Scratch Tests on 4H-SiC Using Micro Laser Assisted Machining (μ-LAM) System

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Abstract

The μ-LAM system is used to preferentially heat and thermally soften the work piece material in contact with a diamond cutting tool. In μ-LAM the laser and cutting tool are integrated into a single package, i.e. the laser energy is delivered by a fiber laser to and through a diamond cutting tool. This configuration provides a natural integration and alignment of the laser beam and cutting tool, and effectively puts the laser energy directly where it is needed at the tool - work piece interface, i.e, the chip formation zone. This paper presents experimental results for scratch tests on 4H-SiC using μ-LAM system.

Keywords: Micro-laser assisted machining (μ-LAM), laser heating, ductile regime machining, single point diamond turning (SPDT), single crystal silicon carbide.

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 [3]. Ceramics have many desirable properties, such as excellent wear resistance, chemical stability, and high strength even at elevated temperatures. In spite of all these characteristics, the difficulty in machining has been a major obstacle that limited the wider application of these materials [3]. The plastic deformation of 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. Machining these mirror-like surface finishes contribute significantly to the total cost of a part. In some cases, grinding alone can account for 60-90% of the final product [4]. In this context, developing a cost effective method to achieve a flawless surface in ultra fine surface machining of an optical lens or mirror has become a challenge. 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. 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. In order to develop a suitable process, ductile regime machining, considered to be one of the potential precision machining techniques, has been continuously studied in the last two decades [5-13]. Laser assisted micro/nano machining is another important development in this direction [14, 15].

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

An IR diode laser (λ=1480nm and P_{max}=400mW,) with a Gaussian profile and beam diameter of 10μm is used in this investigation. The laser beam is guided through a 10μm fiber optic cable to the ferrule, which is attached to the diamond stylus. The μ-LAM set-up with a laser beam integrated diamond tool on a given substrate is shown in Figure 1. In this setup, the laser beam passes through the diamond tip (tool) and impinges on the 4H-SiC work piece material. The laser emerges from a 90° conical single crystal diamond tip with 5μm radius spherical end, as shown in Figure 2.

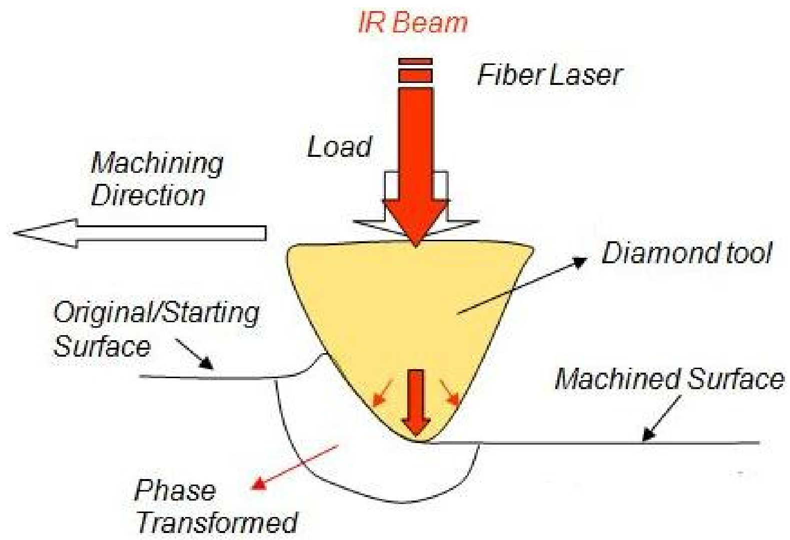
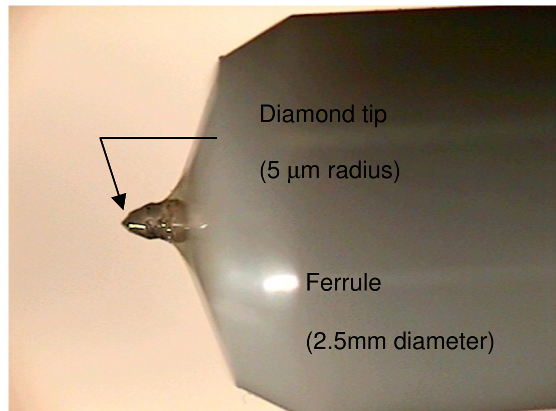
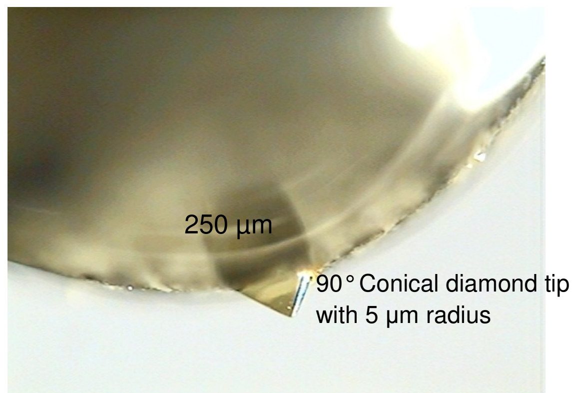


Figure 1. µ-LAM machining of SiC substrate.



