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Fixed Abrasive Diamond Wire Saw Slicing of Single-Crystal Silicon Carbide Wafers

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ABSTRACT

This article investigates the slicing of single-crystal silicon carbide (SiC) with a fixed abrasive diamond wire. A spool-to-spool rocking motion diamond wire saw machine using a 0.22 mm nominal diameter diamond wire with 20 μm average size diamond grit was used. The effect of wire downfeed speed on wafer surface roughness and subsurface damage was first investigated. The surface marks generated by loose diamond grit and stagnation of the wire during the change of the wire-cutting direction were studied. The use of scanning acoustic microscopy (SAcM) as a nondestructive evaluation method to identify the subsurface damage was explored. Effects of using a new diamond wire on cutting forces and surface roughness were also investigated. Scanning electron microscopy has been used to examine the machined surfaces and wire wear. This study demonstrated the feasibility of fixed abrasive diamond wire cutting of SiC wafers and the usage of a SAcM to examine the subsurface damage.

Key Words: Diamond wire; Wire saw; Wafer slicing; Silicon carbide; Scanning acoustic microscopy.

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1. INTRODUCTION

Since the mid-1990s, the wire sawing process has been applied to slicing single-crystal semiconductor ceramics into thin wafers with minimum warp, uniform thickness, and low kerf loss. This process has been successfully implemented in silicon (Si) and silicon carbide (SiC) wafer production with SiC and diamond, respectively, as the loose abrasive. During loose abrasive slurry machining, the abrasive is impregnated as a third-body between the bare wire and workpiece to generate the cutting action. There are two technical challenges using the loose abrasive slurry machining of the hard, difficult-to-machine single-crystal SiC. One is the slow cutting speed and another is the variation in wafer thickness due to the wire wear during cutting. This study investigates the use of diamond impregnated wires for faster amd more accurate slicing of single-crystal SiC wafers.

The recent developments of new metal bond diamond wires, high-speed and rocking motion diamond wire saw machines, and noncontact, in-process wire deflection/bow sensors have made the fixed abrasive diamond wire saw process competitive with the current loose abrasive wire saw machining for precision wafer slicing.[1] Advantages of the fixed abrasive diamond wire saw include thin kerf, better wafer quality, increased cutting speed, elimination of the hazardous waste slurry, and ability to machine hard, brittle ceramics. The key technical challenge for diamond wire slicing of SiC is the surface integrity, including the roughness and subsurface damage, on the machined surface. Research is needed in this area. Goals of this research were to investigate the effect of process parameters and to identify an evaluation method on surface integrity of diamond wire cut SiC wafer surfaces.

SiC is an important electronic ceramic for the blue laser diode for data storage, high-power semiconductors, microwave and radiofrequency power transistors, light-emitting diodes, and optoelectronic applications. Compared with single-crystal Si, SiC is significantly harder (2,800 Knoop hardness) and more difficult to slice into wafers that meet tight specifications on warp and total thickness variation. The scratch marks and subsurface damage on diamond wire cut SiC wafer surfaces have been a major concern for the semiconductor industry. A suitable nondestructive method to quantify the level of subsurface damage on machined SiC wafer surfaces is currently lacking. The scanning acoustic microscopy (SAcM) is explored for this application.

Clark et al.[1,2] and Hardin[3] reviewed the patents and literature in wire saw technology and studied the fixed abrasive diamond wire cutting of wood and foam ceramics. Process monitoring techniques using a capacitance wire bow sensor to measure the normal cutting force and piezoelectric dynamometer to measure the tangential cutting force have been developed.[1] The same techniques are applied to study the fixed abrasive diamond wire sawing of single-crystal SiC. To reduce surface damage, the size of diamond grit impregnated on the wire for wafer slicing has gradually been reduced.[1] Smaller diamond grit size limits the material removal rate, but helps improve the integrity of the cut surface. this study used the fine, 20 μm grit size diamond wire with an electrode plated nitrogen-based bond.

