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Tool Temperature and Cutting Forces during the Machining of Particleboard and Solid Wood

[1]J. Ratnasingam, [2]T. Pew Ma and [1]G. Ramasamy
[1]Faculty of Forestry, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia
[2]Tool Technology (M) Sdn. Bhd. Lot. 18-C, Jalan 2, Sungai Buloh Industrial Estate,
53100 Selangor, Malaysia

Abstract: A series of machining experiments were carried to determine the tool edge temperature and cutting forces when cutting particleboards and solid wood. The experiments were carried out using a specially designed high speed lathe with cemented tungsten carbide tools, which machined a rotating disc of the experimental materials. The cutting forces were measured using a piezoelectric load cell, while the cutting temperature was recorded through thermocouples, specially attached to the knife inserts. The particleboards used in this study were made from oil palm empty fruit bunches and rubberwood, while solid rubberwood was the solid wood specimen. The results showed that the increase in principal cutting forces had a similar pattern with the temperature increase at the tool edge, implying a direct relationship between cutting forces and tool temperature. The cutting temperatures of 196°C for particleboard and 127°C for the solid wood, suggests that tool temperatures are lower than the temperatures at the cutting zone in the work-piece. Further, this study also proves that the possibility of electrochemical mechanisms on the wear of cemented tungsten carbide tools is limited, but the temperatures recorded at the tool edge are sufficient to accelerate the mechanical-abrasive wear of such tools. Nevertheless, the results of the study imply that the development of special cemented tungsten carbide cutting tools is deemed necessary for the cutting of particleboards to ensure its process economics.

Key words: Machining, particleboard, solid wood, tool-wear, oxidation, mechanical-abrasive wear

INTRODUCTION

The use of cemented tungsten carbide tools in the wood products industry has been increasing over the years, due to its superior hardness compared to carbon steels, tool steels and cast cobalt alloys. Consequently, such tools have also been found to provide longer tool life and improved tooling economics (Bayoumi and Bailey, 1985; Sheikh-Ahmad and Bailey, 1999) and are therefore recommended for the machining of the abrasive fiber-composite materials. In a report by Ratnasingam *et al.* (2008), it was noted that cemented tungsten carbide tools have replaced the High Speed Steel (HSS) tools as the predominant cutting tool material for the wood products industry in the South East Asian region. The report also found that cemented tungsten carbide tools was the recommended cutting tool material for machining Oil Palm Empty-Fruit Bunch (OPEFB) particleboard, which is regarded as one of the most abrasive material on cutting tools (Ratnasingam *et al.*, 2009).

Despite its increasing use in machining of wood products, the wear characteristic of cemented tungsten carbides has not been thoroughly studied. Although, several reports are available on the wear of cemented tungsten carbides tools when machining wood products under different conditions (Bayoumi and Bailey, 1985; Sheikh-Ahmad and Bailey, 1999; Sheikh-Ahmad *et al.*, 2003b; Saito *et al.*, 2006), the predominant wear mechanisms of cemented tungsten carbide tools when machining wood products remain inconclusive. Klamecki (1980) suggested that the wear of tungsten carbide tools, generally takes place by preferential removal of the cobalt binder by chemical attack under the influence of high temperatures, followed by the softening of the cobalt matrix, which in turn allows the mechanical removal of the carbide grains (Saito *et al.*, 2006). In other circumstances, electrochemical corrosion was found to be the predominant wear mechanism especially when machining wood products with high moisture contents, in excess of 18% (Klamecki, 1980; Saito *et al.*, 2006). Against this background, it is apparent that the wear mechanisms of cemented tungsten carbide tools is inconclusive and is highly dependent on the conditions prevailing at the tool edge-work piece interface.

Ratnasingam and Tanaka (2002) have suggested that the wear mechanism of the wood cutting tools is influenced by both, the work piece factors, such as density, adhesive content, impurities content (especially

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Corresponding Author: Jegatheswaran Ratnasingam, Faculty of Forestry, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia Tel: +603-89467175 Fax: +603-89432514

silica), extractives content and moisture content, as well as the processing factors, such as feed speed, cutting speed and the stock removal rate. It has also been found that mechanical abrasion was the primary cause of tool wear when machining materials with density lower than 600 kg m^{-3}, while at higher density and in work-pieces with a high content of abrasive impurities, such as silica and crystals, micro-fractures of tool edge is unavoidable, leading to accelerated tool wear (Ratnasingam and Tanaka, 2002). On the other hand, with wood composites such as particleboard, the presence of adhesives and grits also increases tool wear further, through increased rate of mechanical wear, as well as the interactive effects of the other wear mechanisms (Klamecki, 1980; Gauvent *et al*., 2006).

