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Fixed abrasive diamond wire machining—part II: experiment design and results

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Abstract

Experimental results from fixed abrasive diamond wire machining of wood and foam ceramics are presented. Three types of wood—pine, oak, and fir, and three types of foam ceramic—silicon carbide, zirconia, and zirconia toughened alumina, are tested. The research investigates the life of diamond wire and effects of process parameters on the cutting forces, force ratio, and surface roughness. A scanning electron microscope is used to study the worn diamond wire, machined surfaces, and debris. The diamond wire saw is demonstrated to be very effective in machining foam ceramics. The wire life for cutting wood at slow feed rates is low. The short tool life for dry cutting of wood indicates that more research in new fixed abrasive diamond wire and wire saw machining technologies is necessary.

Keywords: Diamond wire saw; Wood machining; Foam ceramics

1. Introduction

Three types of wood and three types of foam ceramics are the work-materials used in the fixed abrasive diamond wire machining experiments. The three types of wood are: white oak (*Quercus alba* L.), eastern white pine (*Pinus strobes* L.), and Douglas fir (*Pseudotsuga menziesii*). Silica-fused silicon carbide (SiC), transformation toughened zirconia (TTZ), and zirconia toughened alumina (ZTA) are the three foam ceramics used. Photographs of the six materials investigated are shown in Fig. 1.

The annual ring or the earlywood and latewood can be recognized on the wire saw cut wood surface. The width of each wood workpiece is 19 mm. The ceramic foam structure consists of ligaments creating a network of inter-connected, dodecahedral-shaped cells. The cells are randomly oriented and mostly uniform in size and shape. The ligament is hollow with a triangular-shaped hole, a result of the manufacturing technique. The pore size is about 2–4 mm or 10 ppi (pores per inch) for the SiC and about 0.7–1.3 mm (30 ppi) for TTZ and ZTA foam. Fig. 1(f) also shows the grooves, cut by the diamond wire saw during the experiment, on the ZTA foam.

During the wire saw cutting experiment, as discussed in [1], the horizontal cutting force was measured using a piezoelectric dynamometer, the vertical cutting force was recorded using a capacitance sensor for wire bow, the wire feed and feed rate were calculated from the yoke motor signal, and the wire speed was determined from the servomotor velocity output signal. The goals of this research were to study the endurance of the wire, investigate effects of process parameters on the force and surface roughness, and use the scanning electron microscopy (SEM) to examine the worn diamond wire, machined surface, and debris.

The experiment design and test matrices are first presented. An endurance test for diamond wire cutting was then conducted. Results from cutting wood and foam ceramics at different wire speeds and rocking frequencies are discussed. SEM micrographs of the diamond wire, machined surface, and debris are analyzed.

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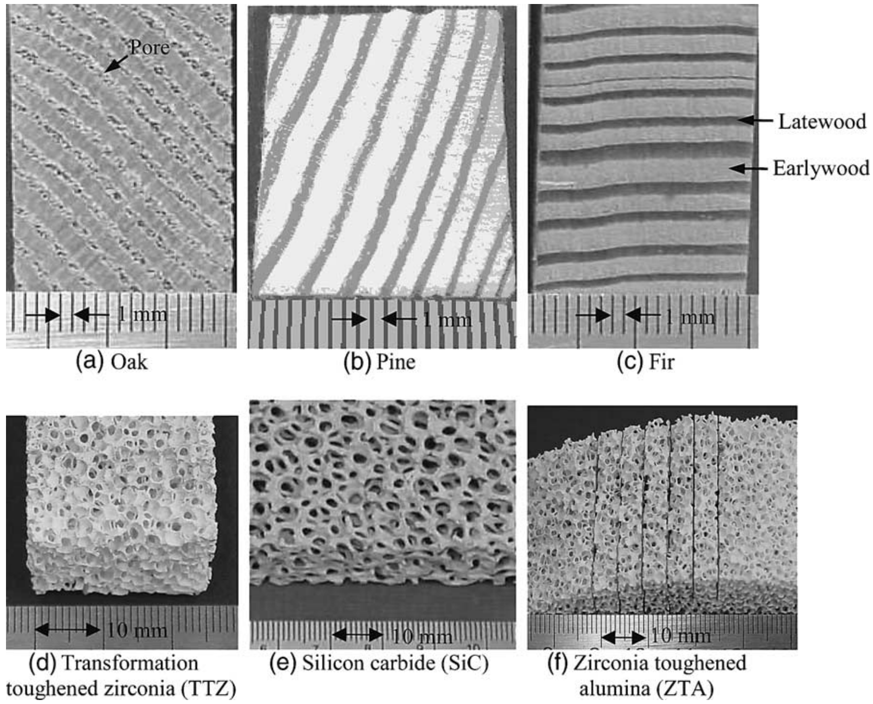


Fig. 1. Materials cut by diamond wire saw in this study.

2. Experiment design

The Millennium spool-to-spool diamond wire slicing machine, manufactured by Diamond Wire Technology at Colorado Springs, CO, was used in this study. Four rocking frequency settings, i.e., no rocking, slow (0.15 Hz), medium (0.3 Hz), and fast (0.5 Hz), are available. The diamond wire used in this study was also produced by Diamond Wire Technology. The wire, shown in Fig. 2, has a 250 μm nominal diameter. The bond is electroplated and treated by laser to enhance the retention of diamond grits. The diamond grits on the new wire, as marked by D in Fig. 2, are partially covered by the plated metal bond and cannot be easily recognized. The average size of diamond is about 64 μm or 230 ANSI mesh. All tests were conducted without coolant. The length of wire used in all tests was 150 m. This limited wire length restricted the wire speed to 9 m/s.