(a)



(b)

Figure 2. Diamond tip attachment:
(a) 5µm radius diamond tip attached on the end of the ferrule using epoxy,
(b) Close up on diamond tip embedded in the solidified epoxy.

The details of the diamond tip attachment were depicted in Figure 2 (a and b), while various types of diamond tools in μ-LAM are shown in Figure 3 and the overall μ-LAM experimental setup is shown in Figure 4. The μ-LAM set-up is commissioned within a 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 system facilitates the cutting speeds as low as 1μm/sec at nanometric cutting depths.

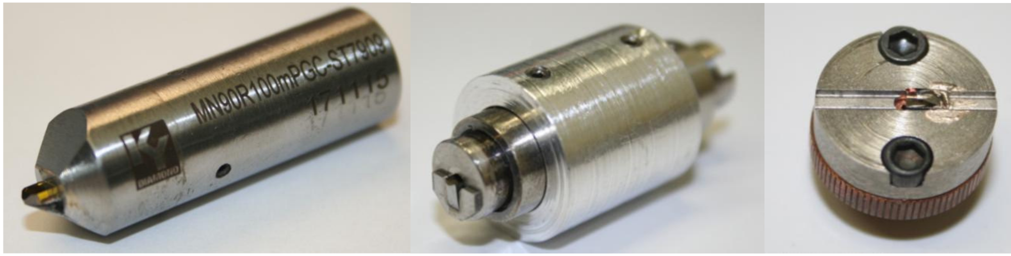


Figure 3. Various types of diamond tool in μ-LAM.

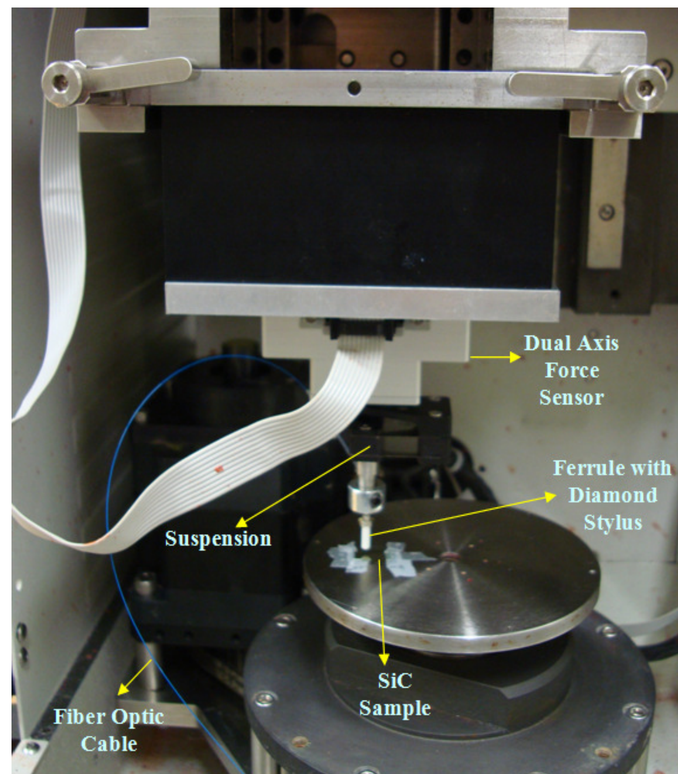


Figure 4. μ-LAM system used in the experiments.

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.

Scratch tests were 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.

In this experiment, scratches were performed with and without laser heating. The results obtained from these tests are compared to previously obtained results [16]. The load used for the scratch tests is 2.5g (~25mN) with a cutting speed of 1μm/sec. The results of these tests were summarized in Table 1 along with the previously reported results in [16].

Table 1. Scratch parameters.

Scratch No.	Load 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 [16].*

***350mW is the laser power, approximately 150mW is actually delivered to the work piece material, the balance of the laser power is lost due to scattering and reflections [2].*

Results and Discussions

The scratch profiles along with the groove width and depth were measured using AFM. Figures 5 and 6 are the AFM profiles that clearly indicating the depth and width of the scratch grooves without and with laser heating respectively. These clearly depict laser heating effect of the scratches made on 4H-SiC. The results of all the scratch tests are presented in the Table 2, including the experiments at higher speed of 305µm/sec conducted previously.

