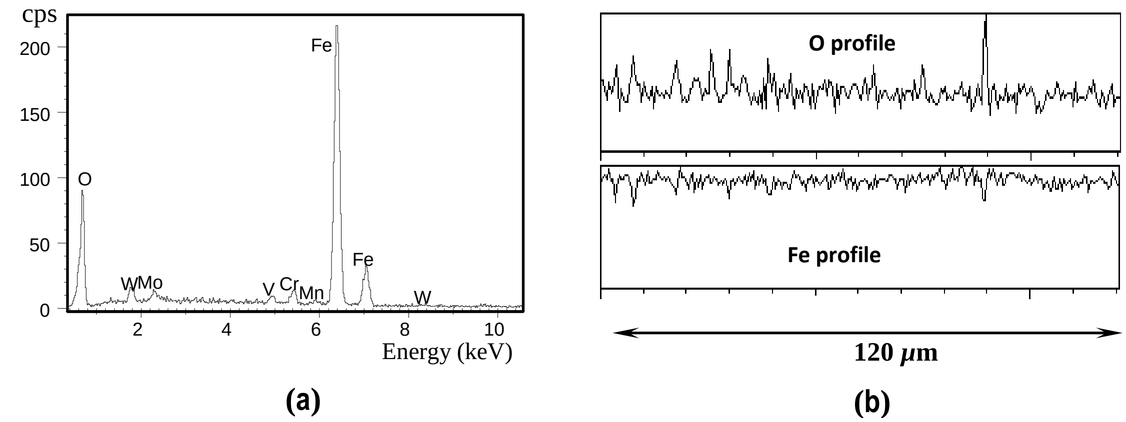

Fig. 3. SEM/EDS analysis indicating corrosion on the surface of the SKH51 tool material after reaction with the Tapi-Tapi wood extract

The SKH51 tool materials suffered higher weight loses when compared to K10 tungsten carbide for all wood materials. This phenomenon is considered to be the result of wide variation in metal components of the SKH51. The iron (Fe) in the SKH51 was susceptible to suffer corrosion as attacked by reactive chemical compounds of wood extractive, rather than tungsten carbide (WC) and cobalt (Co) in the K10 tungsten carbide (Table 1). This fact could also be related to the phenomenon that the microstructure of the tungsten carbide tools, which consists mainly of austenitic and martensitic matrix, are more stable and more resistance to chemical reaction than that of the hardened steel tools, which consists mainly of ferrite (Pipple *et al.* 1999).

Mechanical Wear of Tool Bits

The amount of mechanical wear was determined by the amount of knife-edge recession and abrasion on the clearance face of the bits. Wear behaviour on the clearance face of the bits is presented in Fig. 4, and wear pattern of the bits is presented in Fig. 5. The wear rates of the bits obtained from the linear regression equation in Fig. 4 are summarized in Table 7.

