# Purdue University Study Confirms Benefits Of EXAIR Cold Gun

You can't escape it. Tools wear out. And, not only does it cost you a lot of money to replace them, you have to deal with:

- Slowed production and downtime to change out the tooling
- Poor tolerances and dimensional accuracy due to increased temperature
- Increased cutting force is required (more heat and power consumption)

If you could just make the tooling last longer, you'd not only cut tool cost in half but could increase profits by reducing scrapped parts and downtime.

There is a way. Recently, there was a long term study on the effect of refrigerated air on tool wear in wood machining conducted at the Forestry Products Department of Purdue University by Ms. Judith Gisip. The project was under the direction of Dr. Rado Gazo (professor of the department) and Harold Stewart (professor at North Carolina State University and 35 years in wood machining research). Wood is brutal on tooling. In metalworking, most of the heat goes away with the machined chip. Wood is an excellent insulator and doesn't conduct the heat away, which keeps it all there at the tool. Temperatures can exceed 800°C!

The extensive tests at Purdue were conducted in a 70°F climate controlled room. They tested (4) 1/2" (12.7mm) two-flute cutters on a CNC router at 16,000 rpm. (22) sheets of 3/4" thick MDF (medium density fiberboard) were fed one at a time, cutting away 1/4" (6mm) depth of cut on each pass. Power consumption of the CNC was recorded (current draw increases as the tool starts to dull). When finished, the surface of the tools were examined using a scanning electron microscope. Machining with the Cold Gun's 20°F air reduced tool wear by over 21% compared to the results with no cooling.

## How Much Can You Save?

A 1/2" two flute router bit for wood is approximately $58.

The 21% reduction in tool wear when using a Cold Gun is ***$58 x 0.21*** = **$12.18 savings per bit.**

If you use (1) router bit per working day, the savings is ***$12.18 x 5*** working days = **$60.90 per wk./ $3,167 per yr.**

Fig. B. EXAIR's Cold Gun is mounted under the protective guard.

Fig. A. Purdue's CNC router turns (22) 4x8 sheets into sawdust.

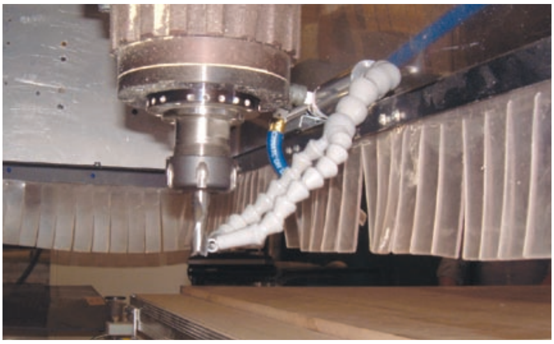

Fig. C. Cold air from EXAIR's Model 5315 Cold Gun System keeps the tooling cool.

# EFFECTS OF REFRIGERATED AIR ON TOOL WEAR

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## ABSTRACT

Increased tool wear of tungsten carbide tools may be attributed to high cutting temperatures. Cooling the tool with liquid coolant and lubricants is impractical for cutting dry wood and wood composites, and thus refrigerated air was used for cooling the tool in this study. A total of three solid tungsten carbide, double-flute, router bits machined medium density fiberboard on a CNC router. Refrigerated air was applied to two tools, while the third tool cut at ambient temperature. The power analysis equipment was used in order to observe the impact of tool wear on power consumption. All tools were examined under the light microscope to capture images in order to measure tool wear. Elemental analysis was performed with scanning electron microscopy to determine the percentage of specific elements present in the tools. Results show that less tool wear occurs when using refrigerated air, thereby increasing tool life when cutting medium density fiberboard.

*Keywords:* Tool wear, medium density fiberboard, cryogenic treatment, refrigerated air, tungsten carbide.

## INTRODUCTION

Abrasion has been considered to be the dominant cause of tool wear when machining wood and wood products (Scholl and Clayton 1987). The accumulation of material residues and black carbon near the tool cutting edge after cutting suggests that other wear mechanisms contribute to the wearing process (Reid et al. 1991). In addition to abrasion, other principal types of wear are adhesion, diffusion (tribochemical reactions), and fatigue. The four mechanisms may occur separately or in a combination.