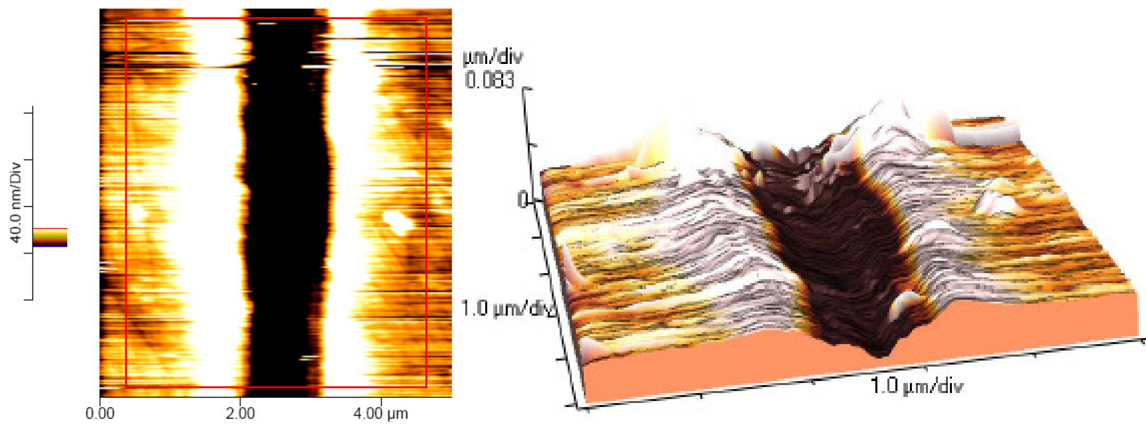


Figure 5. AFM image of the scratch#3; no laser heating, 25mN load, 1µm/sec scratching speed.

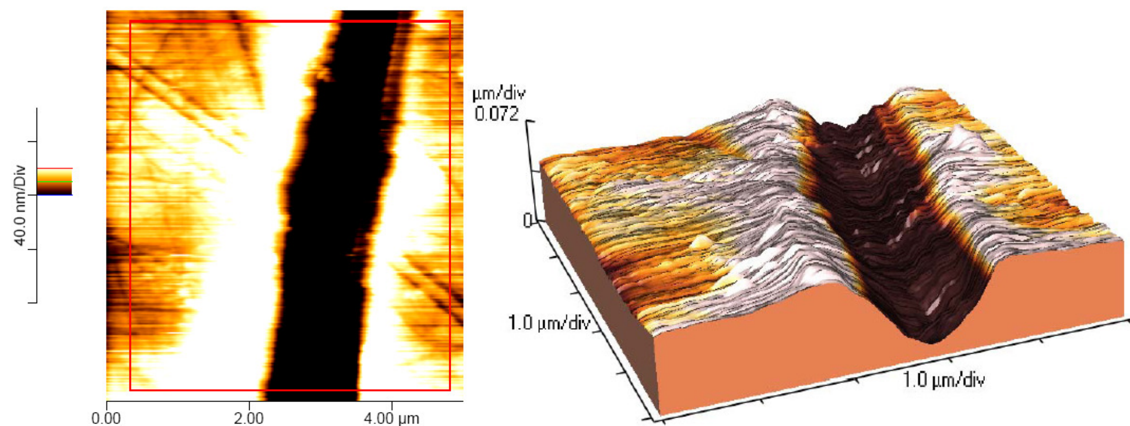


Figure 6. AFM image of the scratch#4; w/ laser heating, 25mN load, 1µm/sec scratching speed.

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 [16].*

Apart from the major difference in the cutting speeds, 305µm/sec (at UNC Charlotte) and low speed 1µm/sec (at WMU), in the two sets of data presented in Table 2, there may be minor differences in the test equipment (profilometer and tribometer respectively) used, operator variability, and other test conditions in which the scratches were performed.

The applied load (thrust force) was kept constant (25mN) 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 (>25GPa) and is the common phenomenon in all of the scratches made on the 4H-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 [2, 17], 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 machining to an unfavorable brittle condition, which is avoided in this study.

In the previous set of scratches performed at 305µm/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 1µm/sec cutting speed, the depth of cut significantly increased with laser heating, nearly doubled, from 54 (w/o laser heating) to 90nm (with laser heating, see Figure 7). This indicates significant laser heating and resultant thermal softening. This result shows that temperature plays a significant role in enhancing the ductile regime machining of 4H-SiC specimen at the cutting speed used in this experiment.