In a recent report by Atkins (2009), it was found that the temperature of the cutting tool and the cutting forces involved were crucial factors governing tool wear mechanisms in wood machining processes, because critical tool material properties, such as hardness, toughness and chemical stability degrade with increasing temperature. In this context, the contribution of the various wear mechanism to cutting tool degradation cannot be ascertained, without having accurate information on tool temperatures and tool forces during the cutting process and how they affect the basic material properties of the cutting tool. Although, Sheikh-Ahmad *et al.* (2003a) have shown that the temperature and cutting forces at the tool edge is dependent on several factors, including cutting speed, feed speed, continuity of the cutting process, depth of cut and tool and work-piece materials, tool temperature has a profound effect on tool wear, even under industrial circumstances, where most of these variables are kept constant. Despite the importance of tool temperature in governing tool wear, studies on tool temperature during the cutting of wood products are very limited (Atkins, 2009). Therefore, the purpose of this study was to ascertain the temperature regimes and cutting forces at the cutting tool of cemented tungsten carbides when machining particleboard and solid wood materials.

MATERIALS AND METHODS

The cemented tungsten carbide tool used in this study had a composition of 86.5% carbide, 10% cobalt and 3.5% chromium, with an average carbide grain size of 1.0 μm. This composition was recommended by Ratnasingam *et al*. (2009), in an earlier study. The tool in the form of an insert of 30 mm in length, 12 mm in width and 2.5 mm in thickness, was attached to a tool holder as shown in Fig. 1. The sharpness angle of the tool insert was 65°. The tool wear experiments were conducted on a high-speed lathe and the machining conditions were as shown in Table 1. The experiments were carried out at the experimental facility of Tool Technology (M) Sdn. Bhd.,

Table 1: Experimental conditions

Conditions	Details
Experimental materials	• OPEFB Particleboard of 700 kg m^{-3} in density 18 mm in thickness • Rubberwood particleboard of 650 kg m^{-3} in density, 18 mm in thickness • Solid rubberwood of 600 kg m^{-3} in density, 18 mm in thickness
Spindle speed	650, 1300, 2450 RPM
Cutting speed	8.5, 18, 27 m sec^{-1}
Tool geometry	Rake 15°, Clearance 20°
Feed speed	0.05 mm rev^{-1}

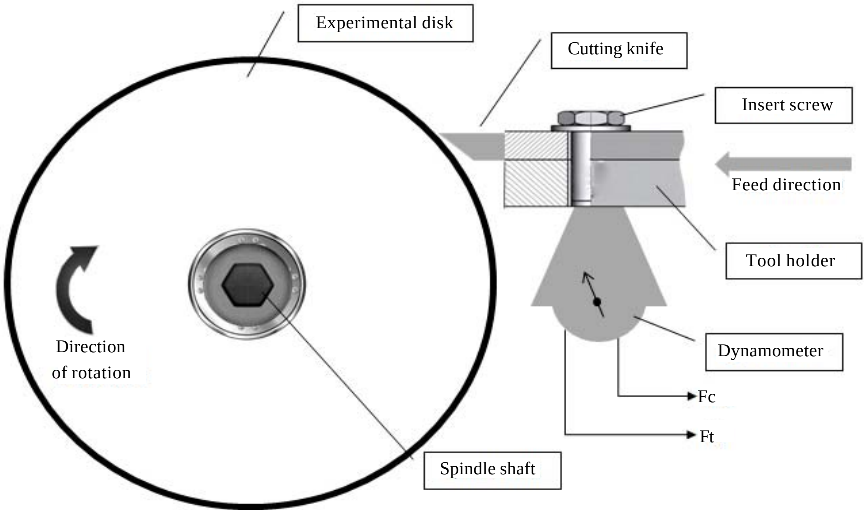

Fig. 1: Experimental set-up

in Sungai Buloh, Malaysia. Machining was carried out in such a manner that the tool cutting edge was parallel to the axis of rotation of the experimental material in the form of a disk and the tool feed direction was perpendicular to the axis of rotation of the disk. During cutting at constant spindle speed, the cutting speed varied continuously as the disk diameter reduced. The cutting distance was taken as the length of the spiral path taken by the tool as it traversed the rotating disk in the radial direction. This set-up ensured that as the diameter of the disk was reduced, the orthogonal cutting conditions were maintained throughout the experiments.

Each insert was used in machining the experimental material until a steady-state temperature was recorded, which marked the end of the experiment. At this stage, the edges of the cutting tools were examined microscopically at a magnification of 100 X and 1000 X, to establish the mode of tool failure. A total of three inserts were used to obtain the average value for each experimental material.