Several studies have been conducted to identify the mechanisms of wear for tungsten carbide tools. Wear mechanisms include tool edge chipping, abrasion, and electrochemical attack. One wear mechanism involves the removal of the cobalt binder by a chemical reaction with extractives found in green wood, followed by the loss

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of tungsten carbide grains due to a weak bond holding the cobalt binder and the tungsten carbide grains together (Bayoumi et al. 1983).

The high temperatures generated at the cutting edge of tungsten carbide tools accelerate wear when machining medium density fiberboard (MDF) through the oxidation or corrosion of the tool surface, and are major factors contributing to tool wear (Stewart et al. 1986). Oxidation is a type of corrosion, and is a deterioration of the tool surface involving excess levels of oxygen (Lai 1990). High-temperature corrosion involves salt deposition, such as sulphate, on the metal surface similar to the combustion of fossil fuels (Birks and Meier 1983); these may react with the parent material, in this case the tungsten carbide grains, cobalt binder, or their oxides.

The application of liquid coolants in metal cutting results in less oxidation and corrosion (Taylor 1907; Lauterbach 1952; Piggot and Colwell 1952). Liquid coolant lowers the cutting temperature of the tool, thereby reducing tool wear (Seah et al. 1995). Lubricants may also reduce wear when cutting metals (Kohn 1965). Due to the hygroscopic nature of wood, however, liquid coolants and lubricants are impractical for maximizing tool life when machining wood or wood-based composite materials. Therefore, solid tungsten carbide tools were cooled with refrigerated air during the machining of MDF.

A concern of tool wear testing is obtaining meaningful results from minimum testing. Consequently, the tools need to be similar and represent the population. Likewise, the workpiece material such as MDF has to be relatively uniform. Randomization of the tools and a large sample of MDF can help the uniformity of the respective populations. If the tool and workpiece material are similar, respectively, then other treatments such as refrigerated air should readily exhibit a difference or no-difference in simple comparative tests.

## MATERIALS AND METHODS

Twelve similarly manufactured double-flute, solid tungsten carbide router bits were randomly distributed to represent the tool population. Each similarly manufactured flute represented a sample (Lipka 2005), and wear data for two flutes were averaged. The total sample of 120 MDF sheets were also randomly distributed to represent the MDF population. If the limited observed data after testing are consistent for each flute, then the data represent a valid test for applying refrigerated air in the tests (Lipka 2005).

Three double-flute, solid tungsten carbide tools of 12.7 millimeter (½ in.) diameter were randomly selected from the sample of twelve tools to cut the MDF. During machining, tools were fed at a feed speed of 9.75 meters per minute and 16,000 revolutions per minute. One of the three tools cut at the ambient temperature of 21°C (70°F), while the other two tools were cooled by a refrigerated air applied to them during cutting The temperature of the refrigerated air was 4.4°C (40°F), and −6.7°C (20°F), respectively. The refrigerated air is produced when compressed air passes through a vortex tube. Cold air was then blown onto the tool during cutting via two flexible nozzles (Fig. 1).

Twenty-two MDF sheets, randomly distributed from a sample of 120 sheets 1.24 meters wide (4 ft), 2.46 meters (8 ft) long and 19.05 millimeters (¾ in.) thick, were cut by each tool. A tool began cutting the sheet in the up-milling direction, cut across the width, retracted, and then returned and repeated the process 360 times per sheet. This produced over 166,000 meters in

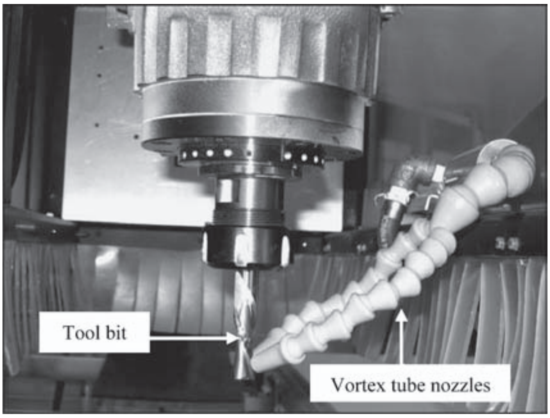


FIG. 1. Experimental setup.

length of cut per flute. The depth of cut was 6.35 millimeters (¼ in.), or one half of the tool diameter. The machining was done with a CNC router. Current (amp) and electrical power (kW) drawn by the router spindle was continuously monitored and recorded with the power analysis equipment and later correlated to tool wear.

