

Diamond wire machining of wood

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Abstract

Wood machining with fixed abrasive diamond wire was investigated. Advantages of diamond wire sawing include the thin kerf and flexibility to change cutting directions. Advancements in new high speed diamond wire cutting machines have made this process suitable for wood machining. Two cutting configurations using a looped and an oscillatory wire saw were studied. Experiments investigating the effects of wire speed, wire feed rate, coolant, and cutting direction on cutting white oak (*Quercus alba* L.) and eastern white pine (*Pinus strobes* L.) were conducted. The results show that the diamond wire saw can effectively machine both types of wood. The looped wire saw machined the wood with the fastest feed rate, and had very good surface quality. The oscillatory wire saw machined with a slower wire speed and lower feed rate, and the surface roughness was not compromised. Overall, both wire saws yielded good surface quality when machining the pine and oak with various feed rates.

Wire saw machining technologies have advanced significantly in the past decade due to the needs for precision slicing of silicon wafers in semiconductor manufacturing. The wire cutting, a concept that originated from the carpenter wire saw in wood machining, can precisely slice the single crystal electronic ceramic to thin wafers with μm -level warp, uniform thickness, and low kerf loss. The loose abrasive wire saw usually slices the wafer. Due to the increase of the wafer size and the need to improve the throughput time and machine harder ceramics, the fixed abrasive diamond wire machining technology has been developed. The goal of this research was to study the diamond wire saw machining of wood.

Three configurations of diamond wire saw machining are common. The first type, the spool-to-spool wire saw,

uses a long wire stored in two spools to cut the workpiece. Fresh diamond wire is continuously introduced during machining, which makes this type of wire saw cutting more precise, but also more expensive. This type of wire saw cutting slices a semiconductor wafer and has been investigated for wood machining with limited success (Clark et al. 2003a, 2003b). This research investigates the other two wire saw machining configurations: looped and oscillatory wire saw

cutting. The looped diamond wire cutting, as shown in **Figure 1a**, uses a loop wire between the upper and lower wheels to cut the wood workpiece. It is similar to the band saw. New technologies to firmly join two ends of a diamond wire segment together to form a wire loop have been developed, for example by Hodsden and Hodsden (2000), and made this technology suitable for wood machining. An advantage of the looped wire saw is the ability to achieve high wire speed for efficient cutting. In this study, the wire speed was 20 m/sec. for the looped wire machine. The other cutting configuration is the oscillatory wire saw, as shown **Figure 1b**. A segment of diamond wire moves back and forth in the pre-machined groove on the peripheral of the upper and lower wheels. Unlike the spool-to-spool wire saw, the length of diamond wire in the oscillatory wire saw is much shorter, which reduces the cost and limits the wire life.

Newly developed diamond wires for slicing semiconductor wafers are becoming more durable. New methods to firmly affix diamond grits to a thin steel wire have been commercialized. These

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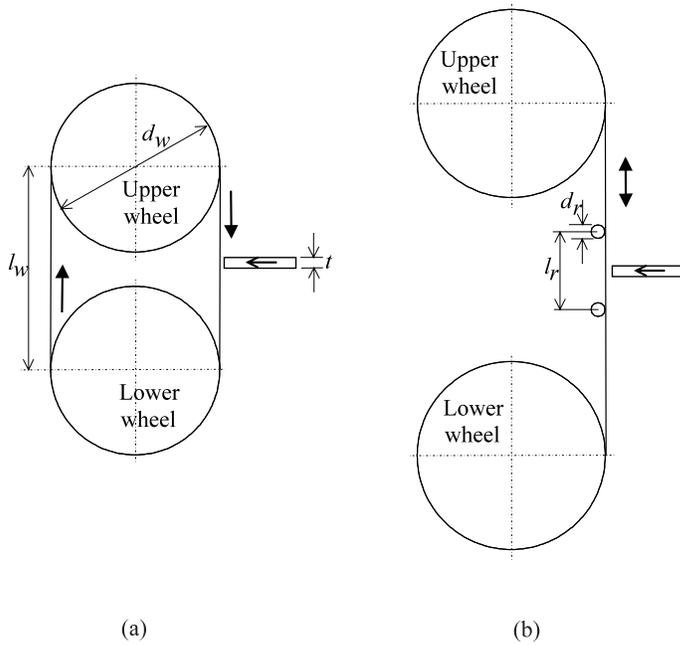


Figure 1. – Configurations of the diamond wire saw cutting tests performed in this study: a) looped wire saw; and (b) oscillatory wire saw.

