PRESSURE AND TEMPERATURE EFFECTS IN MICRO-LASER ASSISTED MACHINING (µ-LAM) OF SILICON CARBIDE

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ABSTRACT

In the deformation and cutting process of semiconductors and ceramics, especially brittle materials such as silicon carbide (SiC), the presence of high pressure phase transformation (HPPT) is of great importance for accomplishing ductile regime machining (Patten 2007). To augment the ductile regime machining of these nominally brittle materials, the high pressure phase can be preferentially heated and thermally softened by using concentrated energy sources such as laser beams (Dong 2006). In this research, the effect of the pressure and temperature and the interactions of these two factors on the micro-laser assisted machining (µ-LAM) process are studied by using a hybrid machining system that consists of a diamond stylus (tool) and infrared (IR) fiber laser heating source. The combinations of loading (pressure) with and without laser heating prior to loading are studied at various cutting depths and speeds. The laser achieves heating and thermal softening as evidenced by the increased ductility of the material. Notably, the results of scratch tests at 1 µm/sec show a doubling of the scratch depth which suggests a ~50% reduction of hardness due to thermal softening by the laser heating. The results are studied by atomic force microscopy (AFM) and confirmed with white light interferometer microscopy to verify the experimental results.

INTRODUCTION

Semiconductors and ceramics share common characteristics of being nominally hard and brittle, which stem from their covalent chemical bonding and crystal structure. Both types of materials are important in many engineering applications, but are particularly difficult to machine in traditional manufacturing processes due to their extreme hardness and brittleness. Ceramics have many desirable properties, such as excellent wear resistance, chemical stability, and the superb ability to retain strength at elevated temperatures. However, it is difficult to machine these materials, which remains a major obstacle that limits the wider application of these hard, but brittle, materials (Jahanmir 1992). The plastic deformation in these brittle materials at room temperature is much less than in metals, which means they are more susceptible to fracture during material removal processes. Surface cracks generated during machining are subsequently removed in lapping and polishing processes, which significantly increases the machining cost. In ultra fine surface machining, such as precision machining the surface of an optical lens or mirror, developing a cost effective method to achieve a flawless surface poses great challenges. In many engineering applications, products require a high quality surface finish and close tolerances to function properly. This is often the case for products made of semiconductor or ceramic materials. Currently, fine grinding, lapping and polishing are typically used to obtain smooth fracture-free surfaces for semiconductor and ceramic materials. These machining methods are capable of producing satisfactory surface finish, but they are costly processes in terms of tool cost and machining time. Consequently, machining these mirror-like surface finishes contribute significantly in the total cost of a part. In some cases, grinding alone can account for 60-90% of the final product (Wobker 1993). The real challenge is to produce an ultra precision surface finish in these nominally brittle materials at low machining cost.

Current limitations for brittle material machining include the high cost of processing and product reliability. The cost is mainly due to the high tool cost, rapid tool wear, long machining time, low production rate and the manufacturing of satisfactory surface figure and form. The low product reliability is primarily due to the occurrence of surface/subsurface damage and brittle fracture. To overcome these obstacles, developing advanced precision machining techniques is required. Ductile regime machining operations, a very promising precision machining method, has been continuously studied in the last two decades (Blake 1990; Blackley 1994; Morris 1995; Leung 1998; Sreejith 2001; Yan 2002, 2004; Patten 2003, 2005). Cost-effective methods for precision part using laser assisted machining techniques continues to be a critical issue (Dong and Patten 2007; Rebro 2002). Recently Suthar (2008) analyzed the laser heating analytically and numerically with good agreement to experimental results (Dong 2006).

Scratch experiments are chosen to be the principle method in this study. Scratch testing is a better candidate for evaluating machining than indenting because the scratching parameters are more applicable to the machining process, such as depth of cut, width of cut and cutting speed parameters.

The objective of the current study is to determine the effect of temperature and pressure in the μ-LAM of the single crystal 4H-SiC semiconductors using scratch tests. The scratch tests examine the effect of temperature in thermal softening of the high pressure phases formed under the diamond tip. The tests also evaluate the difference with and without irradiation of the laser beam at a constant loading and cutting speed. The laser heating effect is verified by atomic force microscopy (AFM) and white light interferometric measurements of the laser heated scratch grooves.

EXPERIMENTAL PROCEDURE

The IR diode laser used in this investigation is a Furukawa 1480 nm 400 mW IR fiber laser with a Gaussian profile and beam diameter of 10 μm. The IR laser beam is guided from the diode laser through a 10 μm fiber optic cable to the ferrule, which is attached to the diamond stylus. A cross section of the μ-LAM operation is shown in Figure 1. In this setup, the IR laser beam passes through the diamond tip (tool) and impinges on the SiC work piece material. The laser emerges from a 90° conical single crystal diamond tip with 5 μm radius spherical end, as shown in Figure 2.