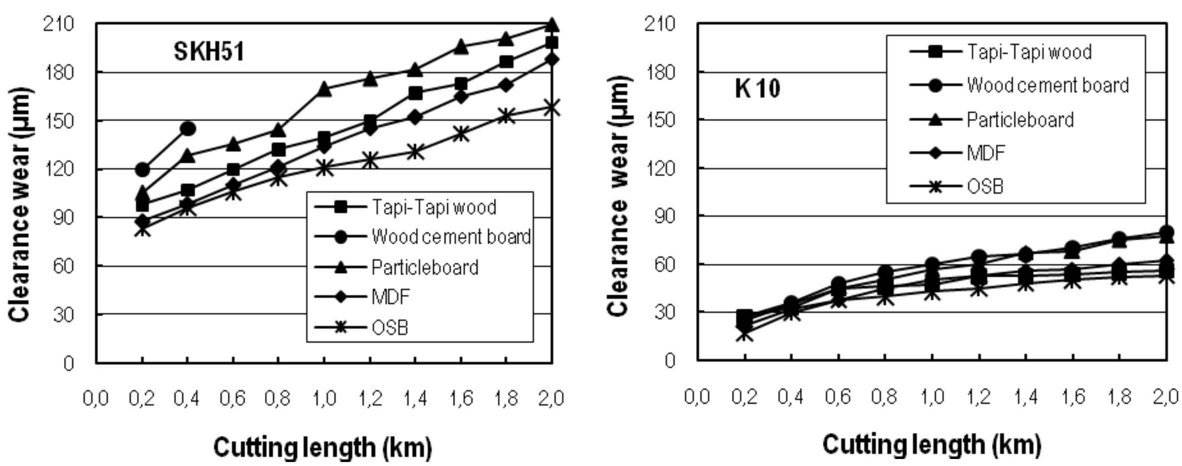

Fig. 4. Wear behaviors of the SKH51 and K10 bits with cutting length in routing wood materials

The results in Fig. 4 indicate that wood cement board and particleboard wore the SKH51 and K10 bits faster when compared to the other wood materials. Wood cement board and particleboard also caused the largest rate of wear of the bits tested (Table 7). High-speed steel suffered a remarkable fracture edge wear at 300 m cutting length in the wood cement board. The cutting test of the high-speed steel for wood cement board was stopped at the 300 m cutting length due to the serious damage of the cutting edge. This is attributed to the much higher content of silica, which has an average hardness of about 1200 HV, in the wood cement board compared to that in the other wood materials tested (Table 5).

Table 7. Rate of Wear (μm/km) of the Router Bits for Different Wood Materials According to Linear Function in Figure 4

Bits	Wood Materials				
	Tapi-tapi	Cement Board	Particleboard	MDF	OSB
SKH51	53.9	150,0	58.4	54.4	39.6
K10	17.6	27.9	27.3	20.9	17.1

It was visually investigated that the hard particles of cured cement were distributed evenly in the matrix of the wood cement board. The cement used in the production of this wood cement board consisted of 75% limestone ($CaCO_3$), 20% silica (SiO_2) and alumina (Al_2O_3), and 5% incidental ingredients (SO_3 and MgO). The SEM photomicrographs of particleboard and OSB also revealed cured thermosetting resin. It was investigated that the outer and inner parts of particleboard contained higher dosage of the thermosetting resin of urea-formaldehyde when compared to OSB and MDF. The cured cement and thermosetting resin were considered to impose severe mechanical abrasion on the cutting tool edges during the cutting the wood cement board and particleboard.

The SEM micrograph of Tapi-Tapi wood in Fig. 6a reveals a few round crystals. EDS analysis indicated the round crystals consisted of Si and O (Fig. 6a, right). This analysis confirms the previous result that silica compounds in wood have the form of silicon dioxide (SiO_2) (Misra *et al.* 1993). In addition, silicon dioxide in woods occurred at the inter-layer of tracheids, ray parenchymas, and bordered pits without any geometrical form (Jing and Zhou 1989). It appears under high magnification that the surface of the silica crystals in the Tapi-Tapi wood was corrugated, which caused high mechanical abrasion when cutting.

The results in Figure 6b-e (right) show EDS analysis of elemental profiling on randomly selected spectra at the surface of the SEM micrographs. The presence of Si and O in the spectra indicated the presence of silica in the tested wood materials. EDS analysis on the SEM micrograph in Fig. 6b shows that the cured cement consisted of Ca, Si, O, Al, K, Mg, and C. This EDS result confirmed the essential raw ingredients of cement (limestone, silica, and alumina). The EDS results from the SEM micrographs of particleboard, MDF, and OSB also revealed the presence of Si and O, which indicated the presence of silica.