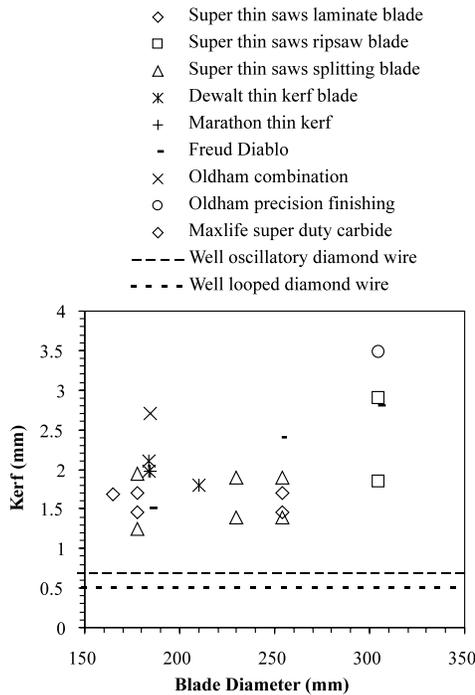


Figure 2. – Kerf loss in circular saw and diamond wire saw machining of wood.

methods include the electroplating and laser conditioning of the metal bond and mechanical crushing of the diamond into the wire (Clark et al. 2003b). Another advancement is the non-contact

wire bow sensor to detect the orientation of the wire for the cutting force measurement and cutting path error compensation. High speed wire saw machines have also been developed to

reduce the cutting force on each diamond grit, lower the wire wear, and achieve higher material removal rate.

Two advantages of the diamond wire saw are the thin kerf and the freedom to change cutting direction and workpiece orientation during cutting. Examples of the level of kerf loss for circular saw and diamond wire saw for wood machining is shown in Figure 2. The kerf of the diamond wire saw is about an order of magnitude smaller. Figure 3 shows the flexibility of the diamond wire saw when cutting wood. The wire cutting direction can easily be changed to generate complicated cutting paths and intricate parts. This is not achievable in traditional band and circular saws. In addition to the change in cutting path, orientation of the wood workpiece can also be adjusted to create even more complicated part geometries.

In this paper, the experimental setup and design for the looped and oscillatory diamond wire saw cutting of wood are first introduced. Results of the cutting forces and surface roughness are analyzed and discussed.

Experimental setup and design

The diamond wire saw machine, diamond wire, design of experiment, and setup for forces and surface roughness measurements are discussed in this section.

Diamond wire saw machines and diamond wires

The looped and oscillatory diamond wire saw experiments were conducted on a Model Murg 400 and Model 7243 machine (Well Diamond Wire Saws, Inc.), respectively. The top speed of the looped diamond wire saw is 20 m/sec., which is fast compared to other conventional diamond wire saws. This was the speed for all looped wire cutting tests in this study. The top wire speed of Model 7243 is 1.5 m/sec.

The d_w and l_w are 394 and 481 mm for the loop wire saw (Fig. 1a) and 470 and 927 mm for the oscillatory wire saw (Fig. 1b), respectively. For the two support pulleys in the oscillatory wire saw, $d_r = 25$ mm and $l_r = 112$ mm.