The workpiece was fixed to the top of a Kistler model 9255B piezoelectric force dynamometer to measure the cutting forces. Signals for wire speed, bow angle, and yoke down feed were collected from the saw's controller.

Three sets of experiments were conducted. The first was an endurance test to evaluate the life of a diamond wire. The workpiece was eastern white pine, denoted as pine hereafter. The width and depth of cut were 19 and 25.4 mm, respectively. The wire down feed speed was 0.051 mm/s and wire speed was 4.5 m/s. Rocking motion was set at the 5° and medium frequency (0.3 Hz).

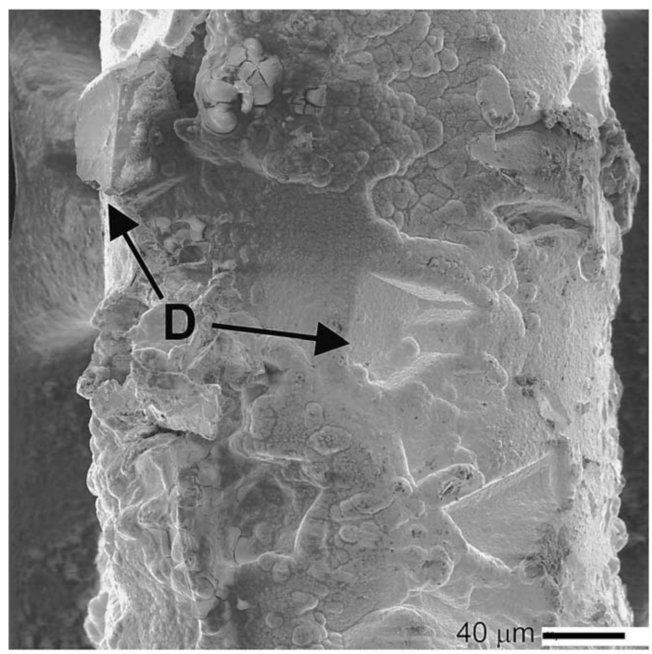


Fig. 2. New diamond wire.

After the initial endurance test, a testing matrix, as shown in Table 1, was designed to examine the machining of pine and white oak, denoted as oak hereafter. Two parameters, wire speed and rocking frequency, were varied for cutting both pine and oak materials. The wire down feed rate, width of cut, and depth of cut were set at 0.051 mm/s, 19 mm, and 25.4 mm, respectively. An additional test was conducted on Douglas fir to examine

Table 1
Test matrices for diamond wire saw cutting of pine, oak, and foam ceramics

Pine and Oak (0.051 mm/s down feed)					
Wire speed (m/s)		Rocking motion (5°)			
		None	Slow	Medium	Fast
4.5		x	x	x	x
6		x	x	x	x
9		x	x	x	x

Foam ceramics				
Rock motion		No rock		5° Fast rock
Down feed rate (mm/s)		0.051	0.635	0.635
Wire speed (m/s)	4.5	x	x	x
	6	x	x	x

x: Experiment conducted

the change in forces for cutting the earlywood and latewood.

Preliminary tests of diamond wire saw cutting of foam ceramics showed a potential for faster wire down feed speed. Therefore, as shown in Table 1, experiments were conducted at the yoke motor's highest programmable down feed rate, 0.635 mm/s, at two extreme rocking frequencies (0 and 0.5 Hz). Another set of tests with no rocking motion was conducted at 0.051 mm/s down feed rate, the same rate used in the endurance and pine and oak cutting tests. Two wire speeds at 4.5 and 6 mm/s were tested. The width of cut for SiC, ZTA, and TTZ were 20, 25, and 39 mm, respectively.

The surface roughness of wood, a porous material, after wire saw cutting was measured by both contact and non-contact methods to evaluate the effects of cutting parameters and to compare results of two surface roughness measurement methods. A Taylor Hobson Talysurf Model 120 profilometer with a 10 μm radius diamond-tip contact stylus and a Rodenstock RM600 optical surface roughness measurement machine using a dynamically focused infrared laser with 2 μm focal point diameter were used in this study. For each cut surface, roughness measurements were taken both along and against the cut. The foam ceramics cut in this experiment were not measured by either method due to their porous nature.

3. Endurance cutting results

The wire endurance test was conducted to evaluate the effect of gradual wear of the diamond wire on cutting forces. A series of 16 identical slices with 19 and 25.4 mm width and depth of cut, respectively, were conducted on the pine. Results of the vertical and horizontal forces, F_V and F_H, in each of the 16 wire saw cuts are shown in Fig. 3. The maximum force recorded during cutting, excluding the transient force in the first two seconds of contact, was used to represent the force in a cutting condition. The first three cuts with a new diamond wire had about the same level of vertical and horizontal cutting force. Comparing the vertical force, it gradually increases from about 2.4 N in the first three cuts to 7.4 N, about three times higher, in the 16th cut. The values for vertical force F_V were always higher than the horizontal force F_H. Also of interest is the ratio of the horizontal to vertical forces, F_V/F_H, which is shown in Fig. 3. Even as the force levels increased, the force ratio F_V/F_H remained between 1.8 and 2.8 for all cuts. Compared to the force ratio of 3–15 for CBN grinding of zirconia [2], 3–10 for CBN grinding of M2 tool steel [2], 4–9 for CBN grinding of silicon nitride, [3] and 5–5.5 for diamond grinding of silicon nitride [4], this force ratio is lower and may indicate more efficient material removal for wire saw cutting of wood.