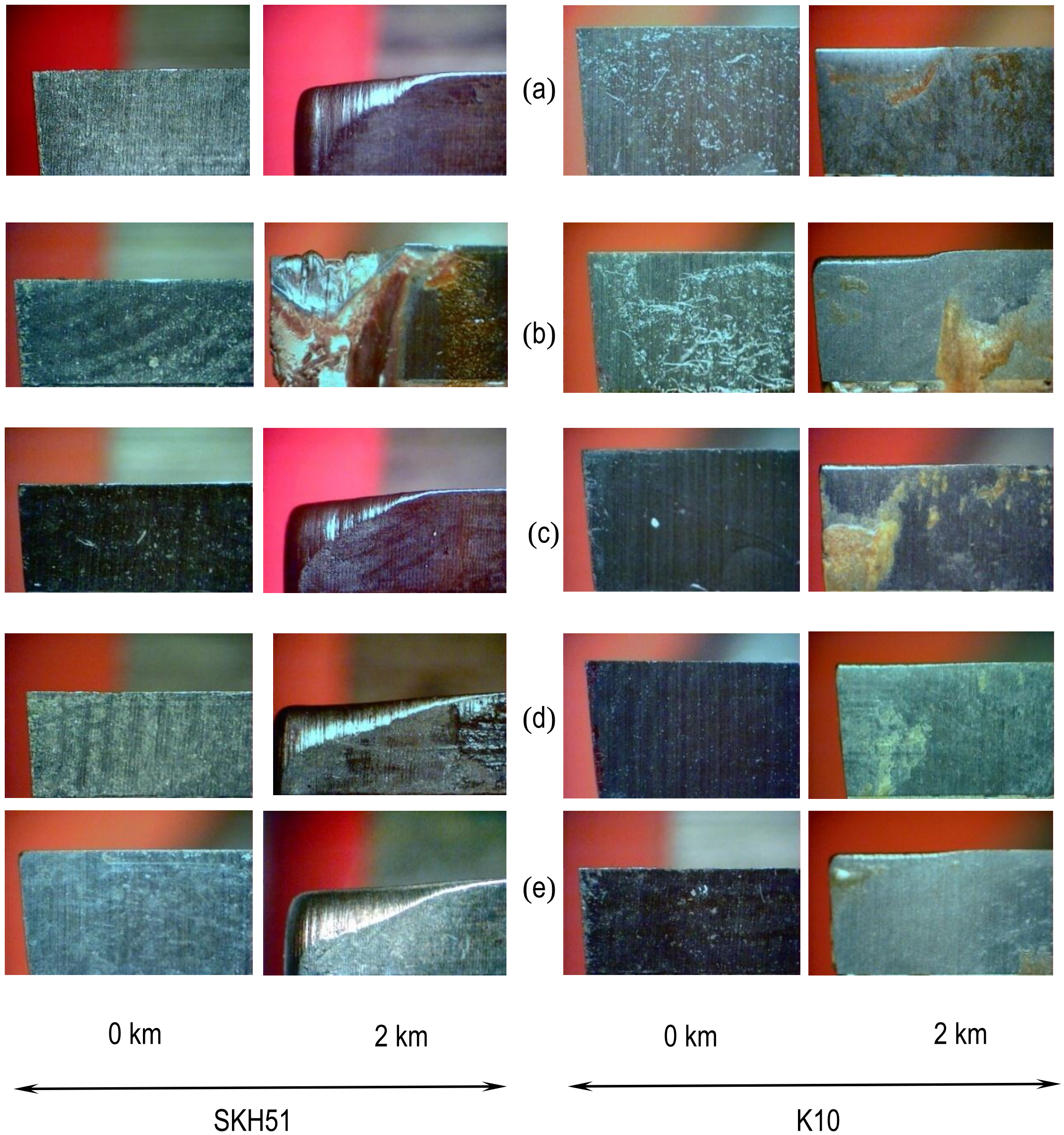

Fig. 5. Wear patterns of the SKH51 high-speed steel and K10 tungsten before and after 2 km cutting length for Tapi-Tapi wood (a), wood cement board (b), particleboard (c), MDF (d), and OSB (e)

The occurrences of silica in Tapi-Tapi wood, wood cement board, particleboard, MDF, and OSB in every 500 μm^2 spectrum of the SEM photomicrographs gives an indication that the cutting edge of the bits would engage the silica during cutting these wood materials. The higher frequency of occurrence of silica in the wood cement board, particleboard, and Tapi-Tapi wood would cause the cutting edge of the bits to be dulled at a faster rate compared to MDF and OSB.