Two components of the cutting forces, i.e., the principal cutting force, F_c (parallel to the cutting velocity vector) and thrust force, F_t (normal to the cutting velocity vector) at the tool edge, were measured through specially attached piezoelectric load cells connected to a Kistler-type amplifier, which was in turn connected to a cutting-force and temperature data acquisition system housed in a desktop PC system operated by the LABVIEW software (version 5.0).

On the other hand, the cutting tool temperature during the machining experiments was measured using the type K gauge (0.125 mm diameter) thermocouples. Three thermocouples (TC1, TC2, TC3) were placed on the rake face of the tool using OMEGABOND 200 epoxy adhesive, along a line perpendicular to the cutting edge at the center of the tool and at 1.0 mm intervals starting 2.0 mm from the cutting edge. Three thermocouples (TC4, TC5, TC6) were placed on the back face (clearance face) of the tool under a similar configuration (Fig. 2). Thermocouples outputs were fed into signal conditioners that allowed for cold junction compensation and the experiments was stopped when the steady-state temperatures were captured, by the data acquisition system.

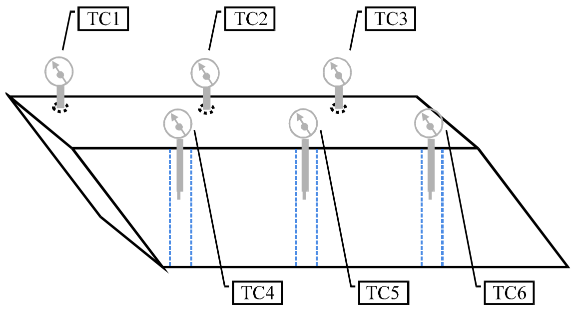

Fig. 2: Position of thermocouples on knife insert

RESULTS

The results from this study are presented in three parts.

Part I: Temperature regimes at cutting tool: Steady-state cutting tool temperature measurements on the rake and clearance faces of the tools are given in Table 2. Figure 3 shows the variations of these temperatures along the rake face of the tool for the three experimental materials investigated. It shows that the highest tool temperature recorded for OPEFB particleboard, Rubberwood particleboard and solid Rubberwood, were 196, 166 and 127°C, respectively on the rake face of the tool, suggesting that material property also influences cutting tool temperature, as it accounts for the amount of cutting resistance present during the machining process (Klamecki, 1980). It is also apparent that the temperature on the rake face increases with a decrease in distance from the cutting edge. Figure 4 also shows that temperature on the rake face increases with an increase in cutting speed, which is most likely due to the increased material removal rate as suggested by Ratnasingam and Tanaka (2002). The increasing trend shown supports the observation that

Table 2: Steady-state tool temperatures at various thermocouple positions when cutting different materials

Thermocouple position	OPEFB particleboard	Rubberwood particleboard	Solid rubberwood
T1	196	166	127
T2	176	151	121
T3	159	138	113
T4	139	126	109
T5	122	118	107
T6	119	113	104

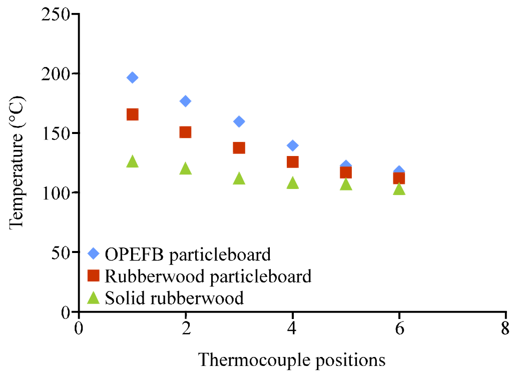

Fig. 3: Steady-state tool temperatures when cutting different materials

Table 3: Cutting forces at tool edge when cutting different materials

Materials	Principal cutting force, F_c (N)	Thrust force, F_t (N)	Steady-state tool temperature on rake face (°C)	Steady-state tool temperature on back face (°C)
OPEFB particleboard	117.8	57.1	196	139
Rubberwood particleboard	108.3	51.9	166	126
Solid rubberwood	83.7	43.4	127	109