Tool wear area was calculated with an image analysis-based method (Gisip 2005). A digital camera attached to the microscope captured images of the clearance face of the tool. Image analysis and measurement software quantified tool wear. The area from which the tool material was worn off completely was termed the wear void, and was calculated as the difference between the area of the original clearance face and the remaining clearance face. Further, the area of the remaining clearance face was divided into two regions, an area that began to show wear through scratches and rounding (termed the wear scar area) and an area that did not exhibit any tool wear (termed the unworn area). In order to compare wear between different tools and treatments, tool wear was expressed as a percentage of the original clearance face area for each flute. The total tool wear was defined as a ratio of the sum of wear void and wear scar areas to the original clearance face areas for both similar flutes combined.

The microstructure and surface morphology of tool cutting edges were examined by scanning electron microscopy for the presence of cobalt binder, fissures, pits, depressions, and other characteristics of the edge surface.

Energy-dispersive spectroscopy (EDS) analysis was performed in order to identify and quantify the elemental composition of the sample areas. Readings were taken at ten different areas on the clearance face positioned across the width of the cutting edge. The quality of MDF edge surface was observed after the entire cutting process was completed.

## RESULTS AND DISCUSSION

### *Tool wear*

The tool wear results for each of two flutes for each combination of milling similar MDF with similar 2-fluted solid carbide router bits with and without refrigerated air are valid, although limited (Lipka 2005). The consistent combined results are shown in Table 1. The consistent tool wear results are further confirmed by the smooth curve trends for electrical current (Fig. 5a) and power (Fig. 5b). Observation of all the results shows the consistent benefits of applying refrigerated air to machining MDF with solid carbide tooling.

Tool wear results for wear void, wear scar, and total wear are shown in Table 1. Analysis of variance (ANOVA) of total wear indicated that temperature was a significant factor at 0.025 level. The effect of temperature based on this p-value was further analyzed with the Tukey multiple comparison procedure; this test showed that refrigerated air temperatures of both 4.4°C and −6.7°C produced significantly lower mean total wear (60% and 66.3%, respectively), compared to the tool cutting at the ambient temperature of 21°C, which resulted in the mean total wear of 76.2%.

We defined total wear as a sum of the percentages of wear void and wear scar areas to the area of the original clearance face of the tool. Table 1 shows that there was not a statistically significant difference in wear void among the three tools. There was, however, a significant difference in wear scar. The two tools that had refrigerated air applied to them had smaller wear scar.

In our laboratory, the temperature of the compressed air exiting the tank was approximately 32°C (90°F). A commercially available vortex tube can reduce the temperature of the compressed air passing through it by about 28°C (50°F), resulting in the air temperature of 4.4°C (40°F). We wanted to see whether an additional

TABLE 1. *Wear void, wear scar, and total wear as a percentage of the original clearance face area for average of two flutes. Superscript letters indicate the significant difference at 0.05 level.*

| Temperature (°C) | Wear void (%) | Wear scar (%) | Total wear (%) |
|---|---|---|---|
| 21 | $32.07^{a}$ | $44.09^{a}$ | $76.16^{a}$ |
| 4.4 | $25.39^{a}$ | $34.64^{b}$ | $60.03^{b}$ |
| −6.7 | $25.68^{a}$ | $40.63^{b}$ | $66.31^{b}$ |

benefit can be achieved with even colder temperature. Therefore, we installed a coil made of copper tubing between the compressed air tank and the vortex tube. The coil was immersed in ice water, cooling the passing air from 32°C (90°F) to 21°C (70°F) before it reached the vortex tube. The vortex tube then cooled the air further to −6.7°C (20°F). Our results show that there was no additional benefit in further reduction of temperature, indicating that colder may not always be better, but that perhaps there is some optimum temperature for reducing tool wear when machining MDF.