The nominal diameters of the diamond wire in the looped and oscillatory wire saws are 0.5 and 0.7 mm, respectively. The diamond grit with an average size of 54 μ m is mechanically crushed into the wire. Figure 4a shows a section of new diamond wire. Diamond grits are

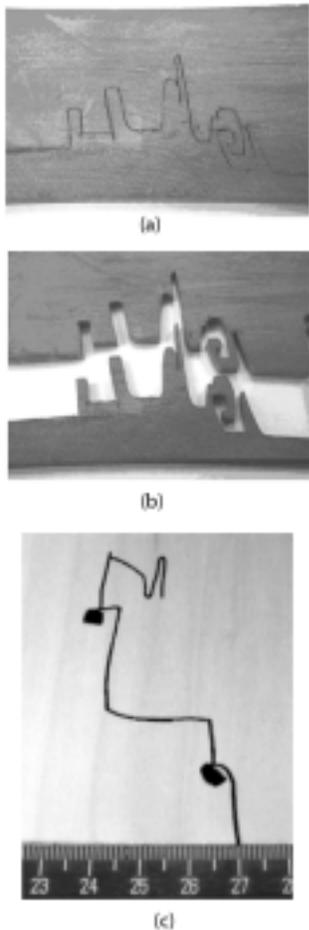


Figure 3. – Flexibility of the diamond wire saw for wood machining: a) a cedar slat cut by a diamond wire saw; b) two pieces separated from the cut cedar; and c) a contour cut on a pine sample.

crushed and embedded in the wire. A section of the used diamond wire is shown in **Figure 4b**. The bond is eroded and diamond grits are exposed on the wire for the oscillatory wire saw.

In both looped and oscillatory diamond wire saw tests, used but not totally worn-out diamond wires were utilized. Although a wire endurance test was not conducted in this study, apparently the diamond wire can last for an extended period of time for wood machining.

Workpiece, fixture, and motion control

The two types of wood studied were white oak (*Quercus alba* L.) and eastern white pine (*Pinus strobes* L.). The thickness of the wood workpiece, denoted as t in **Figure 1**, was 19 mm.

As shown in **Figure 5**, a clamping plate held the wood workpiece on the

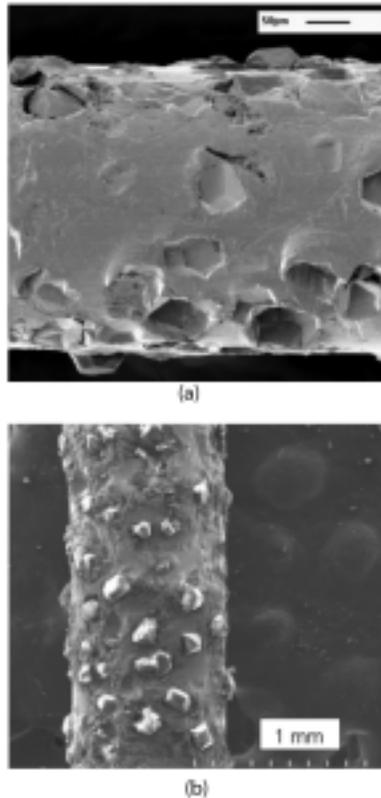


Figure 4. – Diamond wire: a) new diamond wire; and b) used diamond wire.

top of a three-axis force dynamometer (Kistler Model 9255B). Forces normal and tangential to the wire segment in contact with the workpiece, denoted as F_N and F_T , were recorded for all cutting tests. The force dynamometer was bolted into a stepping motor and ball screw controlled Isle Automation slide. This slide moves the wood workpiece at a constant feed rate into the wire. A groove was machined on the wood workpiece with the contact length equal to the thickness of the workpiece.

Design of wire saw cutting experiments

The wire saw experiments involved both the ripcut and the crosscut directions. As shown in **Figure 6a**, the wire traveled along the grain in a ripcut. Grooves cut by diamond wire after testing can also be seen. The wire cut across the grain in a crosscut, as shown in **Figure 6b**. The feed rate and wire speed were the other two key process parameters that were varied.

A set of baseline cutting tests were designed and conducted for the looped and oscillatory wire saw machine, respectively, to investigate the effect of wood type (pine and oak) and cutting direction

(rip and cross). **Tables 1** and **2** summarize the test parameters and the number of wire saw cutting tests conducted.