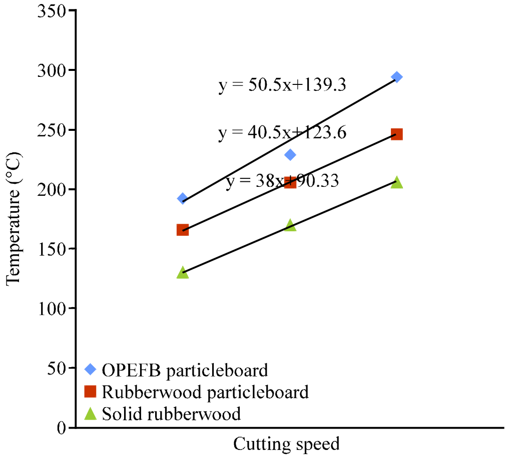

Fig. 4: Effect of cutting speed on steady-state tool temperatures

cutting particleboards is more harsh on the cutting tools compared to cutting solid wood. On the other hand, the temperature on the clearance face of the tool were significantly lower, but showed a similar trend as the rake face. These lower temperature measurements are expected because the tool's clearance face makes little contact with the work-piece during the machining process (Sheikh-Ahmad *et al.*, 2003a).

Part II: Cutting forces at tool edge: The results of the cutting forces at the tool edge, expressed as the principal cutting force, F_c and thrust force, F_t are presented in Table 3. The cutting forces reflect a similar trend to the tool temperatures recorded at the tool edge, suggesting a direct relationship between cutting force and tool temperature (Sheikh-Ahmad *et al.*, 2003a). The results confirms the fact that increasing cutting forces leads to higher temperatures at the cutting tool edge and although the amount of cutting force required is influenced by the machining conditions (Ratnasingam and Tanaka, 2002), the influence of cutting speed and work-piece density is clearly shown in this study (Table 3). Hence, cutting forces at the tool edge increases in the order of OPEFB particleboard>Rubberwood particleboard>solid Rubberwood.

III. Wear characteristics of cemented tungsten carbide tools: Microscopic examination of the cutting tool edges revealed that the wear of cemented tungsten carbide tool when machining particleboards and solid wood, was initially by mechanical abrasion and as the cutting progressed, mechanical wear under the influence of high temperature became more apparent. This observation is confirmed from microscopic evidences of the cutting tool edge, which shows gradual mechanical abrasion (Fig. 5) at an early stage of cutting, followed by the softening of the carbide matrix and the removal of the carbide particles (Fig. 6, 7) at the steady-state temperature stage.

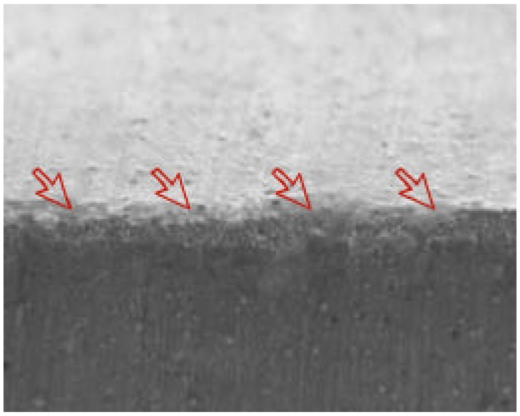

Fig. 5: Mechanical abrasion at the tool edge (100X)

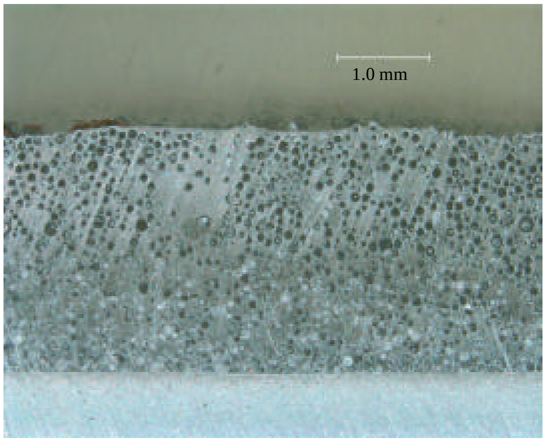

Fig. 6: Carbide particles in the cobalt matrix (100X)

The microscopic evidence presented suggest that temperature plays an important role in the wear of cemented tungsten carbide tools and in order to minimize the effect of temperature on such tools, the tool surfaces could be coated as suggested by Atkins (2009).