The experiment design and setup of the wire saw cutting, process monitoring, and surface quality measurements are first introduced. The results of cutting forces, surface roughness, and microscopic examination of the machined surfaces and subsurfaces are then presented. The diamond wire wear is also presented.

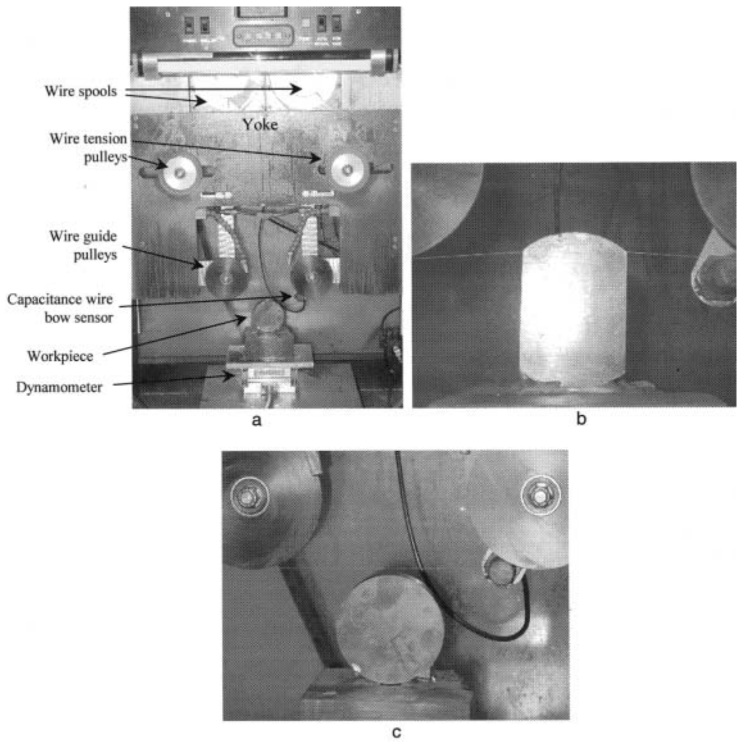

Figure 1. Experiment setup for diamond wire saw cutting of SiC: (a) machine setup, (b) baseline test of 50-mm wide sample (Experiment I), and (c) wire cutting of 75 mm diameter SiC wafer (Experiment II).

2. EXPERIMENT DESIGN AND SETUP

The tests were conducted with a spool-to-spool rocking motion diamond wire saw machine (Millennium model, Diamond Wire Technology, Colorado Springs, CO). Figure 1a shows the overview of the machine, key machine components, and setup for cutting a 75 mm diameter SiC wafer. Close-up views of the SiC workpiece and diamond wire are shown in Figs. 1b and 1c.

2.1. Wire Saw Wafer Slicing Experiments

Two sets of diamond wire saw cutting experiments, denoted as Experiments I and II, were conducted. Table 1 lists the key process paremeters. The workpiece in Experiment I was a 50 mm wide single-crystal SiC block, as shown in Fig. 1b. The constant width ensures the consistency in the normal cutting force measurement. Three downwire feed speeds at 0.0013, 0.0051, and 0.013 mm/sec were used in Experiment I. This experiment produced three wire cut surfaces for SAcM examination of surface and subsurface damages.

Table 1. Process parameters of Experiments I and II.

	Experiment I	Experiment II
Workpiece	50 mm wide SiC	75 mm diameter SiC
Wire condition	Used	New
Wire speed (m/sec)	10.2	8.13, 10.1, 11.2
Rocking frequency (Hz)	0.3	0, 0.15, 0.3, 0.5
Downfeed rate (mm/sec)	0.0013, 0.0051, 0.013	0.013
Common process parameters		
Rocking angle (deg)	2	
Coolant	Water	
Wire nominal diameter (mm)	0.22	
Diamond abrasive size (μm)	20	
Wire tension (N)	22.2	

Experiment II was conducted using a new diamond wire for cutting a 75 mm diameter SiC wafer. Nine cutting tests were conducted at three rocking frequencies, slow (0.15 Hz), medium (0.3 Hz), and fast (0.5 Hz), and three wire speeds, slow (8.13 m/sec), medium (10.1 m/sec), and fast (11.2 m/sec). An additional cutting test without rocking motion was carried out to distinguish the effect of rocking motion on wafer cutting.