The surface roughness of cut surfaces in the wire endurance test was measured using the contact profilometer method. Results of arithmetic average roughness, R_a, of the first 13 cuts are shown in Fig. 4. Six traces were measured, three along the cut and three across the cut directions, on each of the two cut surfaces. The level of R_a remains at about 1.8–2.2 μm and does not vary significantly due to the wear of the diamond wire.

Results from the endurance test assure that the dia-

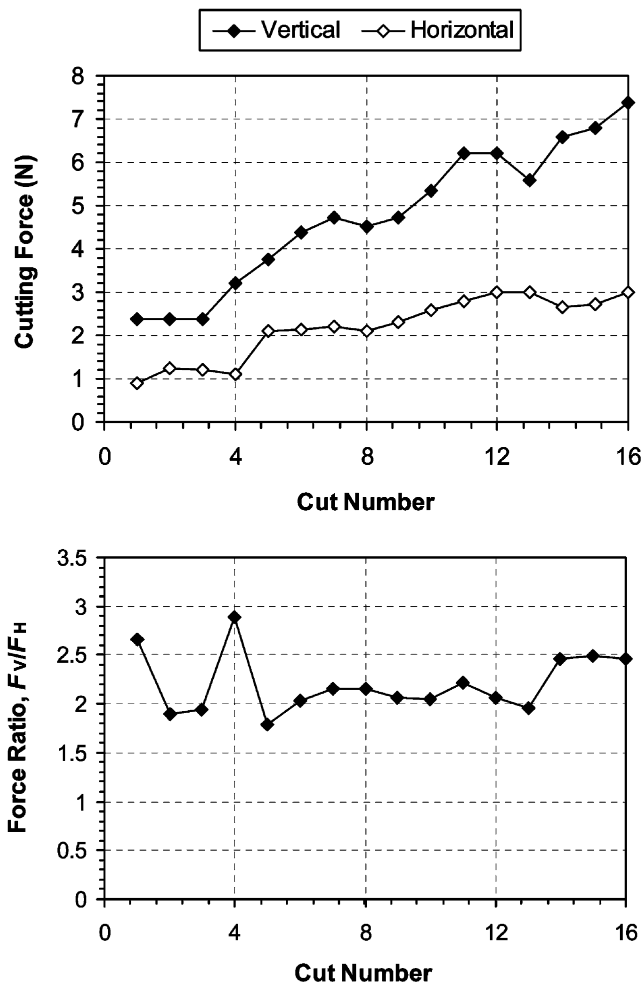


Fig. 3. Force and force ratio in wire endurance cutting of pine.

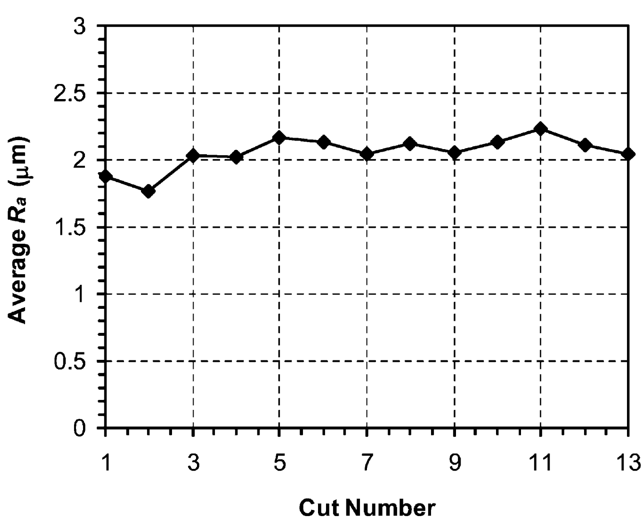


Fig. 4. Surface roughness of pine samples in endurance test.

mond wire can be used for at least three cuts without changing the sharpness and cutting performance significantly. This observation is applied to the pine and oak cutting test in the next section. The endurance test also generated a worn diamond wire, which was examined using the SEM.

Fig. 5 shows SEM micrographs of the worn diamond wire after 16 cuts of pine samples in the endurance test. On the worn diamond wire, as shown in Fig. 5(a,b), some diamond grits (marked by D) still exist. In addition, wear flats, marked by F, were generated on the worn diamond wire surface. Some cavities due to diamond pull-out were observed on the worn diamond wire surface. For example, Fig. 5(c) shows a cavity with recognizable diamond crystalline shape. The bond was rolled over the edge of the cavity, as marked by B in Fig. 5(c).

The debris generated during cutting was captured by a petri dish placed next to the wire cut area in the workpiece. During wire cutting of wood, a significant amount of wood dust was created and spread all over the machine. Most of the debris from wire cutting of wood became airborne and was not caught by the petri dish. Fig. 6(a) shows the SEM micrograph of debris caught in the pine endurance cutting test. Most of the particles can be recognized as diamond grits. Only a few pine debris particles are recognizable. Due to the fracture of diamond during cutting, most of the diamond grits in Fig. 6 are smaller than the 64 μm average size of the original diamond used in the wire. According to the wire manufacturer, a very friable diamond grit was selected to manufacture the diamond wire. Close-up views of flake-shaped pine debris caught in the petri dish are shown in Fig. 6(c,d). The average size of the debris is about 0.1–0.2 mm. The smaller size pine debris likely became airborne and did not show up in the sample observed.