As shown in **Table 1**, the 12 baseline tests for oscillatory wire saw cutting included two types of wood (pine and oak), two cut directions (rip and cross), and three wire speeds (0.5, 1.0, and 1.5 m/sec.). The extended test 1 was conducted to study the effect of high feed rate. The feed rate was increased from 0.5 to 1.0 mm/sec. and six cutting tests for crosscut of pine and oak at 0.5, 1.0, and 1.5 m/sec. wire speed were conducted.

The baseline test for the looped wire saw, as shown in **Table 2**, included rip- and crosscutting pine and oak at four feed rates (0.5, 1.0, 1.5, and 2.0 mm/sec.). The oak ripcut at the highest feed rate (2.0 mm/sec.) was omitted due to the concern of possible high cutting forces. Fifteen baseline tests were conducted for the looped wire saw cut. The extended test 2 was designed to investigate the effect of coolant by adding a small amount of water mist to the running wire. Eight tests were conducted for crosscut of pine and oak at 0.5, 1.0, 1.5, and 2.0 mm/sec. feed rate. Due to the high wire speed (20 m/sec.) in looped wire cutting, additional tests at much higher feed rates of 2.5, 3.0, 3.5, and 4.0 mm/sec. were achievable and conducted in the extended test 3.

Cutting forces and surface roughness measurement

A Mitutoyo SurfTest system with a diamond-tip contact stylus measured the roughness of the machined wood samples. Two measurement traces were each conducted along and across the cutting direction. The average of arithmetic average roughness (R_a) on the four measurement traces represented the roughness of machined wood surfaces.

Two cutting force components normal and perpendicular to the section of wire in contact with the workpiece were measured with the dynamometer. Calibration factors were obtained to convert dynamometer voltage output to force. Adding and removing known weights on the dynamometer in the normal and tangential force directions determined the calibration factors. The cutting forces in wire machining took 30 to 90 seconds to reach the steady-state condition. The output voltage drifted due to discharge of the quartz piezo-ceramic in the dynamometer. The drift was ob-



Figure 5. – Setup of the clamp, dynamometer, and slide for diamond wire cutting of wood.

served as linear. A correction factor was obtained for each cutting direction. The measured forces were converted to a specific cutting force by dividing the force with projected area of contact (length of contact times the nominal wire diameter). Different nominal diameters of diamond wire were utilized in the looped and oscillatory wire saws. The specific cutting forces enable the mutual comparison of force results.

As the normal force gradually reached a constant level, the magnitude of both normal and tangential force was measured. This force was further analyzed to calculate the specific normal and tangential forces.

Cutting force and surface roughness results

Oscillatory wire saw cutting

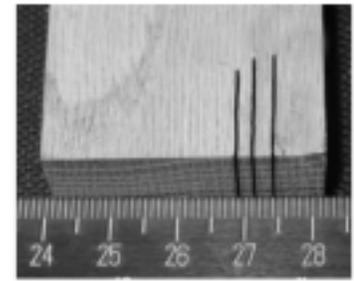
Figure 7 shows the baseline and two extended test results for oscillatory wire saw cutting. The crosscut and ripcut data points are represented by triangular and circular shape symbols, respectively.

Baseline tests are shown in solid marks and connected by solid lines. Two extended tests are represented in open symbols and connected by dashed lines. In baseline tests, the effects of types of wood, cutting direction, and wire speed were investigated. In extended test 1, the effect of feed rate was studied. Observations are summarized as follows.

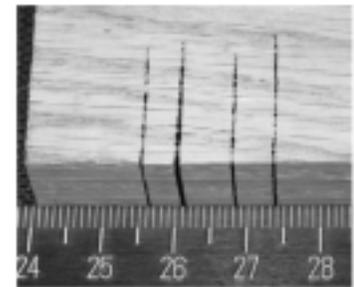
Effect of the type of wood. — No distinguishing difference existed on the level of forces and surface roughness in oscillatory diamond wire saw cutting of pine and oak samples.

Effect of cutting direction. — The ripcut, in general, had higher cutting forces in both net force and normal and tangential cutting forces. The surface roughness, under various process parameters and for different types of wood, remained at about $3 \mu\text{m } R_a$.