In summary, 3 tests were conducted in Experiment I and 10 tests were conducted in Experiment II.

2.2. Cutting Forces and Surface Roughness Measurements

The normal and tangential diamond wire cutting forces were recorded using techniques developed by Clark et al.[1] The piezoelectric dynamometer was unable to measure the normal cutting force, F_N, due to the decay of signal in long duration cutting test. The capacitance sensor was used to measure the wire bow during cutting. Due to the rocking motion, the capacitance sensor output signal is sinusoidal in nature. The varying wire bow signal is averaged and converted to the normal cutting force. The tangential cutting force, F_T, can be measured using the piezoelectric dynamometer because of the periodic reversal of wire from one spool to another and the change of cutting force direction.

The average surface roughness, R_a, of the diamond wire cut surface was measured using a Taylor Hobson Talysurf stylus profilometer. The cutoff length was set at 0.8 mm.

2.3. Scanning Acoustic Microscope Characterization

A scanning acoustic microscope was used to evaluate the very shallow damage on the machined SiC wafer surfaces. Compared with optical or scanning electron

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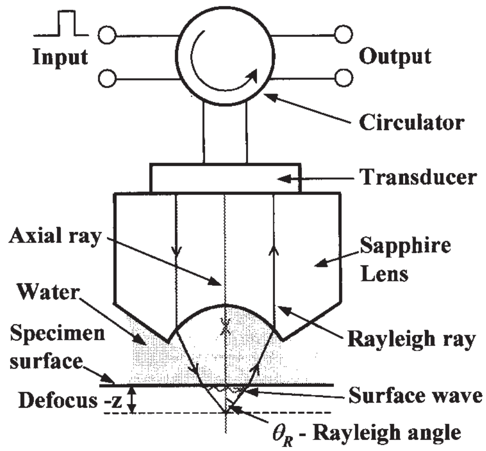

Figure 2. Setup of the scanning acoustic microscope for subsurface examination.

microscopy (SEM) the SAcM can nondestructively detect subsurface features using the penetration of acoustic waves.[4,5] SAcM uses high-frequency acoustic waves to generate visual images of both the surface topography and the underlying structure of materials by detecting reflected echoes. The concept of the SAcM is illustrated in Fig. 2. The Kraemer Scientific Instruments SAM2000 scanning acoustic microscope with operating frequency up to 2 GHz was used in this study.

3. RESULTS OF CUTTING FORCE, SURFACE ROUGHNESS, AND WIRE WEAR

After wire saw cutting, three measured results are the horizontal and normal cutting forces and surface roughness. In Experiment I, the normal and horizontal cutting forces are divided by the diameter of the wire (0.22 mm) and length of contact (50 mm) to calculate the specific normal and tangential (or horizontal) cutting forces, denoted as f_N and f_T, respectively.

Figure 3 shows f_N, f_T, force ratio f_N/f_T, surface roughness R_a, and net or resultant specific force for Experiment I. The specific normal force increases at a higher wire downfeed rate. On the contrary, the specific tangential force increases slightly and then drops at higher wire downfeed rate. This is possibly due to the increase in the cut depth, which enables fracturing and efficient material removal in brittle SiC. The material removal is more efficient, and sliding friction between the wire and workpiece is less significant at high wire downfeed rates. The resultant cutting force remains at about the same level due to the combination of the increase in normal force and reduction in tangential force.