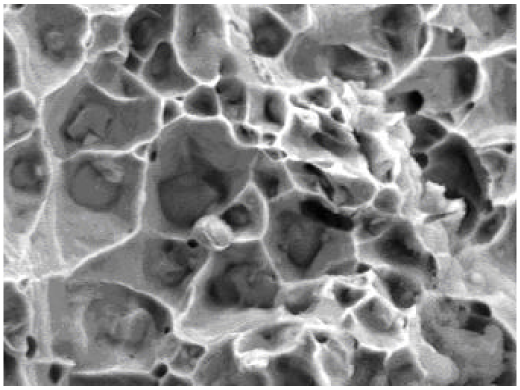

Fig. 7: Removal of carbide particles from the cobalt matrix (1000X)

DISCUSSION

The results of this study provide fundamental information on tool temperature regimes and cutting forces during the machining of particleboard and solid wood. Although, the study by Ratnasingam and Tanaka (2002) and Ratnasingam *et al.* (2009) have reported tool temperatures in excess of 400°C during the machining of wood products, such high readings were not found in this study. This difference could be attributed to the accuracy in the equipments used and the point of measurement as suggested by Atkins (2009). Since, most cutting tools are better conductors of heat compared to wood products, it is unlikely that such high tool temperatures could be attained at the tool edge (Atkins, 2009). Consequently, it may be implied that much of the heat produced as a result of the cutting process is carried away by the chips leaving the work-piece. This argument is supported by the previous findings of Sheik-Ahmad *et al.* (2003a), who found that the portion of the cutting power that is conducted as heat into the cutting tool is only about 5-7%, which means that the bulk of the heat generated during the machining processes is dissipated from the cutting region via the chips and work-piece surface. Atkins (2009) showed that a temperature rise of 56°C was recorded at the machined surface of the work-piece as it exited the cutting region, providing further evidence to suggest that the higher temperature reported in the study by Ratnasingam and Tanaka (2002) and Ratnasingam *et al.* (2009), was the temperature at the work-piece surface and not at the cutting tool.

Nevertheless, as the land area at the tool edge increases due to wear, tool temperature will show progressive increments (Sheikh-Ahmad *et al.*, 2003a). This increase in tool temperature is a result of the increasing cutting forces required as the wear land area increases (Aknouche *et al.*, 2009; Atkins, 2009). Therefore, accelerated tool wear and the work-piece thermal properties, especially its thermal conductivity and specific heat capacity, play crucial roles in determining the tool temperature during the machining process. Inevitably, the results of this study confirm the findings of previous reports by Eyma *et al.* (2005) and Sheikh-Ahmad *et al.* (2003a), that cutting tool temperature and cutting forces have a direct relationship and as tool wear manifest, the changes in the cutting forces will increase tool temperature.

In the case of the wear characteristics of cemented tungsten carbide tools, this study confirms that the wear of such tools is primarily by abrasion and mechanical wear. With a thermal conductivity of 100 W m^{-1} °C, the cemented tungsten carbide tool is able to dissipate the resultant heat quickly and therefore the previously reported cutting temperature in excess of 400°C by Ratnasingam *et al.* (2009), is most likely the temperature at the cutting region and the machined surface. In fact, this is highly probable as wood materials have a specific heat of approximately 1400 J kg^{-1} °C and a thermal conductivity of about 0.5 W m^{-1} °C, which explains the higher temperature observed at the machined surface (Sheikh-Ahmad *et al.*, 2003a; Eyma *et al.*, 2005). Nevertheless, it appears that steady-state cutting tool temperature of 196°C for particleboard and 127°C for solid wood found in this study, is sufficient to soften the cobalt matrix in the tool and facilitate the eventual removal of the hard carbide particles. This point is further supported by the report by Saito *et al.* (2006) who showed that increasing temperature under the influence of intermittent forces as experienced during cutting, creates the ideal condition for the wear of cemented tungsten carbide tool. Therefore, the results of this study provides compelling evidence to support the findings of other researchers (Sheikh-Ahmad and Bailey, 1999; Saito *et al.*, 2006; Gauvent *et al.*, 2006; Ratnasingam *et al.*, 2009), that the wear of cemented tungsten carbide tools is brought about by the gradual removal of the carbide particles from the tool surface.

Industrial implications: This study provides evidence to show that the tool temperature during the cutting of wood materials is much lower than the temperature recorded at the machined surface of the work-piece. Further, the established direct relationship between cutting tool temperature and cutting forces found in this study, shows that as the wear land area at the tool edge increases, so does the cutting forces, which in turn increases the tool temperature. Hence, minimizing the development of wear land area at the tool edge could also improve the cutting process economics, by reducing the required cutting forces as well as the resultant tool temperature (Atkins, 2009). The study also proves that work-piece characteristics, especially its density and thermal properties play an important role in dictating the rate of tool wear. Against this background, the expanding market share of cemented tungsten carbide tools for the machining of wood products is justified, as it is not only a hard material, but has superior material properties, which in turn improves the cutting process economics.

CONCLUSIONS

This study shows that the tool temperature and cutting forces have a direct relationship and tool temperatures are generally lower than the temperatures recorded at the cutting region during the machining process. Further, the study proves that the wear of cemented tungsten carbide tools is primarily by the removal of the hard carbide particles from the softened cobalt matrix.

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