Effect of wire speed. — The net specific cutting force showed the clear trend of lowering cutting forces at higher wire speed. The same trend was seen on the normal force, but not as obvious in the



(a)



(b)

Figure 6. – Cutting directions and groove cut by a diamond wire saw: (a) ripcut; and (b) crosscut.

tangential force for oak cutting. High wire speed did not improve the surface roughness. The effect of wire speed will be further discussed in the high speed, 20 m/sec., looped diamond wire saw cutting.

Effect of feed rate. — The faster feed rate in crosscutting of pine and oak increased the cutting forces but did not significantly affect the surface roughness.

The ratio of normal to tangential cutting forces (F_N/F_T) is an important indicator to represent the efficiency of a wire cutting process. In the previous study of spool-to-spool diamond wire cutting of wood (Clark et al. 2003a), the F_N/F_T ratio in the range of 0.6 to 2.5 and 1.5 to 3.2 for pine and oak, respectively, was observed. In our oscillatory wire saw tests, the force ratio for both types of wood stayed in the 1 to 3 range. Slow feed rates generate lower force ratios. The same trend has been seen in the dia-

Table 1. – Experiment design for oscillatory wire saw cutting tests.

Experiment	Workpiece	Cut direction	Feed rate	Wire speed	No. of tests
			(mm/sec.)	(m/sec.)	
Baseline	Pine, oak	Rip, cross	0.5	0.5, 1.0, 1.5	12
Extended test 1: feed rate	Pine, oak	Cross	1.0	0.5, 1.0, 1.5	6

Table 2. – Experiment design for looped wire saw cutting tests.

Experiment	Workpiece	Cut direction	Feed rate	Wire speed	Coolant	No. of tests
			(mm/sec.)	(m/sec.)		
Baseline	Pine, oak	Rip, cross	0.5, 1, 1.5, 2	20	No	15 ^a
Extended test 2: coolant effect	Pine, oak	Cross	0.5, 1, 1.5, 2	20	Yes	8
Extended test 3: feed rate	Pine	Rip	2.5, 3, 3.5, 4	20	No	4

^aRipcut of oak at 2 mm/sec. feed rate was not conducted due to the possible high cutting force.

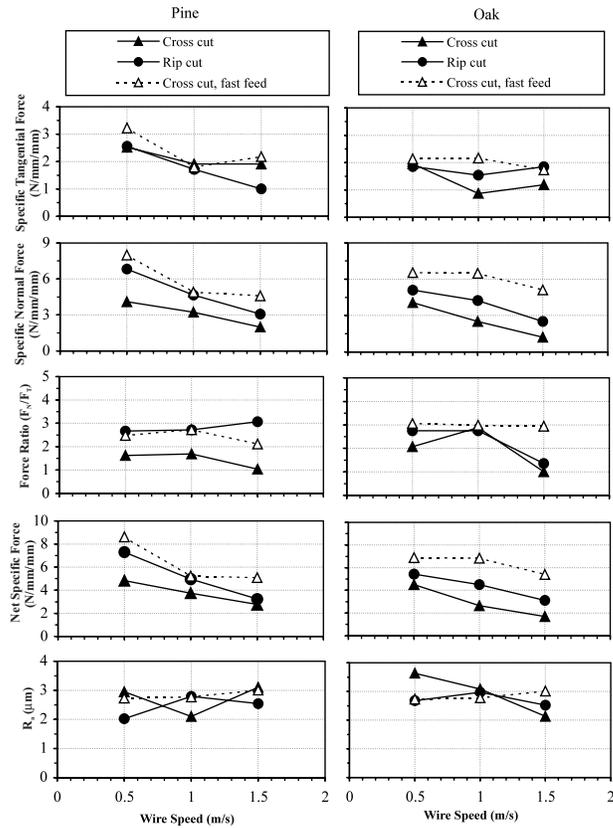


Figure 7. — Oscillatory wire saw cutting forces and surface roughness results.