The force calculation based on the formula derived in the companion paper [1] is applied to calculate the wire tension during cutting. In cut #16 at the horizontal rocking position ($\alpha = 0$), $F_H = 3.0$ N, $F_V = 7.4$ N, and the wire bow angle $\theta = 4.6°$. The estimated wire tension forces on both sides of the wire are $T_1 = 44.63$ N and $T_2 = 47.64$ N. In comparison, in cut #1 at the horizontal rocking position ($\alpha = 0$), $F_H = 1.0$ N, $F_V = 2.4$ N, and the wire bow angle $\theta = 2.4°$. The wire tension forces are $T_1 = 28.16$ N and $T_2 = 29.16$ N. Under the small angle of α and θ, the difference in T_1 and T_2 is almost identical to F_H.

4. Pine and oak cutting results

As shown in Table 1, tests were conducted to determine effects of wire speed and rocking frequency on the wire cutting of oak and pine. Fig. 7 shows the horizontal and vertical cutting forces and the ratio of vertical to horizontal cutting force (F_V/F_H).

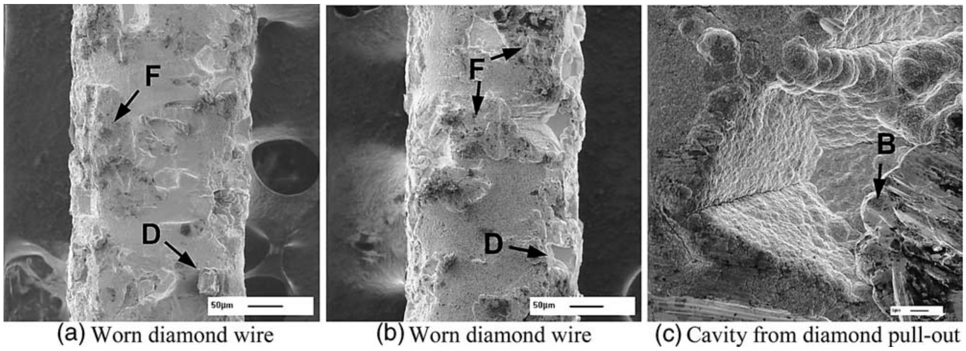


Fig. 5. Worn diamond wire from pine endurance cutting test.

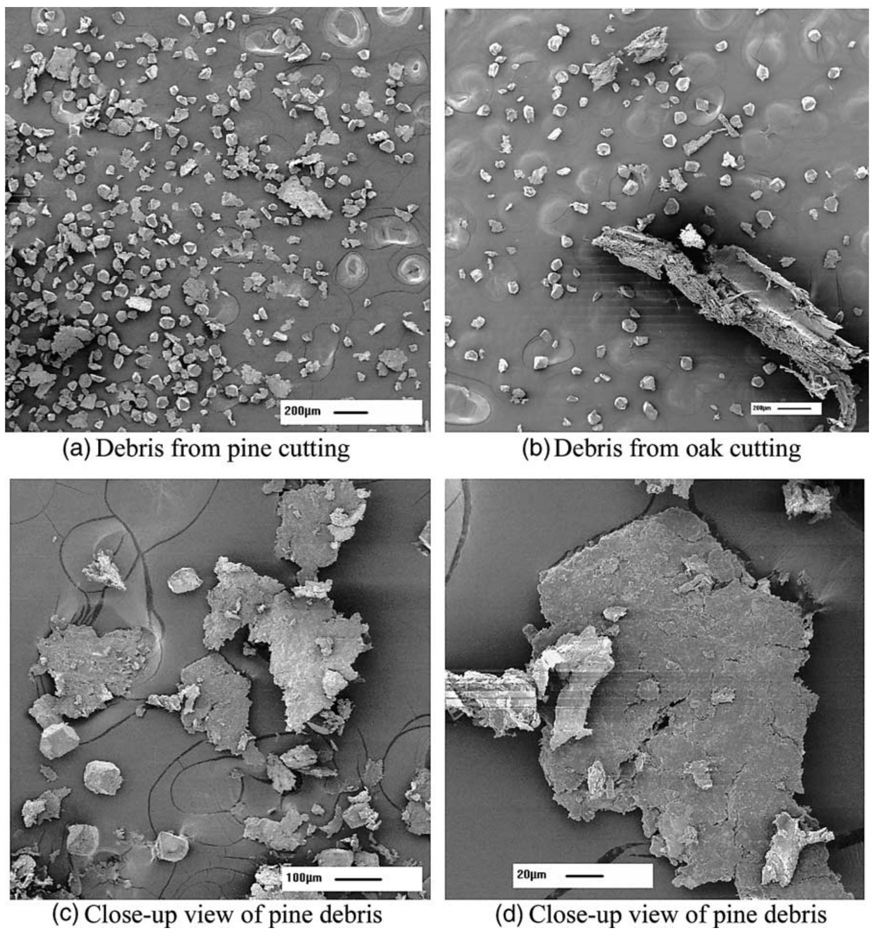


Fig. 6. Debris collected from pine and oak cutting tests.

For pine, the highest wire speed at 9 m/s results in lower F_H, F_V, and F_V/F_H. At the other two wire speeds (4.5 and 6 m/s), the results are mixed. The advantage of high wire speed for cutting oak can also be recognized; however, it is not as obvious as in pine cutting. The change in rocking frequency did not seem to produce a clear advantage for pine or oak cutting.