The force ratio (f_N/f_T) is an important indicator for the efficiency of a cutting process. The force ratio from 0.3 to 1.3 observed in this study is very low compared with the force ratio of 3 to 15 for CBN grinding of zirconia,[6] 4 to 9 for CBN grinding of silicon nitride,[7] 5 to 5.5 for diamond grinding of silicon nitride,[8] and

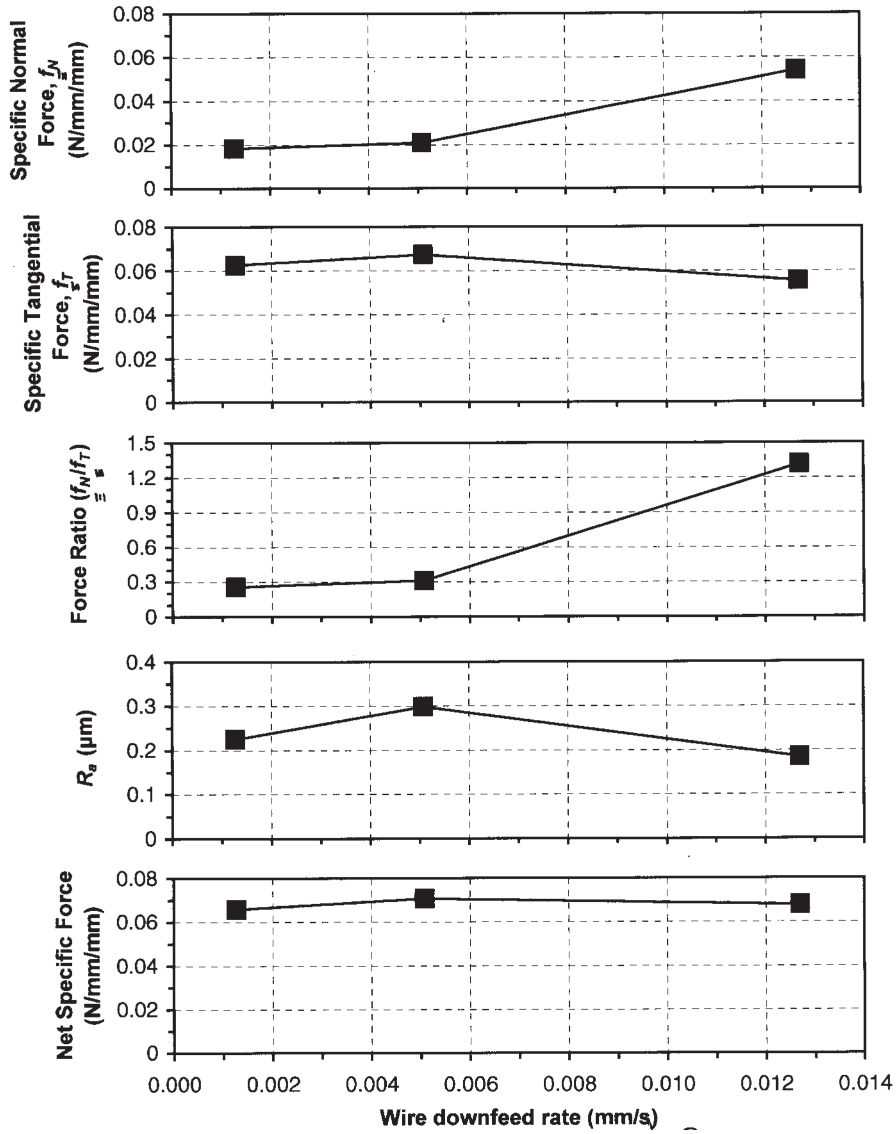

Figure 3. Cutting forces and surface roughness results of Experiment I.

0.6 to 2.5 and 1.5 to 3.2 for diamond wire machining of pine and oak, respectively.[2] The low force ratio is likely due to the very slow wire downfeed rate used. At the very slow wire downfeed and high wire speed, it is more difficult to build up the normal cutting force in the wire. This is confirmed by the high f_N/f_T of 1.3 at the highest, 0.013 mm/sec downfeed rate.