### *Elemental analysis and tool microstructure*

Elemental analysis was performed on a clearance face of one flute of each tool at ten locations, each progressively further removed from the cutting edge of the tool. These locations are shown in Fig. 2 (a).

The EDS analysis allowed for identification of elements present on the surface of cutting tools. We found tungsten, cobalt, nitrogen, oxygen, sodium, phosphorus, sulfur, chlorine, potassium, and calcium. All of these elements can help in understanding tool wear process (Padilla et al. 1989). For example, the presence of sulfur can corrode the cobalt binder (Reid 1989), and is also known to be one of the most corrosive contaminants in high-temperature environments (Lai 1990), although the exact mechanism has not been identified (Padilla et al. 1989). The cobalt binder is removed through reaction with MDF decomposition products, such as sulfur, potassium, silicon, chlorine, and phosphorus (Reid et al. 1991). Elemental analysis indicated a high concentration of sulfur deposited on the tool that cut at room temperature (Table 2), as compared to the tools that were cooled with the refrigerated air (Tables 3 and 4).

The primary reaction between sulfur and the cobalt binder occurs early in cutting (Reid et al. 1991). When the cobalt binder is weakened, the tungsten carbide grains fall out via mechanical action. As the cutting process continues, high temperatures are generated at the cutting edge, causing oxidation of both the more reactive cobalt and the less reactive tungsten carbide grains.

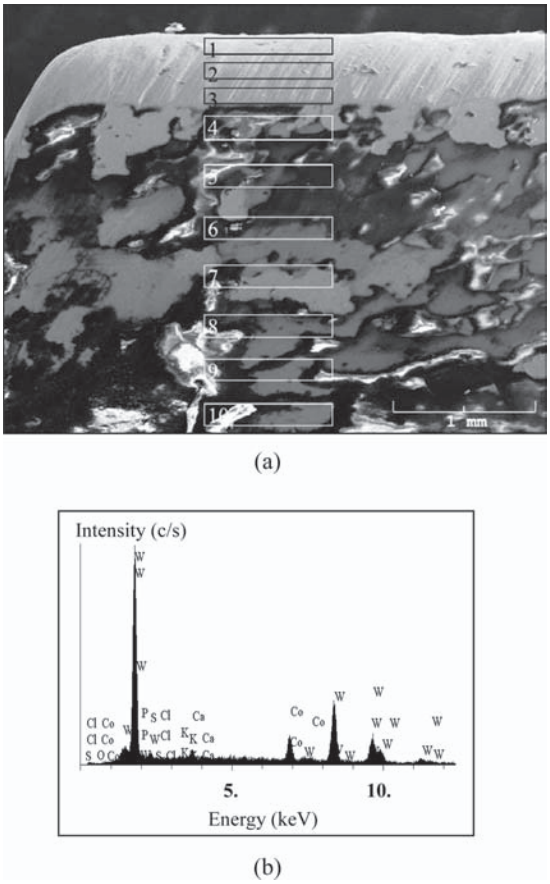


FIG. 2. SEM micrograph and EDS spectra of the clearance face of the tool cutting edge at −6.7°C. Shown are the (a) SEM micrograph of the clearance face with locations of elemental analysis and (b) EDS spectrum at location 1.

The presence of nitrogen, oxygen, and chlorine indicates nitridation, halogenation, sulfidation, oxidation, and potentially more complex reactions. Metals are susceptible to nitridation if exposed to nitrogen-base atmosphere at elevated temperatures (Lai 1990). During nitridation, nitrogen is absorbed from the environment, resulting in the formation of nitrides, which cause the alloy to become brittle (Lai 1990).