In general, under the same setup, the horizontal force (F_H) for wire cutting of pine is higher than that of oak while the vertical force remains at about the same level. This contributes to the lower force ratio F_V/F_H for the pine cutting.

To study the difference in cutting earlywood and latewood, a Douglas fir sample with relatively straight grain structure as shown in Fig. 1(c) was used. The latewood is harder and is expected to be more difficult to machine. The test was set up at 6 m/s wire speed and 0.051 mm/s down feed rate. No rocking motion was applied to ensure that the wire cuts only in earlywood or latewood at a given time. Force recordings were taken at times when

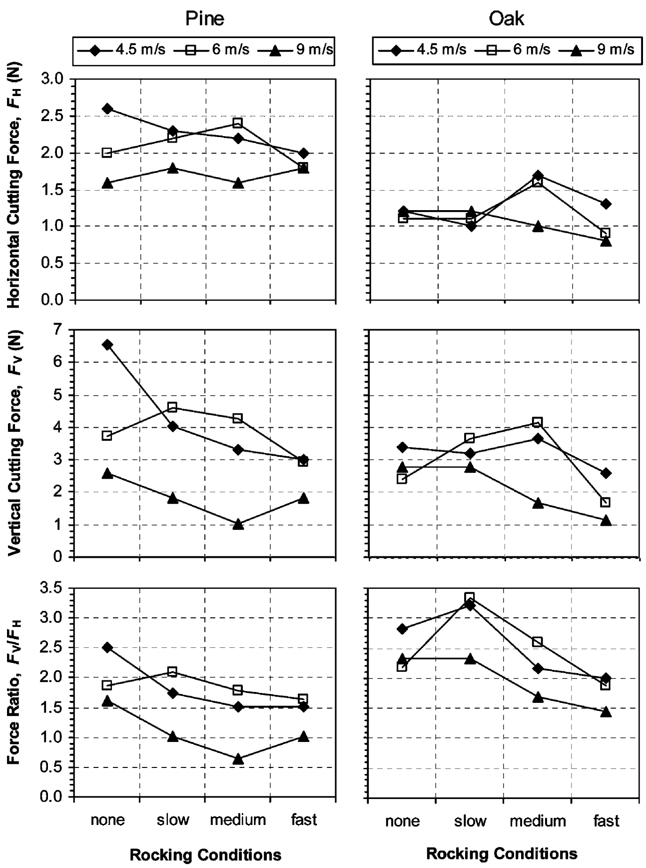


Fig. 7. Force results from pine and oak cutting tests.

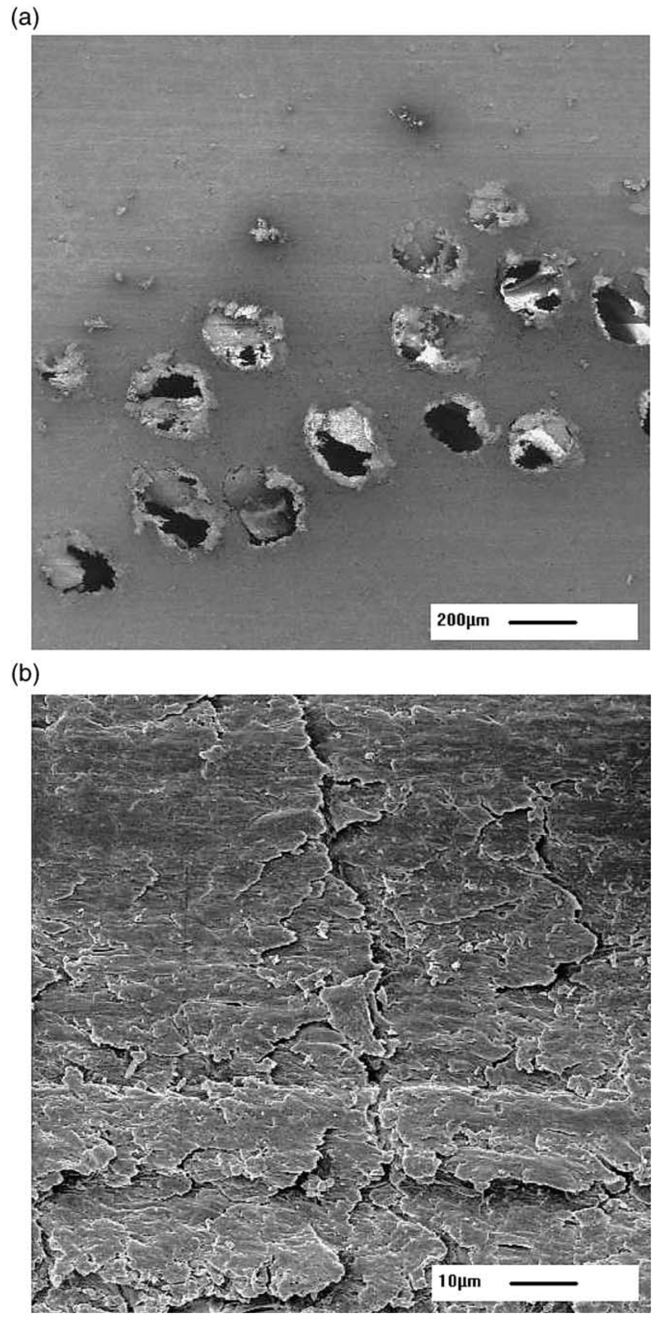


Fig. 8. SEM micrographs of oak surface after diamond wire saw cutting. (a) Porous holes on the oak surface; (b) Close-up view of oak cut surface.

the wire cuts from one type of wood to the other. There was no noticeable change in the horizontal cutting force F_H due to the change in type of wood. There was a noticeable change in wire bow and the vertical thrust force F_V when the cut moved from one type of wood to another. The wire bow angle was consistently measured at values between 1.2 and 1.3° (about 1.2 N vertical force) when the wire was cutting latewood. At the same constant wire down feed rate, the wire bow angle rapidly dropped down to 0.75° or 0.6 N vertical force when the cut moved into earlywood. When the cut passed back into latewood, the wire bow angle increased back to 1.2 or 1.3°. The force ratio F_V/F_H is higher when cutting the latewood.