The surface roughness is independent of the wire downfeed speed and falls in the 0.18 to 0.29 µm R_a range. The industry standard of R_a using a loose abrasive

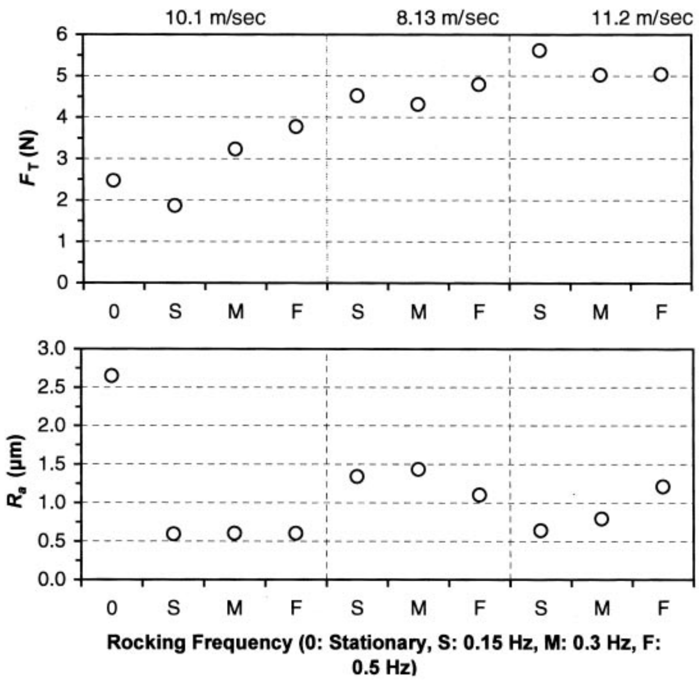

Figure 4. Tangential force and surface roughness of a new diamond wire slicing of SiC in Experiment II (0.013 mm/sec downfeed rate).

diamond slurry saw is 0.1 µm. This indicates that, although the results are promising, more reasearch work is needed to further improve the surface roughness. Lower wire downfeed speed alone is not able to achieve the desired surface roughness. Using diamond with a grit size smaller than 20 µm is the likely direction for future fixed abrasive wafer cutting research.

Results of the tangential cutting force and the surface roughness while using a new diamond wire in Experiment II are shown in Fig. 4. The width of contact varies during cutting the 75 mm diameter wafer; therefore, only the tangential cutting force, F_T, was measured. F_T is plotted following the sequence of cutting tests, from the first to the tenth cut. A gradual increase of F_T, independent of the change in wire speed and rocking frequency, is observed. The very high surface roughness with no rocking motion demonstrates the benefit of rocking motion. The effect of rocking frequency on the surface roughness was not obvious.

4. SEM MICROGRAPHS OF DIAMOND WIRE WEAR AND WIRE CUT SURFACES

SEM micrographs of new, partially used, and extensively used diamond wire are shown in Fig. 5. The new diamond wire in Fig. 5a shows the 20 µm size diamond held

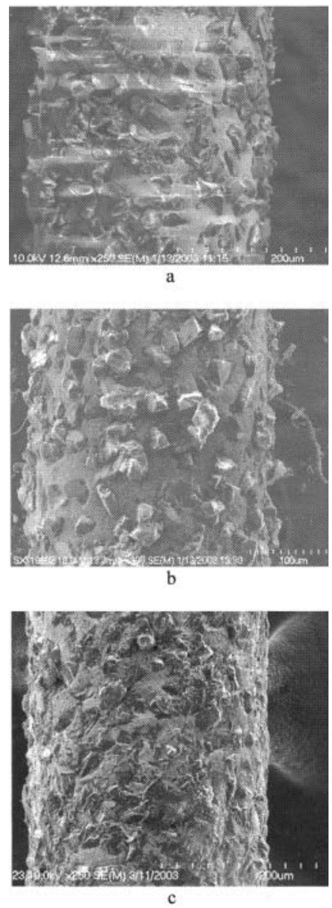

Figure 5. SEM micrographs of diamond wire wear: (a) new wire, (b) partially used wire, and (c) used wire.

by the electrode plated Ni-based bond. After the first 15 mm cut into the 75 mm diameter SiC wafer, a segment of diamond wire was examined using the SEM and shown in Fig. 5b. The diamond is exposed due to the erosion of bond during cutting. A used diamond wire segment after slicing two 75 mm diameter SiC wafers is shown in Fig. 5c. This is still a usable wire with a significant amount of diamond grits left. Wear flats on the diamond grit can be identified. By observing the pockets in the wire, pull-out of diamond grits was noticed. This contributed to the scratch marks and damage on the SiC wafer surface.