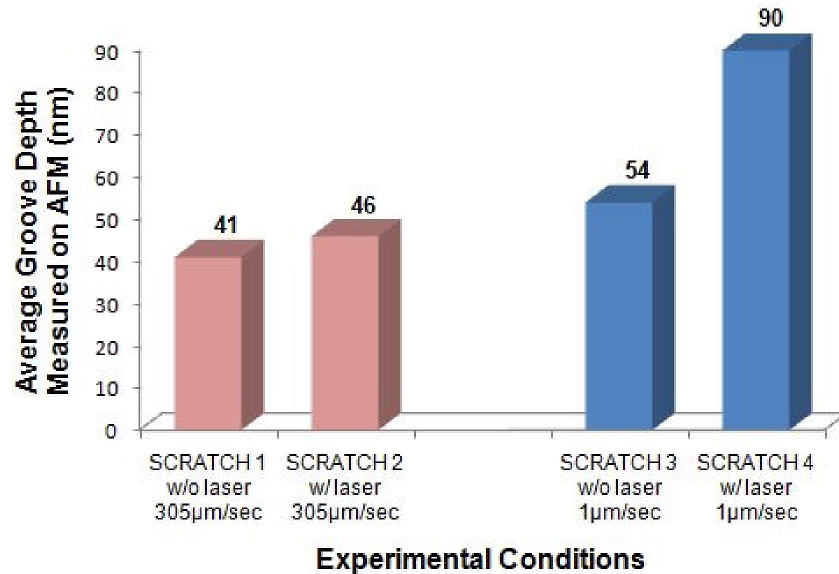


Figure 7. Average groove depth measured with AFM in (nm) with two different speeds and w/ and w/o laser.

Based upon the scratch (groove) depth and load, the relative hardness of 4H-SiC with laser heating is estimated to be 18GPa and the relative hardness of the scratch with no laser heating is calculated to be 30GPa [18]. Estimating the temperature achieved for the laser heated 4H-SiC, based upon published hardness-temperature data [19] suggests a temperature increase of 700-800°C in the scratch #4. At the laser power (350mW) used in these experiments, (150mW actually delivered to the work piece surface), 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 compared to that observed at lower cutting speed.

Conclusion

Laser heating was successfully demonstrated as evidenced by the significant increase in groove depth, i.e., reduced calculated relative 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.

Acknowledgments

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Biographies

Amir R. Shayan has received his PhD in Mechanical Engineering from the University of Toledo, and currently is a Doctoral Associate in the Manufacturing Research Center at WMU. He is active in setting up the µ-LAM systems at the Manufacturing Research Center at Western Michigan University. His research interests are high pressure phase transformations and optical properties of semiconductors and ceramics.

Huseyin Bogac Poyraz is a recent PhD student from the Department of Materials Science and Engineering at Anadolu University in Eskisehir, Turkey and he has been working as a research scholar with Dr. Patten in Manufacturing Research Center at Western Michigan University since 2008. His research interests are material characterization techniques, high pressure phase transformations in semiconductors and ceramics, laser assisted machining of semiconductor and ceramic materials (such as Si and SiC).

Deepak Ravindra is currently pursuing his Doctorate in Mechanical Engineering at Western Michigan University. His master’s thesis was on ductile regime machining of ceramics. His PhD field of research is along the similar lines of research. He has been working in the nanomanufacturing field for over 4 years now. Some of Deepak’s past research work includes determining the ductile-to-brittle transition (DBT) of a 4H single crystal Silicon Carbide wafer. Single Point Diamond Turning (SPDT) of CVD Silicon Carbide to improve surface quality, developing a hybrid method between laser ablation and SPDT for CVD coated Silicon Carbide, establishing ductile machining conditions for Quartz, ductile regime machining of Spinel. Besides these materials, he has also worked on other emerging materials such as AlTiC, AlON and Sapphire.

Dr. Patten’s machining research has always coupled experimental, theoretical, and included modeling components. For the past 25 years, Dr. Patten has concentrated his machining research on nominally brittle materials, e.g. ceramics and semiconductors. These materials have included germanium, silicon, silicon nitride, and silicon carbide. His research is concentrated on the anomalous behavior of these hard and brittle materials to possess a ductile regime machining mode under certain process conditions. Dr. Patten and his colleagues were the first to report on the origins of this ductile regime as a result of the high pressure phase transformation of these materials.

Dr. Ghantasala is an Associate Professor in the department of Mechanical and Aeronautical Engineering at Western Michigan University. He has been working in the area of MEMS, microsensors and laser micromachining for the past 15 years. He published many papers on laser micromachining of polymers, metallic and ceramic thin films or layers. His current research interests include micro and nanomanufacturing of structures using Laser assisted techniques.