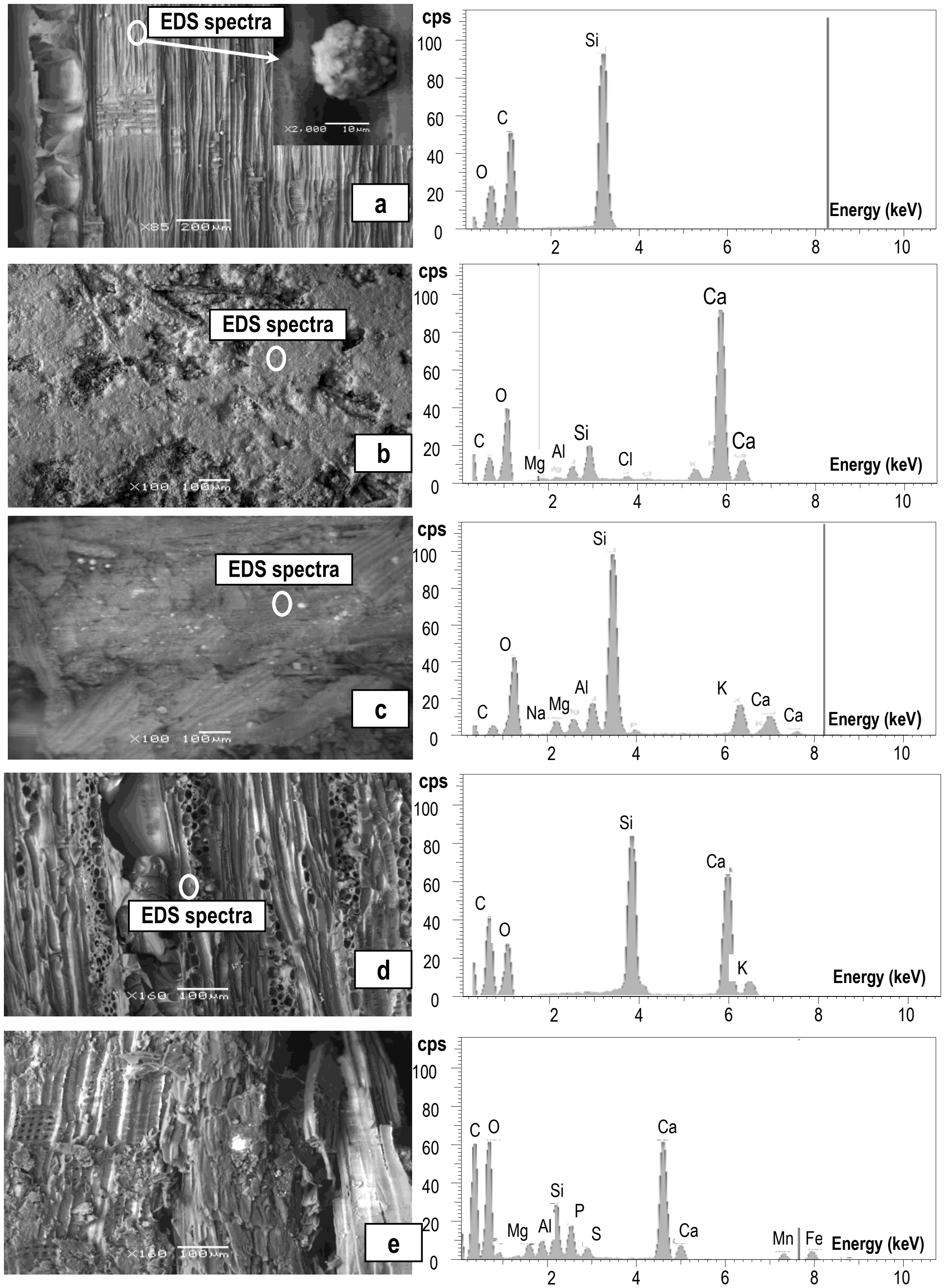

Fig. 6. SEM/EDS analysis of the wood materials showing the abrasives for Tapi-Tapi wood (a), wood cement board (b), particleboard (c), MDF (d), and OSB (e)

It appears from the results in Fig. 4 and Table 7 that the clearance wear and the wear rate of the SKH51 bit were twice as large compared to those of the K10 tungsten carbide bit when cutting the same wood materials. Further, the results in Fig. 7 give an indication that the rate of clearance wear for both SKH51 and K10 increased linearly with increasing in the silica content. However, the progress of wear rate with increasing in the silica content was quite different. The clearance wear of the SKH51 would increase at a faster rate compared to that of the K10 carbide with an increase in the silica content of the work materials. The lower resistance to chemical attack by extractive and the reduced hardness of the SKH51 compared to that of K10 carbide bit (Table 3) is considered as the reason for this phenomenon.