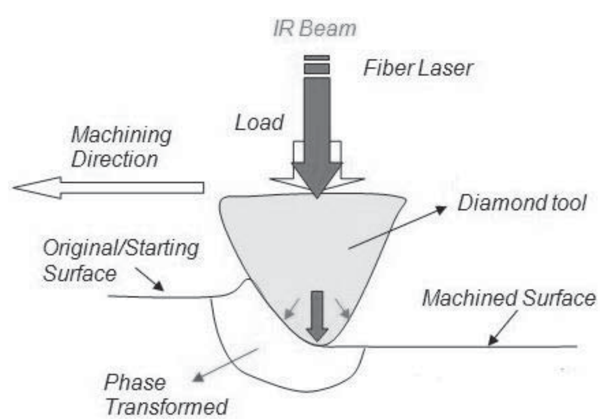
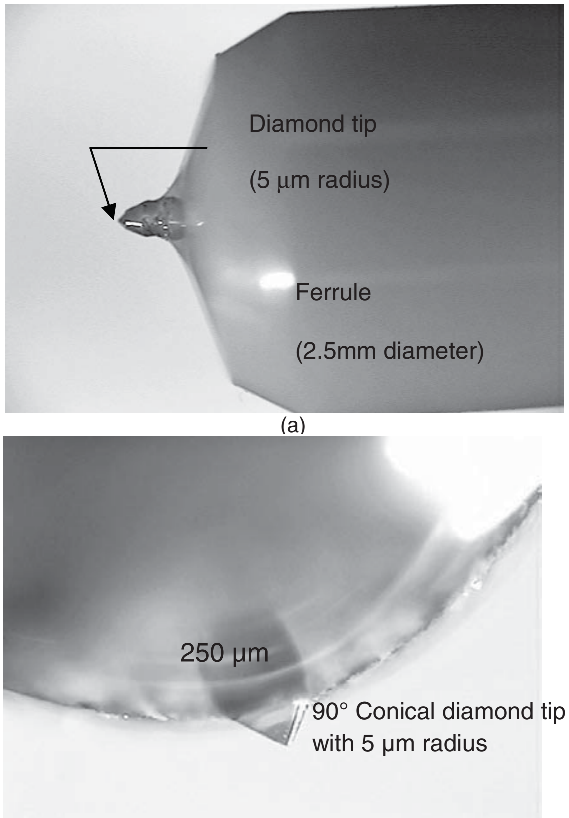


FIGURE 1. SCHEMATIC CROSS SECTION OF μ-LAM PROCESS.



(b)

FIGURE 2. DIAMOND TIP ATTACHMENT. (a) 5 µM RADIUS DIAMOND TIP ATTACHED ON END OF FERRULE USING EPOXY, (b) CLOSEUP ON DIAMOND TIP EMBEDDED IN SOLIDIFIED EPOXY.

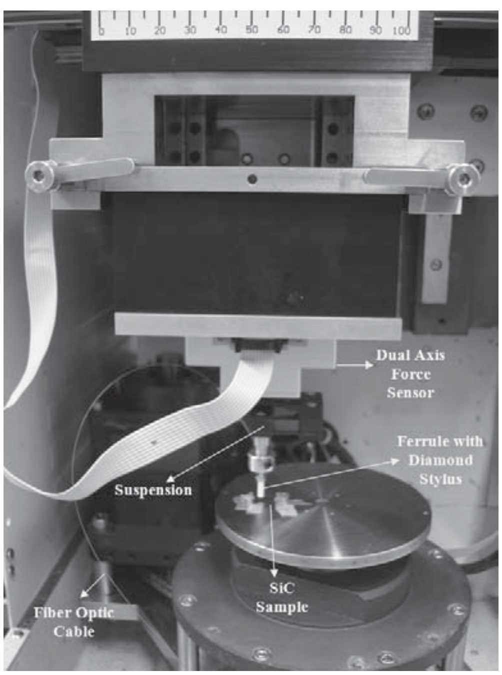


FIGURE 3. µ-LAM SYSTEM USED IN EXPERIMENTS.

The µ-LAM experimental setup is shown in Figure 3. The equipment used to carry out the scratch tests was the Universal Micro-Tribometer (UMT) from the Center for Tribology Research Inc. (CETR). This equipment was developed to perform comprehensive micro-mechanical tests of coatings and materials at the micro scale. This precise equipment allows for cutting speeds as low as 1 µm/sec at nanometric cutting depths.