Many metals and alloys are susceptible to corrosion when exposed to gases known as halogens, such as chlorine, forming volatile metal compounds at elevated temperatures (Lai 1990

TABLE 2. *Elemental analysis of the 21°C cutting temperature tool at ten different locations. Location 1 is adjacent to, and location 10 is the furthest from, the tool cutting edge.*

| Element/location | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| | (wt.%) | | | | | | | | | |
| N | 0.16 | 0.60 | 0.20 | 0.50 | 0.60 | 1.15 | 0.57 | 2.29 | 3.76 | 0.00 |
| O | 0.05 | 0.19 | 0.18 | 0.52 | 0.26 | 0.71 | 0.52 | 1.16 | 1.09 | 5.60 |
| Na | 0.04 | 0.02 | 0.02 | 0.03 | 0.10 | 0.10 | 0.11 | 0.14 | 0.26 | 0.40 |
| P | 0.62 | 0.07 | 0.14 | 0.02 | 0.00 | 0.60 | 0.26 | 0.35 | 0.77 | 1.59 |
| S | 0.92 | 0.46 | 0.51 | 0.10 | 0.28 | 0.17 | 0.21 | 1.80 | 0.85 | 2.85 |
| CL | 0.05 | 0.07 | 0.05 | 0.15 | 0.23 | 0.43 | 0.12 | 0.94 | 0.82 | 2.87 |
| K | 0.31 | 0.11 | 0.20 | 0.29 | 0.32 | 0.91 | 0.70 | 1.62 | 1.80 | 3.51 |
| Ca | 0.98 | 0.50 | 0.46 | 0.28 | 0.36 | 0.45 | 0.32 | 1.40 | 1.84 | 4.28 |
| Co | 6.20 | 7.54 | 6.92 | 7.61 | 8.83 | 8.68 | 8.22 | 7.94 | 8.96 | 8.79 |
| W | 90.68 | 90.45 | 91.33 | 90.51 | 89.02 | 86.82 | 88.99 | 82.37 | 79.86 | 70.11 |

TABLE 3. *Elemental analysis of the 4.4°C cutting temperature tool at ten different locations. Location 1 is adjacent to, and location 10 is the furthest from, the tool cutting edge.*

| Element/location | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| | (wt.%) | | | | | | | | | |
| N | 0.00 | 0.30 | 0.00 | 1.17 | 0.09 | 0.10 | 0.90 | 1.26 | 0.33 | 1.02 |
| O | 0.47 | 0.13 | 0.00 | 0.06 | 0.24 | 0.19 | 0.32 | 0.47 | 0.23 | 0.06 |
| Na | 0.04 | 0.09 | 0.07 | 0.02 | 0.03 | 0.03 | 0.04 | 0.05 | 0.03 | 0.05 |
| P | 0.34 | 0.16 | 0.12 | 0.20 | 0.31 | 0.35 | 0.03 | 0.28 | 0.07 | 0.20 |
| S | 0.72 | 0.57 | 0.35 | 0.28 | 0.09 | 0.13 | 0.27 | 0.28 | 0.14 | 0.16 |
| Cl | 0.20 | 0.12 | 0.09 | 0.24 | 0.03 | 0.08 | 0.19 | 0.11 | 0.28 | 0.13 |
| K | 0.17 | 0.10 | 0.13 | 0.17 | 0.23 | 0.26 | 0.30 | 0.18 | 0.10 | 0.09 |
| Ca | 1.07 | 0.79 | 0.31 | 0.42 | 0.10 | 0.23 | 0.19 | 0.34 | 0.19 | 0.30 |
| Co | 2.72 | 3.67 | 5.18 | 7.30 | 7.66 | 7.50 | 7.59 | 5.44 | 4.45 | 4.73 |
| W | 94.27 | 94.07 | 93.74 | 90.15 | 91.22 | 91.23 | 90.17 | 91.60 | 94.18 | 93.26 |

TABLE 4. *Elemental analysis of the −6.7°C cutting temperature tool at ten different locations. Location 1 is adjacent to, and location 10 is the furthest from, the tool cutting edge.*