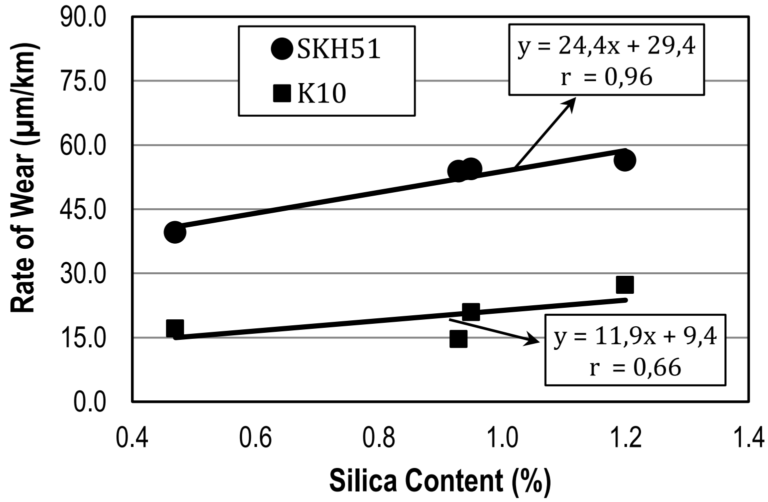

Fig. 7. Relationship between rate of clearance wear and silica content for SKH51 and K10 bits. Note : y (Rate of Wear), x (silica content), r (correlation coefficient)

The results in Fig. 5 give an indication that wear patterns of the SKH51 bits were the same for all wood materials, except for wood cement board. The cutting edge with sharpness angle of 65^{o} used in this experiment was not strong enough for the SKH51 bit to cut the wood cement board.

The initial failure of the cutting edge occurred due to severe fracture wear. Therefore, it could be recommended to use a sharpness angle around 90^{o} with a negative rake angle, especially for the cutting the wood cement board. Considering the results in the previous paper (Darmawan *et al.* 2001) and the facts that the wood materials tested are air-dried and are routed at a low cutting speed, the wear patterns of the bits in Fig. 5 were predominantly caused by mechanical abrasion. However, there was a slight difference in clearance wear pattern between the K10 tungsten carbide and SKH51 high-speed steel.

The cutting edge of K10 tungsten carbide compared to SKH51 was more corrugated, especially when cutting the wood cement board and particleboard (Fig. 8, under). The SEM micrograph of the K10 reveals that the corrugated edge was caused by lower toughness of the K10 tungsten carbide compared to the SKH51, which leads to retraction of carbide grain from the fraction.