The surface roughness of the pine and oak cutting samples were measured by both contact profilometer and non-contact light reflection methods. It was noticed that the oak has porous holes, about 0.15 mm in diameter, on the surface. These porous holes can be recognized in the photograph in Fig. 1(a) and in the SEM micrograph of the oak surface in Fig. 8(a). The diamond tip of the contact stylus occasionally falls into these holes and gives a false reading of the surface roughness. The non-contact optical reflection method also had a similar problem attempting to accurately measure the surface roughness of the machined oak surface. Only the results of pine surface roughness are presented. Fig. 9 shows the R_a, measured using the contact stylus method and averaged on six traces in each of the two cut surfaces for the 12 pine cutting tests. Effects of wire speed and rocking frequency on the surface roughness are not significant. The surface roughness remains at about 2.2–2.6 μm R_a range for all tests. This is also comparable to the R_a measured on the pine surface from the wire endurance test.

The contact and non-contact methods were used to

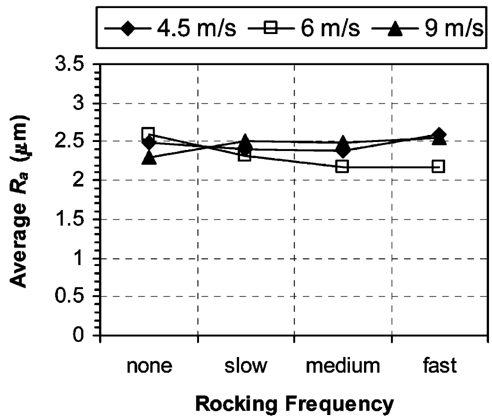


Fig. 9. Surface roughness of the pine cutting test.

measure and compare the surface roughness of two pine samples from the endurance test and the wire speed and rocking motion test. Results are summarized in Table 2. The non-contact optical reflection method gives about 16–35% higher R_a values over that measured using the contact stylus method.

The SEM micrograph of debris from diamond wire cutting of oak is shown in Fig. 6(b). Similar to the debris observed in pine cutting in Fig. 6(a), most of the fine size oak debris became airborne. A large piece of oak debris, about 0.4 × 2.5 mm, is recognized among the fine, fractured diamond grits in Fig. 6(b). This large debris is possibly a piece of burr at the edge of the oak workpiece during the wire saw cutting. Fig. 8 shows an SEM micrograph of a typical oak surface cut by the diamond wire saw at different setups. A close-up view of the oak surface after wire saw cutting is shown in Fig. 8(b). The horizontal diamond wire cutting marks and the cracking and flaking on the surface can be recognized. This surface will be compared to the close-up view of the wire cut surface of foam ceramics in the next section.

SEM micrographs of the diamond wire used for cutting oak are shown in Fig. 10(a,b). A diamond grit, marked by D, and wear flats, marked by F, can be seen on the wire. The diamond grit is exposed and the bond around the diamond grit has been eroded away. This is similar to the wear of bond and diamond grit observed in metal bond grinding wheel [5]. A close-up view of the wear flat on the diamond wire is shown in Fig. 10(b). The abrasion and plastic deformation of the metal bond can be recognized.

5. Foam ceramics cutting results

The specific cutting force is defined as the cutting force divided by the width of cut. Results of the specific horizontal and vertical cutting forces, denoted as f_H and f_V, and the force ratio for diamond wire saw cutting of three foam ceramics, SiC, TTZ, and ZTA, at 0.635 mm/s down feed rate are summarized in Table 3. The vertical and horizontal cutting forces for the slow, 0.051 mm/s down feed rate were too small to be accurately measured. Only results from the 0.635 mm/s down feed rate, the highest down feed rate attainable by the wire saw machine, are reported. It is noted that the specific cutting forces are used for foam ceramics due to the change in width of the workpiece, as shown in Fig. 1(d–f), used in this study.