The specimens are single crystal 4H-SiC wafers (provided by Cree Inc). The primary flat is the {1010} plane with the flat face parallel to the <1120> direction. The primary flat is oriented such that the chord is parallel with a specified low index crystal plane. The cutting direction is along the <1010> direction.

In this experiment, two scratches have been employed; with and without laser heating. The results obtained from these tests are then compared to previously obtained results (Dong and Patten 2005). The load used for the scratch tests is 2.5 g (~25 mN) with a cutting speed of 1µm/sec. Previously performed scratch tests with cutting speeds of 305µm/sec are reported here for comparison to the present work (Dong and Patten 2005). Table 1 summarizes the experimental conditions.

TABLE 1. SPECIFICATIONS OF THE SCRATCHES.

Scratch No.	Loading g (mN)	Machining Condition	Cutting speed (µm/sec)	Laser Power (mW)
*1**	*2.5 (25)*	*w/o laser*	*305**	*0*
*2**	*2.5 (25)*	*w/ laser*	*305**	*350***
3	2.5 (25)	w/o laser	1	0
4	2.5 (25)	w/ laser	1	350**

**Experiments performed previously (Dong and Patten 2005), **350 mW is the laser power, approximately 150 mW is actually delivered to the work piece material, the balance of the laser power is lost due to scattering and reflections (Dong 2006).*

RESULTS AND DISCUSSION

AFM measurements, shown in Figures 4 and 5, have been used to measure the groove size and to study the laser heating effect of the scratches made on SiC. The results of all the scratch tests are presented in the Table 2, including the experiments at higher speed of 305 µm/sec conducted previously.

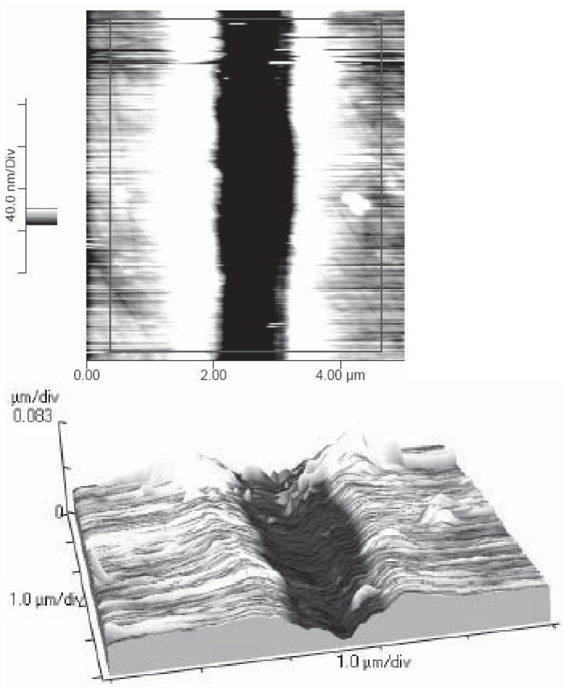


FIGURE 4. AFM IMAGE OF SCRATCH #3 (NO LASER HEATING, 25 mN LOAD, 1 µm/sec SCRATCHING SPEED).

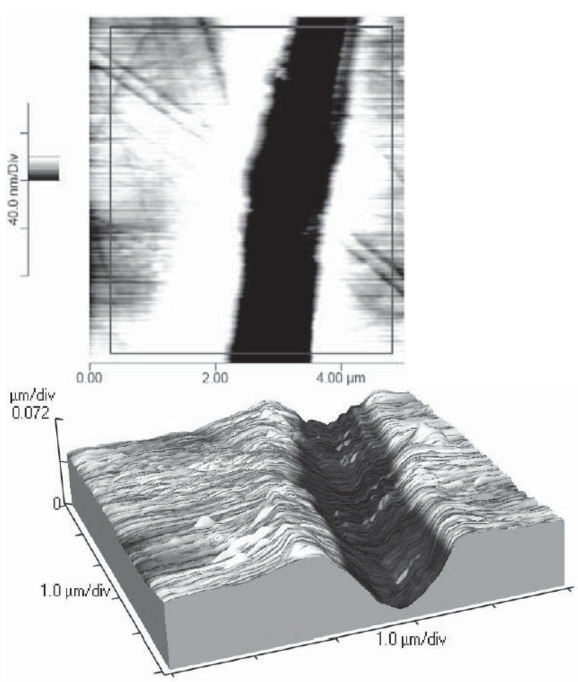


FIGURE 5. AFM IMAGE OF SCRATCH #4 (WITH LASER HEATING, 25 mN LOAD, 1 µm/sec SCRATCHING SPEED).

TABLE 2. AVERAGE GROOVE DEPTHS MEASURED ON AFM.