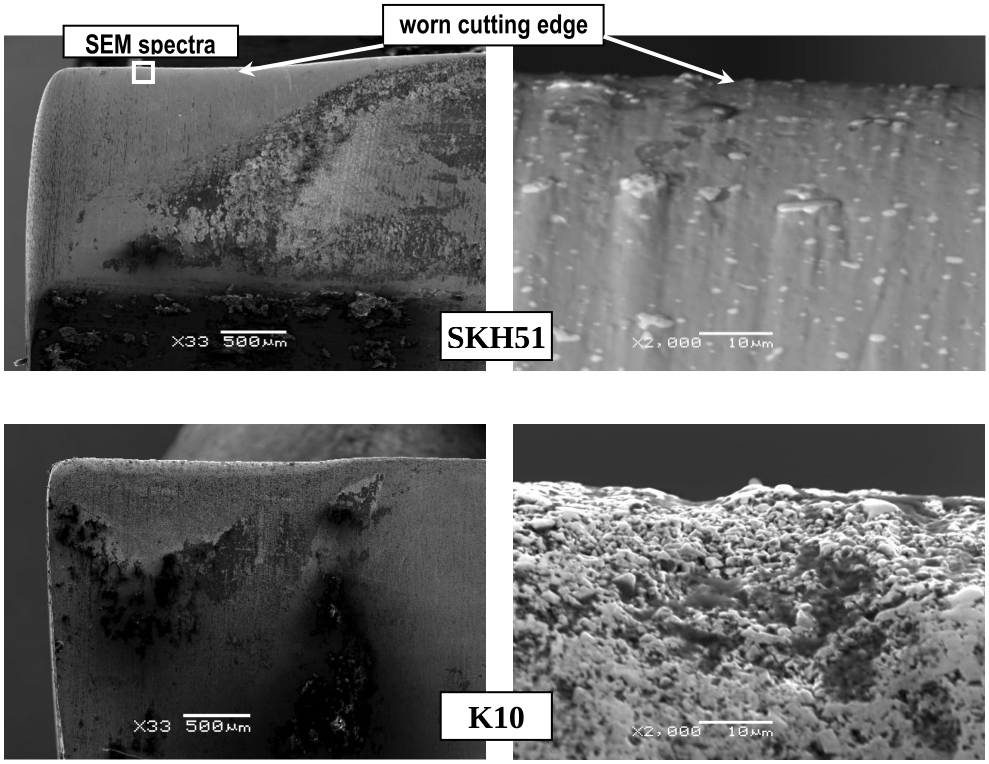

Fig. 8. SEM micrograph of the worn cutting edge of the high-speed steel (upper) and tungsten (under) in cutting Tapi-Tapi wood at the 2 km cutting length

The Importance of Silica and Extractive in the Wearing of SKH51 and K10

Mechanical and chemical interactions of silica and extractives onto cutting tool surfaces played an important role in the process of wearing of SKH51 and K10. The wearing of the SKH51 and K10 cutting edges was observed due to corrosion and abrasion mechanisms. The dominant type of wear in routing the Tapi-Tapi, wood cement board, particleboard, MDF, and OSB was mechanical abrasion due to silica. However, a corrosion/oxidation mechanism was also found to provide an important contribution to the wear of SKH51 and K10 when cutting the Tapi-Tapi, wood cement board, particleboard, MDF, and OSB. The results in Fig. 9 indicate that the silica and extractives determined the wear rate of the SKH51 and K10 to a varying degree. Though Tapi-Tapi wood compared to MDF is lower in density and silica content, they caused almost the same rate of wear to the SKH51. This phenomenon gives an indication that the corrosion mechanism was a major contributor to the wear of SKH51 when cutting the Tapi-Tapi wood.

In this study, high percentages of Fe and O were detected in the surface of the SKH51 after it had been soaked in the extract of Tapi-Tapi wood (Table 6, Fig. 3). Further, the Fe and O were observed to form red brown compounds of iron oxide on the surface of cutting edge of SKH51 after routing the Tapi-Tapi wood. The red brown compounds were easily removed by mechanical abrasion as the cutting edge of the SKH51 engaged the Tapi-Tapi wood. Therefore, the presence of corrosion will promote faster rate of cutting tool wear. However, when the Tapi-Tapi was routed using K10 cutting tool, corrosion /oxidation mechanism was found to be a minor contributor to the wear of the K10. It also appears from the results in Fig. 9 that a silica content of 0.47% in OSB and of 0.75% in Tapi-Tapi wood caused almost the same wear rate to the K10 cutting tool. This result indicates that wear mechanisms other than abrasion by silica and corrosion by extractive may contribute to the wear of K10 when cutting the OSB. In this study, OSB and particleboard machined consisted of urea formaldehyde resin, additives, and catalyst. Kim *et. al.* 1999 stated that the acidity effect and corrosion/oxidation mechanisms of anionic components of additives and catalysts are responsible for an increase in cutting tool forces and cutting tool wear.