| Element/location | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| | (wt.%) | | | | | | | | | |
| N | 0.28 | 0.36 | 0.19 | 0.31 | 0.16 | 0.57 | 1.67 | 1.06 | 0.55 | 0.03 |
| O | 0.01 | 0.04 | 0.15 | 0.00 | 0.60 | 0.16 | 0.82 | 0.73 | 0.46 | 0.58 |
| Na | 0.06 | 0.03 | 0.12 | 0.01 | 0.00 | 0.03 | 0.03 | 0.02 | 0.06 | 0.04 |
| P | 0.39 | 0.06 | 0.19 | 0.00 | 0.51 | 0.38 | 0.08 | 0.01 | 0.00 | 0.12 |
| S | 0.93 | 0.54 | 0.30 | 0.37 | 0.45 | 0.16 | 0.14 | 0.29 | 0.00 | 0.15 |
| Cl | 0.08 | 0.11 | 0.05 | 0.52 | 0.43 | 0.21 | 0.12 | 0.45 | 0.84 | 0.27 |
| K | 0.22 | 0.24 | 0.09 | 0.40 | 0.30 | 0.32 | 0.12 | 0.40 | 0.44 | 0.22 |
| Ca | 1.35 | 0.72 | 0.70 | 0.49 | 0.62 | 0.23 | 0.17 | 0.36 | 0.51 | 0.29 |
| Co | 7.04 | 7.66 | 8.20 | 9.12 | 9.51 | 8.03 | 7.78 | 8.21 | 8.46 | 7.91 |
| W | 89.65 | 90.25 | 90.03 | 88.79 | 87.42 | 89.93 | 89.09 | 88.46 | 88.68 | 90.40 |

and Stewart 1992). During sulfidation, salt vapors are formed from the reaction of sodium, potassium, and chlorine, with sulfur (Lai 1990). The result of sulfidation is the deposition of salt on metal surfaces.

Figure 2 shows the SEM micrograph and EDS spectrum of the tungsten carbide clearance face after cutting at a temperature of −6.7°C. The SEM micrographs indicated the formation of a layer of black carbon and other material residues near the cutting edge. The breakdown of tungsten carbide grains may also occur (Lai 1990)

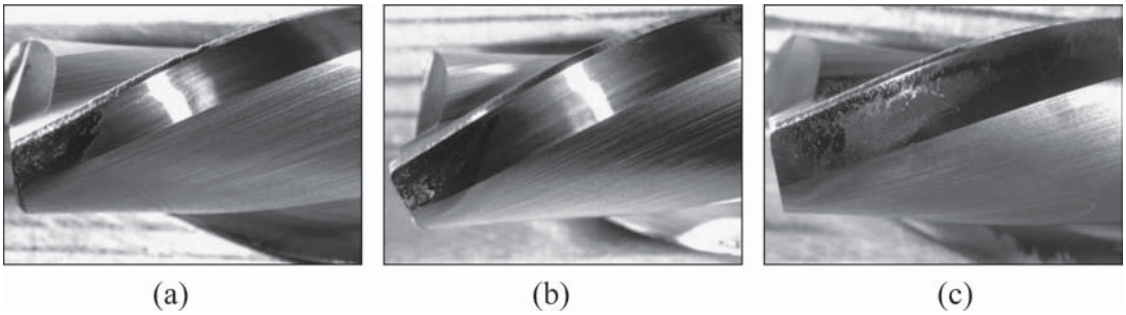


FIG. 3. Tungsten carbide tools after cutting at (a) −6.7°C, (b) 4.4°C, and (c) 21°C.

through the formation of tungsten oxide and/or tungsten oxychloride. The effect of refrigerated air during cutting was observed by comparing the condition of tool surfaces, as shown in Fig. 3 (a–c). The tool cutting at 21°C exhibited the worst condition,

Tungsten carbide grains may be seen clearly due to the removal of the cobalt binder that was used to bind the grains together (Fig. 4 (a)). The areas labeled by the letter "X" indicate depressions or pits larger than the tungsten carbide grain size, created due to the cobalt depletion. Figure 4 (b) appears to show a groove formed by two materials rubbing against each other. It also indicates smearing of cobalt binder on the surface or possibly flaking or scaling. The cobalt binder has not been completely removed. It forms thin scales and eventually will be rubbed away.

### *Electrical current and power consumption*

An increase in current (amp) and electrical power (kW) may indicate increase in tool wear. Figures 5 (a) and (b) show an increasing trend in both current and power as the length of cut increases. ANOVA shows a highly significant difference between the cutting temperatures. The 4.4°C cutting temperature resulted in better performance than the other two temperatures.