SEM micrographs of the three diamond wire cut surfaces in Experiment I are shown in Fig. 6. The most noticeable features on the surfaces are the long, deep grooved scratches. These scratches originate from two sources. One is the stagnation of the diamond wire during the reversal of its direction when one spool is full and the other is empty. The wire continues to feed downward into the workpiece while the cutting speed drops to zero. A groove is therefore scratched. For example, the length of wire used was 186 m and the wire speed was 10.2 m/sec. The wire reverses its direction every 18.3 sec. At the downfeed rate of 0.0013 mm/sec in Fig. 6a, the theoritical spacing between stagnation grooves is 0.023 mm. This matches to the distance between two scratch grooves, marked by G, in the close-up view of box A in Fig. 6a. The close-up view of B in Fig. 6a shows the groove and damage of materials around the groove.

The second source of the scratches on the wire cut surface is due to a diamond pull-out from the wire which abrades to the surface. A likely example of such surface is shown in Fig. 6b, across box C. At the higher magnification of 2,500×, the pulverization of the SiC surface[9,10] can be recognized in Fig. 6b. It is very likely that microcracking, as reported in Zhang et al.,[11] also exists on the surface.

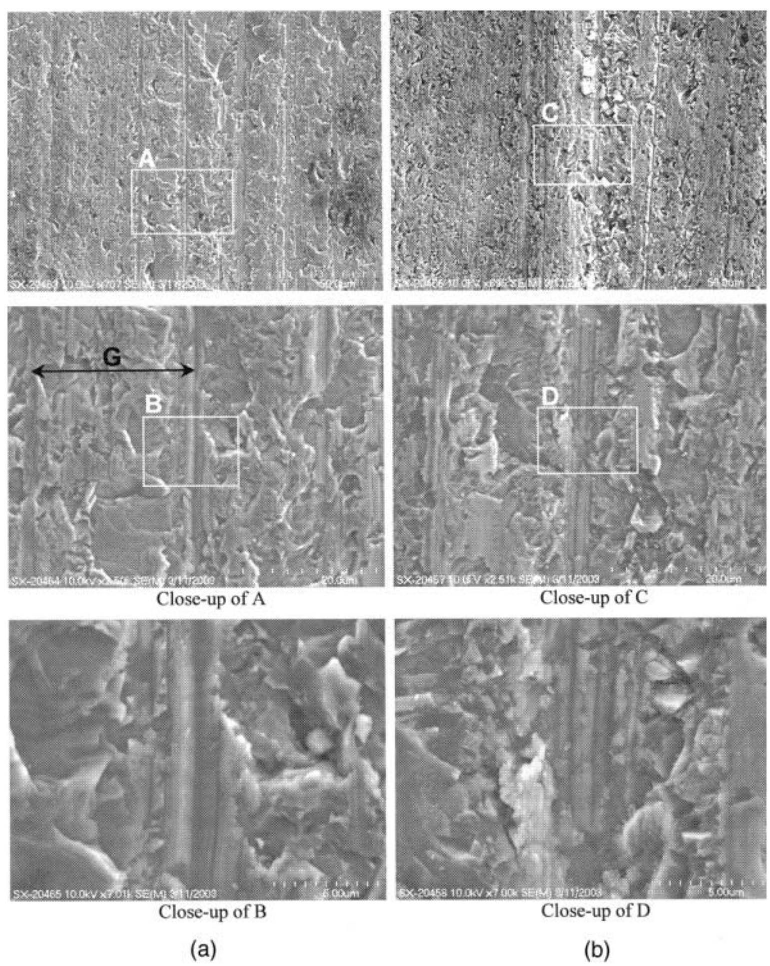

Figure 6. SEM micrographs of diamond wire cut SiC surface in Experiment I with downfeed rate of (a) 0.0013 mm/sec, (b) 0.0051 mm/sec, and (c) 0.013 mm/sec.