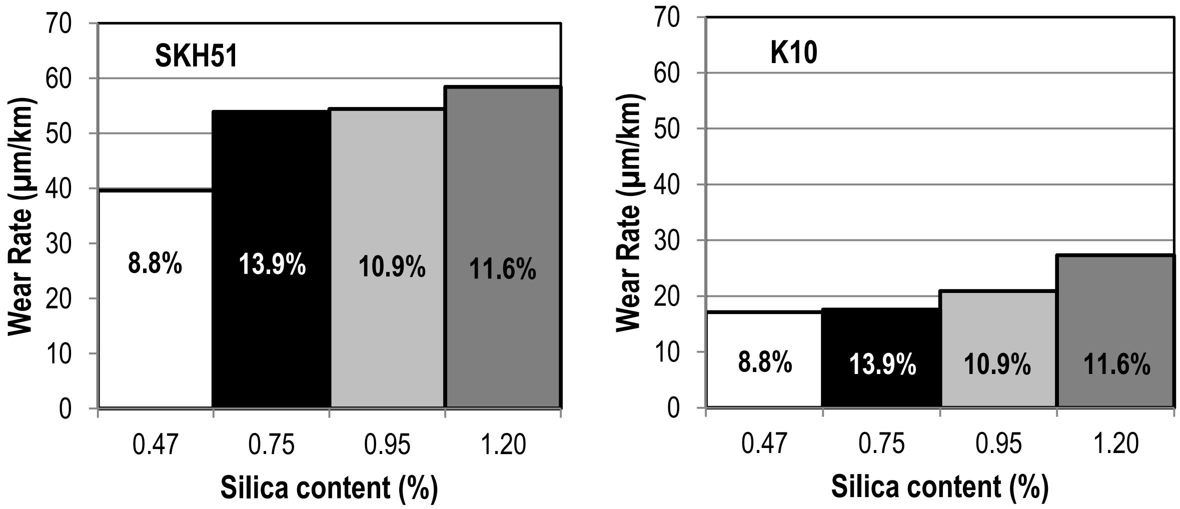

Fig. 9. Interaction effect of silica and extractive on the wearing rate of SKH51 and K10 cutting tools. Note : extractive content of 8.8% (OSB), 10.9% (MDF), 11.6% (particleboard), 13.9 (Tapi-Tapi)

Abrasion has been considered to be the major tool wear mechanism in cutting the MDF, particleboard, and wood cement board in this study. However, machining wood based products such as MDF, particleboard, and wood cement board also involve high temperatures and presures near the cutting tool edge. In the previous study, temperatures were measured and estimated to be in the range 300 to 400^{o}C at the cutting tool edge when cutting MDF and wood cement board at 20 m/s cutting speed (Darmawan *et. al.* 2001). Further, Reid *et al.* (1991) noted that thermal decomposition of MDF was evident at 325^{o}C. The results of energy dispersive spectroscopy (EDS) mapping of worn cutting tool edge in these studies indicated that oxidation/corrosion mechanism contributed significantly to the wear of tungsten carbibe cutting tools when cutting MDF and wood cement board.

CONCLUSIONS

From the findings in this experiment, it could be summarized that extractives of the wood materials were important in the chemical wearing of SKH51 and K10 tool materials. Among the wood materials, Tapi-Tapi wood caused the largest percentage of weight loss of the tool materials due to corrosion.

Silica content and distribution in the wood materials were important in determining the mechanical wearing of the SKH51 and K10 bits. The rate of the mechanical wear increased with increasing in the silica content. Wood cement board and particleboard were the most abrasive materials, and they wore the SKH51 and K10 bits faster when compared to other wood materials.

Though SKH51 high-speed steel tool material had lower resistance to chemical wearing by wood extractives and to mechanical wearing by the silica compared to K10 tungsten carbide, the worn edge of SKH51 was less corrugated when compared to K10.

Abrasion has been considered to be the major tool wear mechanism for the SKH51 and K10 cutting tools. However, in this study a corrosion/oxidation mechanism was also found to provide an important contribution to the wear of SKH51 and K10 when cutting the Tapi-Tapi wood, MDF, particleboard, wood cement board, and OSB. The silica and extractive determined the abrasion and corrosion wear mechanism of the SKH51 and K10 to a varying degree.