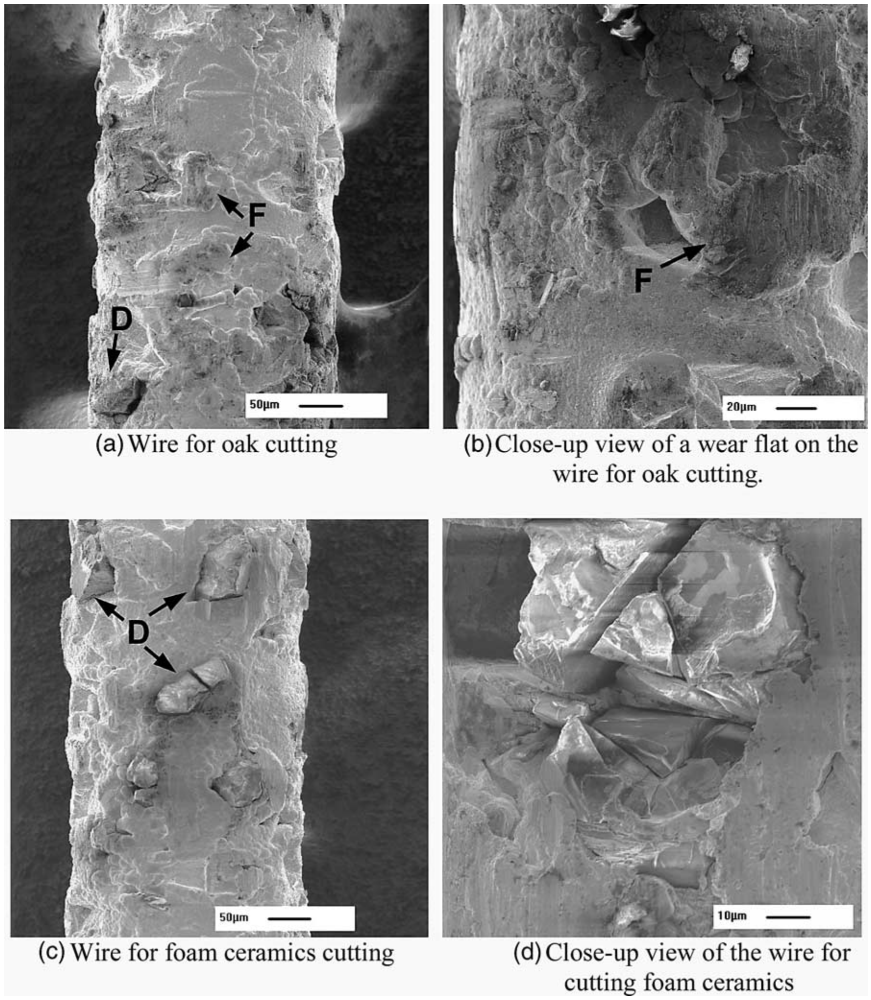
The horizontal force for cutting brittle SiC at 4.5 m/s wire speed with no rocking was too low and not measurable. Under the other three cutting conditions for SiC, the specific horizontal cutting force was also low, which, in turn, generated the high, above 22, f_V/f_H force ratio. The force ratio f_V/f_H for cutting TTZ and ZTA are about an order smaller, between 2 and 4, and comparable to that of pine and oak wire saw cutting (Figs. 2 and 7). This indicates that, compared to cutting SiC, relatively high horizontal force occurs in diamond wire cutting of TTZ and ZTA foam ceramics. Comparing the forces and force ratios for cutting TTZ and ZTA shows that TTZ has a lower specific horizontal force and a higher specific vertical force. Under the same cutting condition, the force ratio f_V/f_H for TTZ is slightly higher than that of ZTA.

The effect of wire speed in reducing the specific cutting force can be identified for both rocking and no-rocking conditions. At the high wire speed (6 m/s), the specific forces are lower for both TTZ and ZTA foam ceramics. Cutting foam ceramics with a rocking motion, in general, slightly increases the specific forces.

SEM micrographs of the worn diamond wire, debris, and cut surface are shown in Figs. 10–12, respectively. The ceramic material erodes the bond and exposes the

Table 2
Comparison of contact profilometer (Talysurf) and non-contact optical light reflection (Rodenstock) methods for surface roughness measurement

	Average R_a (μm)	
Sample	Talysurf	Rodenstock
Wire endurance test (pine), cut #9	2.12	2.47
Pine experiment (4.5 m/s wire speed, slow rocking frequency)	2.40	3.25



(a) Wire for oak cutting (b) Close-up view of a wear flat on the wire for oak cutting.

(c) Wire for foam ceramics cutting (d) Close-up view of the wire for cutting foam ceramics

Fig. 10. Worn diamond wire from oak and foam ceramics cutting tests.

Table 3
Specific cutting forces and force ratio for diamond wire saw cutting of foam ceramics at 0.635 mm/s down feed rate

Wire speed (m/s)	Parameter	SiC		TTZ		ZTA	
		No rock	5° Fast rock	No rock	5° Fast rock	No rock	5° Fast rock
4.5	f_H (N/mm)	[a]	0.005	0.060	0.060	0.064	0.077
	f_V (N/mm)	0.112	0.112	0.170	0.172	0.152	0.155
	Ratio (f_V/f_H)	—	22.3	2.84	2.86	2.34	2.02
6	f_H (N/mm)	0.005	0.005	0.052	0.044	0.056	0.071
	f_V (N/mm)	0.112	0.112	0.158	0.164	0.136	0.152
	Ratio (f_V/f_H)	22.3	22.3	3.05	3.74	2.40	2.13

[a] Force level was too small to measure.

diamond grits for very efficient cutting of the foam ceramics. This can be seen in the SEM micrograph of the diamond wire used to cut foam ceramics in Fig. 10(c). Many diamond grits are exposed and no recognizable wear flat can be found on the bond of the wire. The close-up view in Fig. 10(d) shows the erosion of the bond and the exposure and fracture of a diamond grit. Wear marks can be seen on the diamond grit in Fig. 10(d).