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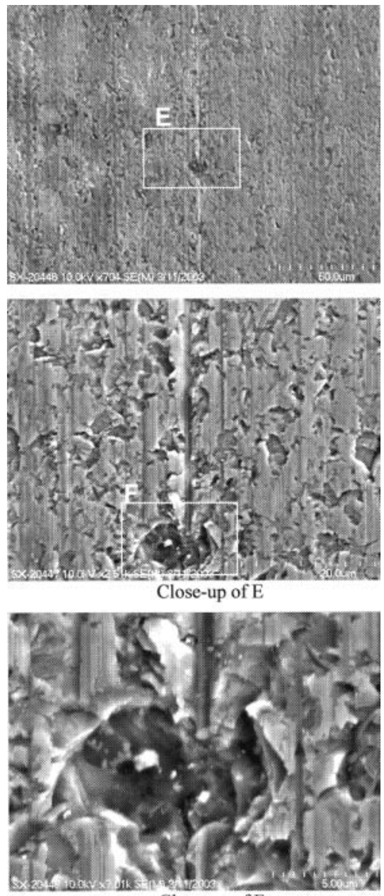

Close-up of E

Close-up of F

(c)

Figure 6. Continued.

The theoritical spacing between the stagnation scratch marks at 0.0051 mm/sec downfeed rate in Fig. 6b should be 0.092 mm or four times that in Fig. 6a. As shown in Fig. 6b, the spacing of scratch lines is a lot closer than 0.092 mm. This indicates the scratch groove is due to the loose diamond particles or due to overprotruding diamond particles on the wire. The vibration of the wire may also cause a diamond grit to randomly generate scratch marks on the cut surface.

At the very fast downfeed speed of 0.013 mm/sec, as shown in Fig. 6c, the spacing of theoritical stagnation lines is farther apart, 0.23 mm. The scratched grooves on the surface, as shown in the close-up of E and F in Fig. 6c, are not likely due to stagnation of the wire during cutting. Due to the generally uniform groove pattern in the close-up of E in Fig. 6c, it is likely that the overprotruded diamond grit in the wire caused the scratch marks on this cut surface area. The close-up of F in Fig. 6c shows possibly a more severe level of damage at high magnification (7,000×)

relative to the surfaces cut at lower downfeed speeds in Figs. 6a and 6b. This was further investigated using the SAcM.

5. SAcM CHARACTERIZATION OF WIRE CUT SURFACES

Figure 7 shows the SAcM pictures of a 0.5 mm × 0.5 mm surface area on the 75 mm diameter SiC machined by diamond wire saw at 0.013, 0.0051, and 0.0013 mm/sec downfeed rate. The operating frequency was 400 MHz and resolution was 2 μm. By adjusting the reflection signal to the highest level, the datum of the examined surface area was determined. This is represented by the three pictures focused on the surface, as shown in Fig. 7. Dark scratch marks on the surface are apparent for two high downfeed rates (0.013 and 0.0051 mm/sec). Less significant surface damages can be observed at the slowest downfeed rate, 0.0013 mm/sec. This demonstrates the potential to use SAcM to qualitatively compare the level of surface damages.