Scratch #	Machining Condition	Cutting speed (µm/sec)	Average Groove Depth (nm)
*1**	*w/o laser*	*305**	*41*
*2**	*w/ laser*	*305**	*46*
3	w/o laser	1	54
4	w/ laser	1	90

**Experiments performed previously (Dong and Patten 2005)*

The experimental differences between the scratch test results performed at high speed 305 µm/sec (at UNC Charlotte) and low speed 1 µm/sec (at WMU), when comparing the scratches without laser heating can be attributed to the different test equipment (profilometer and tribometer respectively), operator variability, and other test conditions, including different AFMs used to make the measurements.

The applied load (thrust force) was kept constant (25 mN) throughout the entire experiment enabling the evaluation of heating effects on the material. The high pressure phase, due to the HPPT, of the 4H-SiC occurs within the contact interface as a result of externally applied pressure (>25 GPa) and is the common phenomenon in all of the scratches made on the SiC specimen. As the result of heating by the laser beam, the temperature of the surface material adjacent to the diamond stylus rises to achieve the desired thermal softening. Previous work on silicon demonstrated that the temperature increased to ~600°C (Dong 2006; Suthar 2008), which thermally softened the HPPT phase and assisted the machining process.

The depth of cut is a crucial parameter and if it exceeds the critical depth (ductile to brittle transition depth), this will shift the ductile regime cutting to an unfavorable brittle cutting condition. Brittle mode cutting is avoided in this study.

In the previous set of scratches performed at 305 µm/sec, the difference in the depth of cut for w/ and w/o laser heating was measureable but not significant, indicating some but not much laser heating and thermal softening. In the current set of scratches with 1 µm/sec cutting speed, the depth of cut significantly increases with laser heating, nearly doubling, from 54 (w/o laser heating) to 90 nm (see Figure 6). This latter result indicates significant laser heating and resultant thermal softening occurred. This result shows that temperature plays a significant role in enhancing the ductile regime machining of 4H-SiC specimen at this speed.

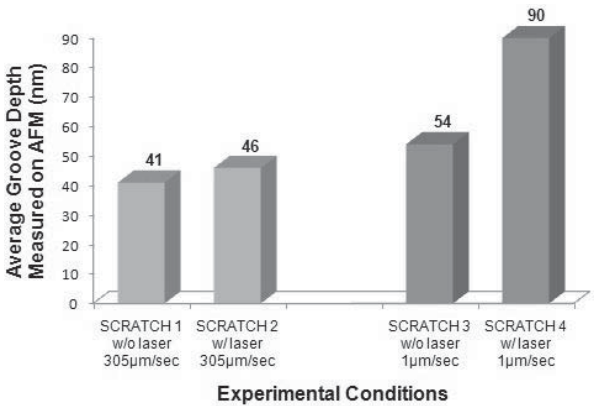


FIGURE 6. AVERAGE GROOVE DEPTH MEASURED WITH AFM (in nm) WITH TWO DIFFERENT SPEEDS AND W/ AND W/O LASER.

Based upon the scratch (groove) depth and load, the hardness of SiC with laser heating is estimated to be 13 GPa, which is one-half of the room temperature value of 26 GPa. Estimating the temperature achieved for the laser heated SiC, based upon published hardness-temperature data (Yonenaga 2000) suggests a temperature increase of 700-800°C in the scratch #4. At the laser power utilized in these experiments, 350 mW (150 mW actually delivered to the workpiece surface), thus significant laser heating is achieved at the low speed, while minimal heating occurred at the higher speed, as reported in previous work. Thus increasing the cutting speed reduces the thermal softening in contrast to the enhanced effect as seen at the lower cutting speed.

CONCLUSION

Laser heating was successfully demonstrated as evidenced by the significant increase in groove depth, i.e., reduced hardness, indicative of enhanced thermal softening. AFM measurements of the laser-heat assisted scratch grooves show deeper and wider grooves compared to scratches made without the laser heating assisted methods; which indicates favorable thermal softening effects.

FUTURE WORK

Related work on laser heating of 4H-SiC by using nano-indentation techniques is in progress. This work will provide additional insight into the mechanism of the combined pressure and temperature effects during laser assisted machining. This will allow a better understanding of the complex interplay of the pressure and temperature effects on μ-LAM machining processes. Force data, normal (thrust) and friction (cutting), has been collected for scratches 3 and 4 and will be analyzed with respect to the depth of cut, i.e., normalized to determine the relative (and counter acting) effects of increased depth and softer material response associated with the laser heating. Additional cutting tests using the μ-LAM process will be conducted using high power laser systems, power on the order of 1 to 100 watts, which allows larger cuts at higher speeds.

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