Fig. 11(a–c) show the debris of SiC, TTZ, and ZTA, respectively. A majority of the fine ceramic debris also becomes airborne during the wire saw cutting. Only the

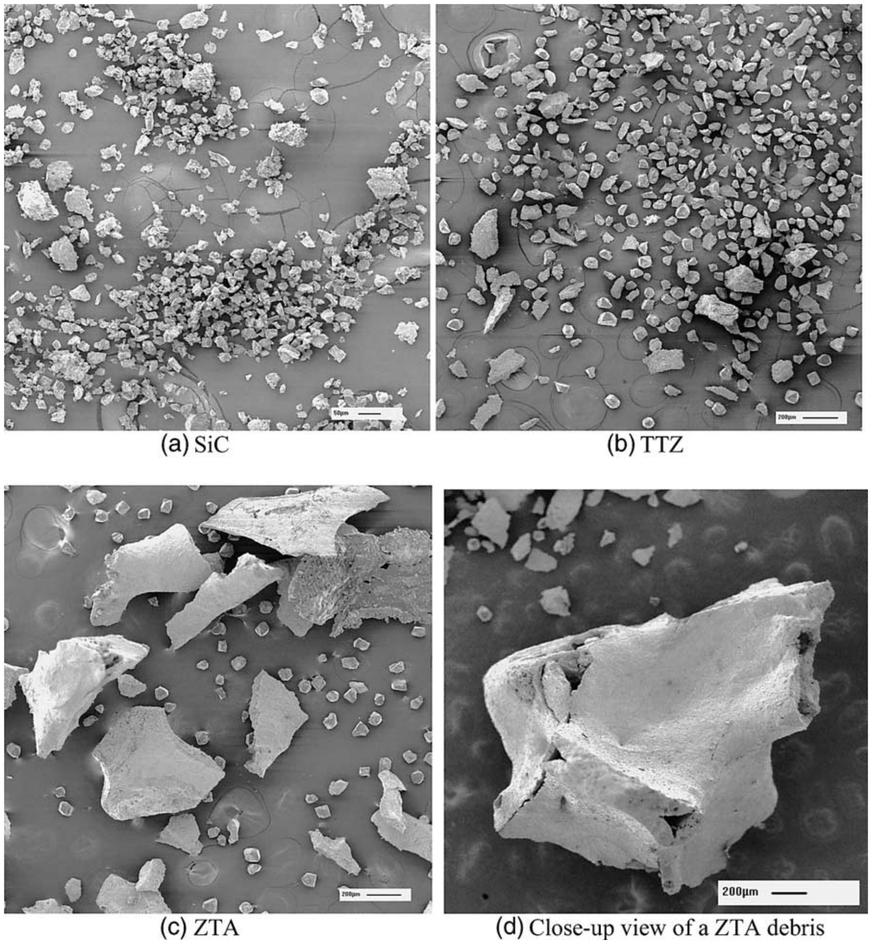


Fig. 11. Debris collected from foam ceramics cutting tests.

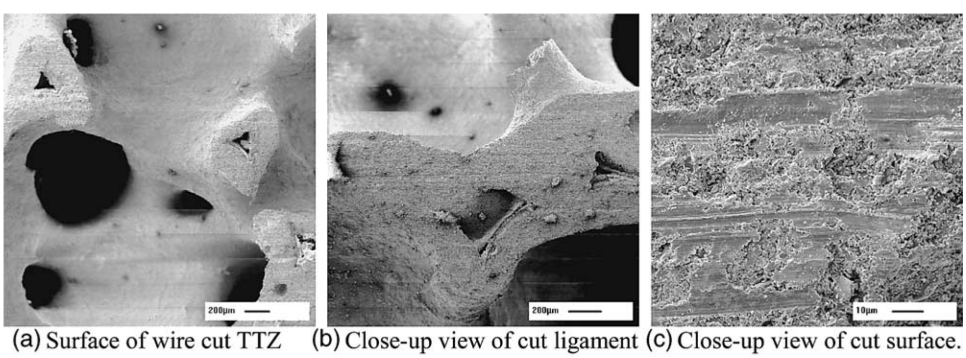


Fig. 12. Wire cut surface of TTZ foam ceramic.

large ceramic particles, possibly due to the fracture of the ligaments, were captured by the petri dish next to the cut area. For ZTA, such ligament fracture is more prominent and many large pieces of debris can be seen in Fig. 11(c).

Fig. 11(d) shows a close-up view of ZTA debris. The triangular-shaped hole inside the ligament is easily recognized. The ceramic foams used in this study were produced using open-cell polyurethane foam as templates [6]. The ceramic slurry was coated to the polyurethane foam and fired in a kiln. The polyurethane foam was burned out during the firing, leaving the triangular-shaped hollow hole inside each of the ligaments.

Fig. 12(a) shows the surface of TTZ foam ceramic cut by the diamond wire. The triangular-shaped hollow hole inside the ligament can be seen. The diamond wire could cut across a ligament, as shown in Fig. 12(b). The close-up view of the cut surface, as illustrated in Fig. 12(c), shows the porosity of the original material and the diamond wire cutting marks.

6. Concluding remarks

Experimental results of force and force ratio for diamond wire cutting of pine, oak, fir, and three types of foam ceramics were presented. SEM micrographs of the worn diamond wire, debris from cutting, and cut surface were used to gain more insight into the fixed abrasive diamond wire saw machining process. The diamond wire saw was demonstrated to be very effective for cutting foam ceramics. However, the life of the diamond wire used in this study for cutting wood was low. Preliminary test with mist of water as the lubricant shows significant improvement the wire life. This indicates that new diamond wires and the development of advanced wire cutting processes are necessary to improve this process for wood machining.

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