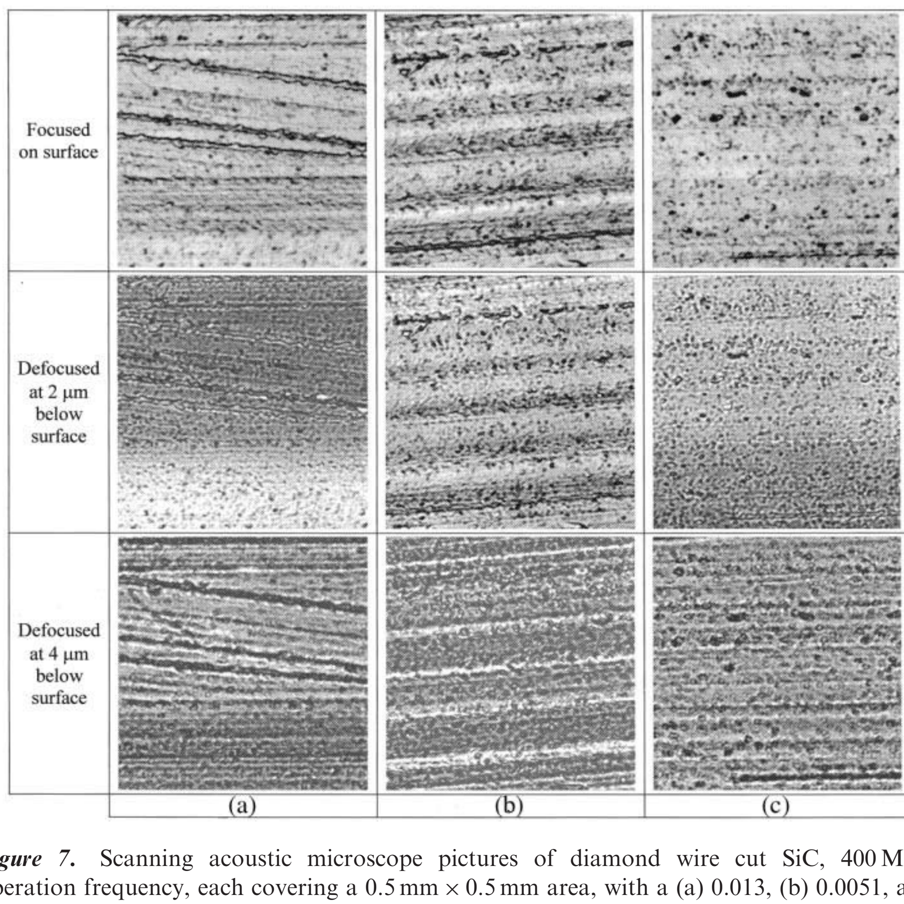

Figure 7. Scanning acoustic microscope pictures of diamond wire cut SiC, 400 MHz operation frequency, each covering a 0.5 mm × 0.5 mm area, with a (a) 0.013, (b) 0.0051, and (c) 0.0013 mm/sec downfeed rate.

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After establishing the datum surface, the SAcM was defocused at 2 and 4 μm below surface to examine the subsurface damage. The defocus is illustrated in Fig. 2. Figure 7 shows that the SAcM subsurface pictures become more uniform and featureless for all three surfaces. It is important to note that the SAcM images focused on the subsurface reflect the features of both the surface and subsurface. The SAcM cannot show pure subsurface damage unless the surface is free of defects. The diamond wire machined surface is not free of damage; therefore, dark marks and lines in the focused surface can also be identified in both 2 and 4 μm defocused SAcM subsurface pictures.

6. CONCLUSION

The diamond wire saw slicing of single-crystal SiC was investigated in this study. Two sets of experiments were conducted to investigate the effects of wire downfeed speed, new diamond wire run-in, and rocking frequency. Normal and tangential cutting forces were measured and studied. SEM and SAcM were used to examine the surface and subsurface damages. SEM micrographs showed the pulverization and microcracking on the machined surfaces. The SAcM revealed the damage levels on the surface and at a specific depth underneath the surface. Problems with the SAcM examination of subsurface damage due to the influence of imperfections on the surface were also identified.

Results in this study show the effectiveness of diamond wire saw in slicing the hard, brittle SiC wafer and the severity of surface damage, including stagnation grooves, pulverization, and microcracks. To further improve surface roughness and reduce the subsurface damage, wires with diamond grit size smaller than 20 μm are recommended. Effects of the diamond size on wire downfeed speed and surface damages are the topics of further studies.

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