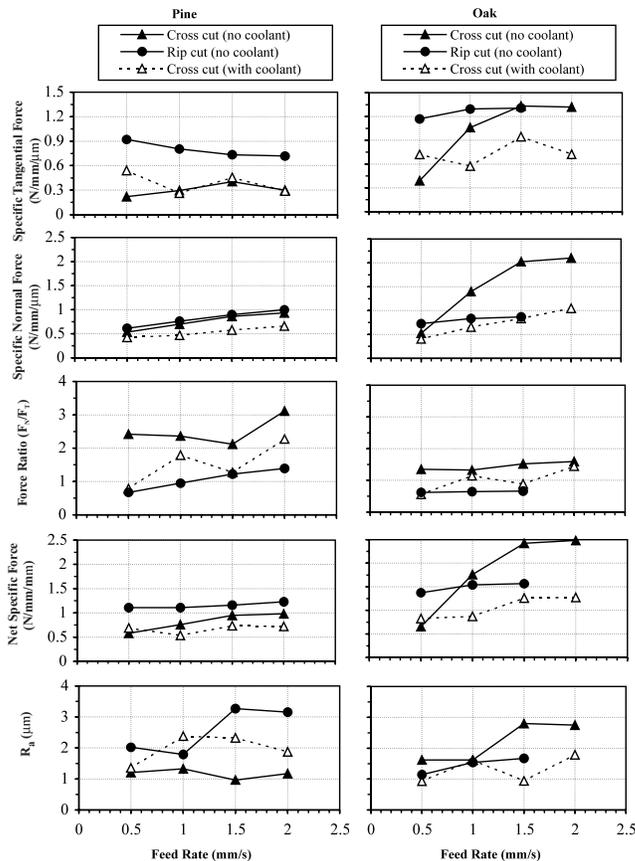


Figure 8. — Looped wire saw cutting forces and surface roughness results.

mond wire saw cutting of single crystal SiC (Hardin et al. 2004). Low F_N/F_T in the range of 0.3 to 1.3 was obtained at a very slow wire feed rate, which hindered the build up of normal cutting force and resulted in a low force ratio.

Looped wire saw

Figure 8 shows the results of the baseline test and extended test 2 (coolant effect) in looped diamond wire cutting. The same sign conventions in Figure 7 were applied. Compared to the oscillatory diamond wire saw cutting, the specific cutting forces in looped diamond wire were much lower. This is caused by the very high wire speed, 20 m/sec., in looped diamond wire saw cutting. The trend of lower cutting forces at high wire speed has been observed in Figure 7 and further reinforced in Figure 8. The looped configuration helped to achieve the high wire speed desired for efficient diamond wire saw cutting.

Effect of type of wood. — The oak exhibited slightly higher cutting forces, particularly at high feed rate cutting. Such a distinct high cutting force for oak, which likely was caused by the wire speed effect, was not obvious in the oscillatory wire cutting. For oak and pine, the surface roughness was about the same at low feed rate. As the feed rate increased, the surface roughness for pine remained at the same, 1 to 2 μm R_a range. The force ratio (F_N/F_T) showed distinctly different levels for oak and pine. Oak had a lower F_N/F_T ratio.

Effect of cutting direction. — For pine, the ripcuts generated distinctly higher tangential force and about the same level of normal force compared to that of crosscut. For oak, the ripcut had higher tangential force and, in general, lower normal force at a high feed rate. This phenomenon was also observed in the net force.

Effect of feed rate. — Higher feed rate, in general, generated higher cutting forces. This is particularly apparent in results of the net force. Higher feed rate generated higher net force for both pine and oak. On individual force components, higher normal forces were seen at a high feed rate in all cutting conditions. For the tangential force, an obvious exception was the ripcut of pine. A lowering trend of tangential force was observed from a high (2 mm/sec.) feed rate. An extended test of the ripcut of pine with feed rates from 2.5 to 4 mm/sec. was conducted to investigate tan-