### *Edge quality of MDF*

The quality of MDF edge surface for all tool treatments was examined and ranked by a panel

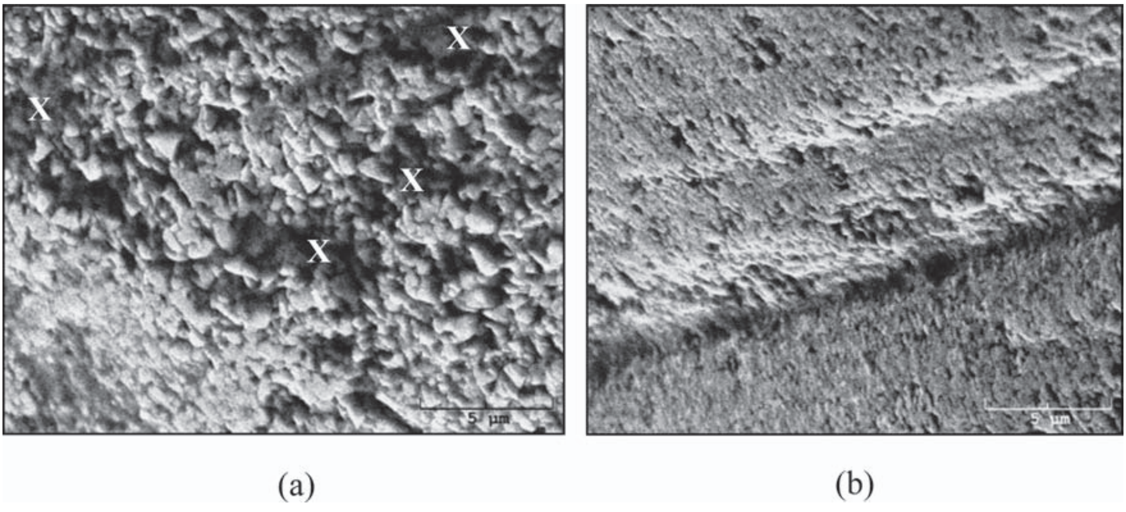
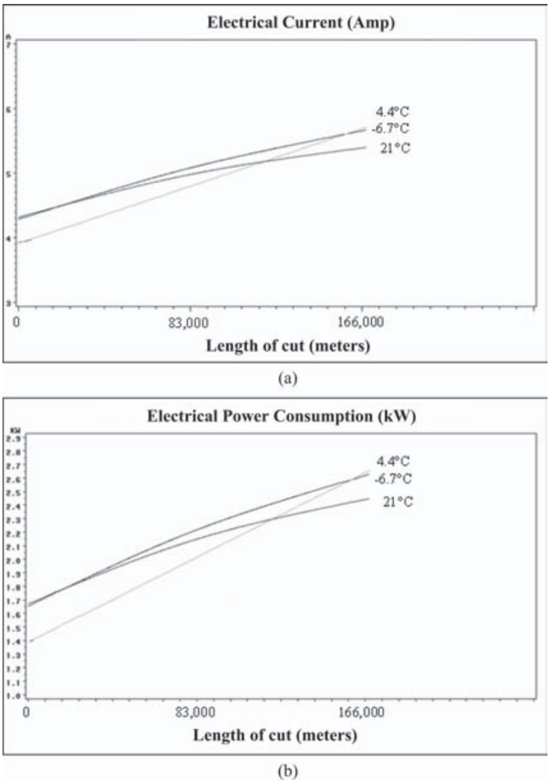


FIG. 4. Top view of the cutting edge of a tungsten carbide tool. Shown are tools that cut at (a) 4.4°C and (b) 21°C.



(a)

(b)

FIG. 5. Graphs of (a) electrical current and (b) power consumption.

of observers. Tools cooled with refrigerated air consistently produced smoother surface for a longer period of time.

## CONCLUSIONS

Cooling solid tungsten carbide tools with refrigerated air when machining MDF resulted in reduced tool wear. As compared to cutting at ambient temperature of 21°C, a tool cooled by 4.4°C air reduced wear from 76% to 60%. Further reduction in temperature to −6.7°C did not result in corresponding reduction in wear. It is apparent that when machining MDF, tool wear in solid tungsten carbide tools with cobalt binder is caused by oxidation and high-temperature phenomena as evidenced by presence of sulfur and other elements, rather than by abrasion. Cooling tools by refrigerated air may have potential applications in the wood industry.

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