ACKNOWLEDGEMENTS

The authors thank KANEFUSA for supporting the SKH51 and K10 tool materials and thank the Directorate for Research and Community Service of the Ministry of National Education for the Republic of Indonesia for the research grant.

REFERENCES CITED

Darmawan, W., Tanaka, C., Usuki, H., and Ohtani, T. (2001). "Performance of coated carbide tool in turning wood-based material: Effect of cutting speeds and coating materials on the wear characteristics of coated carbide tools in turning wood-chip cement board," *Journal of Wood Science* 47(5), 342-349.

Darmawan, W., and Tanaka, C. (2006). "Chemical and mechanical wearing of woodworking cutting tools by tropical woods," *Journal of Tropical Forest Science* 18(4), 166-172.

Fukuda, H., Banshoya, K., and Murase, Y. (1992). "Corrosive wear of wood-cutting tools I. Effects of tool materials on the corrosive wear of spur machine bits," *Mokuzai Gakkaishi* 38(8), 764-770.

Hillis, W. E., and McKenzie, W. M. (1964). "Chemical attack as a factor in the wear of woodworking cutters," *Forest Products Journal* 14(7), 310-312.

Huber, H. (1985). "Tool wear influenced by the contents of particleboard," In: *Proceedings of the 8th International Wood Machining Seminar*, 7–9 October 1985, California, pp. 72–85.

Jing, X.-M., and Zhou, Y. (1989). "SEM observation on crystals and silica in wood species of Chinese Gymnospermae," *Acta Botanica Sinica* 31(11), 835-840.

Kim, M. G., Stewart, H. A., and Wan, H. (1999). "Effects of anionic components of urea formaldehyde resins used as particleboard binders," *Forest Products Journal* 49(4), 60-65.

Kirbach, E., and Chow, S. (1976). "Chemical wear of tungsten carbide cutting tools by western red cedar," *Forest Products Journal* 26(3), 44-48.

Krilov, A. (1986). "Corrosion and wear of sawblade steels," *Wood Science and Technology* 20(4), 361-368.

McKenzie, W. M., and Hillis, W. E. (1965). "Evidence of chemical acceleration of wear in cutting plant materials," *Wear* 8(3), 238-243.

McKenzie, W. M., and Karpovich, H. (1968). "The frictional behaviour of wood," *Wood Science and Technology* 2(2), 139-152.

Martawijaya, A., Kartasujana, I., Kadir, K., and Prawira, S. (1989). *Atlas Kayu Indonesia*, Forest Products Research Institute, Bogor.

Misra, M. K., Ragland, K. W., and Baker, A. J. (1993). "Wood ash composition as a function of furnace temperature," *Biomass and Bioenergy* 4(2), 103-116.

Morita, T., Banshoya, K., Tsutsumoto, T., and Murase, Y. (1999). "Corrosive wear characteristics of diamond-coated cemented carbide tools," *Journal of Wood Science* 45(6), 456-460.

Murase, Y. (1984). "Effect of tool materials on the corrosive wear of wood-cutting tools," *Mokuzai Gakkaishi* 30(1), 47-54.

Pipple, E., Woltersdorf, J., Pockl, G., and Lichtenegger, G. (1999). "Microstructure and nanochemistry of carbide precipitates in high-speed steel S6-5-2-5," *Materials Characterization* 43(1), 41-55.

Porankiewicz, B., and Gronlund, A. (1991). "Tool wear-influencing factors," In: *Proceedings of the 10th International Wood Machining Seminar*, 2-4 October 1991, Kyoto, pp. 220-229

Reid, A., Stewart, H. A., and Rapp, A. (1991). "High-temperature reactions of tungsten carbide cobalt tool material with MDF," *Forest Products Journal* 41(11/12), 12-18.

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

TAPPI. (1991b). *TAPPI Test Methods: Solvent Extractives of Wood and Pulp* (T 204 om-88), Volume 1, TAPPI Press, Atlanta.

Article submitted: June 1, 2012; Peer review completed: July 15, 2012; Revised version received: July 28, 2012; Accepted: August 4, 2012; Published: August 10, 2012.