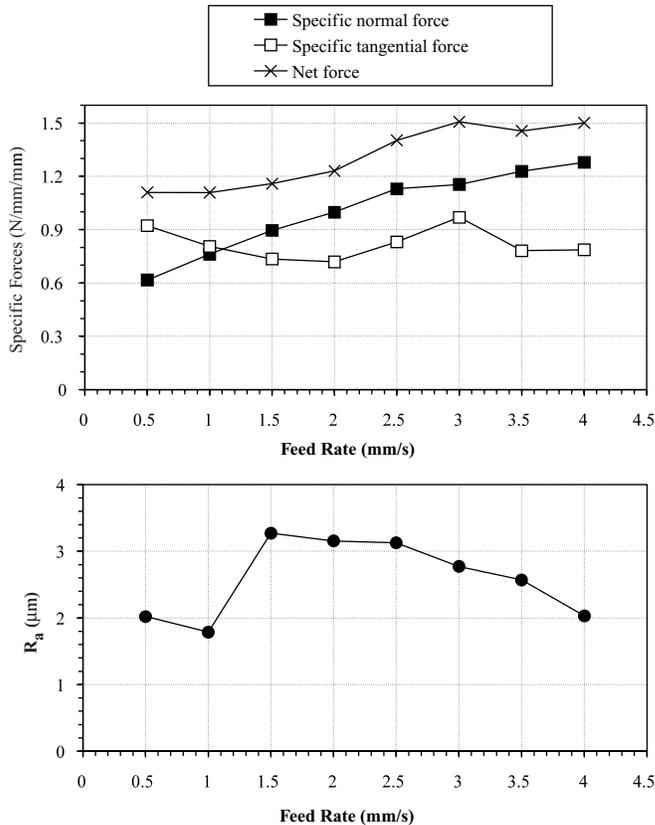


Figure 9. – Effect of feed rate on cutting forces and surface roughness.

gential force at high feed rates. Results of the cutting force and surface roughness across a feed rate from 0.5 to 4 mm/sec. are shown in **Figure 9**. The lowering trend of tangential force stopped at 2 mm/sec. The specific tangential force, in general, remained in the 0.85 to 0.9 N/mm/mm range. Across the wide range of feed rates, the normal force continued to increase at higher feed rates. The net force, which combined the effects on normal and tangential forces, increased at high feed rates. Surface roughness remained in the 2 to 3 μm R_a range, regardless of the feed rate.

Effect of coolant. — The coolant did not affect the tangential force significantly. It did, however, help to reduce the normal force by about 30 to 50 percent, particularly at the high feed rates (1.5 and 2 mm/sec.). The addition of coolant did not provide much help to reduce the cutting force at the low feed speed (0.5 mm/sec.). With coolant, the surface roughness increased for pine but de-

creased for oak. The reason for such an opposite trend, which may be caused by different material characteristics of pine and oak, is not known and requires further study.

In comparison, an oak sample surface was cut with a band saw for mutual comparison. The surface roughness was high, about 9.6 μm R_a . It was also noted that all diamond wire cut surfaces had the glazed texture.

Conclusions

Oscillatory and looped diamond wire saw cutting tests were conducted and results of cutting forces and surface roughness were reported in this study. The capability of the high speed looped diamond wire saw for high feed rate cutting of wood was demonstrated. The surface roughness remained relatively consistent below 3 μm R_a under all different wire saw cutting configurations.

Cost is a key factor to successfully implement the diamond wire saw technol-

ogy. The high cost of diamond wire is significantly reduced with the looped and oscillatory diamond wire cutting configurations investigated in this study. The longevity of the diamond wire remains as a major concern and potential research area. This study utilized used diamond wires for all tests. It demonstrated a certain level of wire life by completing all cutting tests without noticeably affecting the wire cutting performance. The roughness on diamond wire saw surfaces was not compromised, even with the large increases in feed rate. Many post-cutting operations, such as sanding, could be reduced or eliminated because of the excellent surface quality. The current feed rates achieved are much faster than initial tests performed by Clark et al. (2003a). However, it is still slow compared to the current wood machining operations.

In the future, new, more durable diamond wires and wire saw machines are expected to be available in the market for semiconductor wafer slicing. Such development is expected to continuously push the feed rate and precision in diamond wire cutting of wood to a new level. However, the practical limitations of feed rate due to clogging makes the diamond wire saw an unlikely process for all but some specialized industrial applications.

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