

The Effects of Laser Heating on the Material Removal Process in Si and SiC Nanomachining

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Abstract: This study compares the results of scratch tests on single crystal silicon (Si) and 4H silicon carbide (4H-SiC), with and without laser heating. The effects of laser heating were studied by verifying the depths of cuts for scratch tests carried out with increasing loads (thrust force) where within the scratch shows both ductile and brittle response, with a ductile to brittle transition (DBT) region within the scratch. Cutting forces and two-dimensional cross-sectional profiles were investigated using a white light interferometer. Laser heating was successful in enhancing the ductile response and decreasing the brittleness of the material resulting in a greater ductile to brittle transition depth. Finally, numerical simulations were conducted to study the material behavior of SiC and the results reported a decrease in cutting forces, thrust forces and pressures at elevated temperature.

1. Introduction: Advanced ceramics and semiconductors (i.e. SiC, Si, etc.) are increasingly being used for industrial applications. These ceramics/semiconductors are hard, strong, inert, and light weight. This combination of properties makes them ideal candidates for tribological, semiconductor, MEMS and optoelectronic applications. Manufacturing these materials without causing surface and subsurface damage is extremely challenging due to their high hardness, brittle characteristics and poor machinability [1]. Often, severe fracture can result when trying to achieve high material removal rates during the machining of ceramics and semiconductors due to their low fracture toughness. Brittle fracture during processing results in excessively rough surfaces and causes detrimental sub surface damage, which has to be removed in subsequent processing steps. These additional processing steps reduce the overall

productivity and increase the manufacturing cost associated with machining these nominally brittle materials. Machining 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 cost of final product [2]. 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 by reducing the tool wear, machining time with increased production rate. 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 [3-11]. Laser assisted micro/nano machining is another important research development in this direction [12, 13].

Previously, the ductile regime machining of these materials is demonstrated using a single point diamond tool, which was attributed to the high pressure phase transformation (HPPT) occurring in the material caused by the high compressive and shear stresses induced by the tool tip [14, 15]. To further augment the ductile response of the nominally brittle materials, traditional scratch/single point diamond turning (SPDT) tests are coupled with a micro-laser assisted machining (μ -LAM) technique [16]. A schematic of the basic underlining concept of the μ -LAM process is shown in Figure 1. This hybrid method is believed to potentially increase the critical depth of cut (DoC), i.e., a larger ductile-to-

brittle transition, (DBT), depth, in ductile regime machining, resulting in a higher material removal rate.

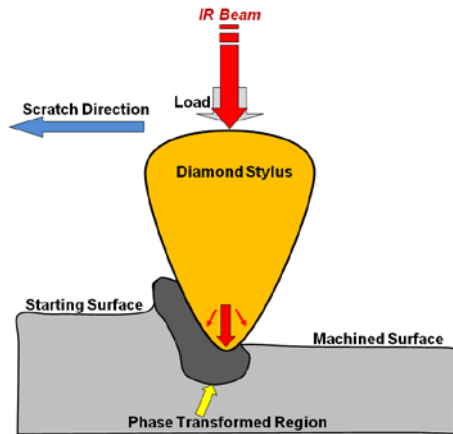


Figure 1: A schematic cross-section of the μ -LAM system.

In the simulation model, to reflect the ductile behavior in ceramics promoted by the HPPT, a pressure sensitive Drucker-Prager constitutive model is used [24]. A realistic thermal softening curve was developed based on various references to study the thermal softening behavior of SiC [18-23], as shown in Figure 2.

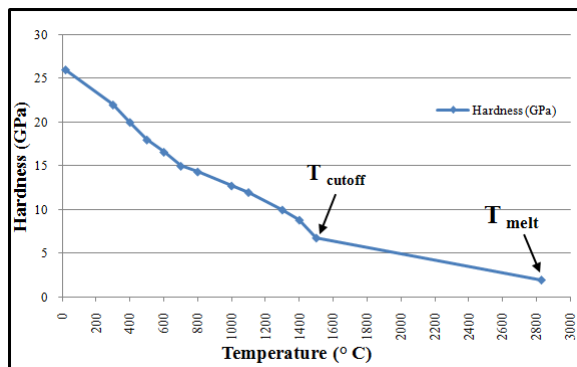


Figure 2: Hardness vs. Temperature curve

Figure.2 shows the variation of hardness with temperature, which was plotted based on the data points obtained from literature. The curve shows two important points with respect to the temperature, the thermal cutoff point and melting point, which were identified at 1500°C and 2830°C respectively. The curve was obtained through applying a third order polynomial fit up to thermal softening temperature. It may be noted that no data is available (in the literature) for the high pressure phase beyond the thermal cutoff point (1500°C). A boundary condition was defined on the workpiece top surface to mimic the actual heating effect during the μ -LAM process [25]. The change in cutting and thrust forces, and cutting pressures were studied.

The objective of the current study is to determine the effect of laser heating (in the μ -LAM process) on the material deformation and removal of Single Crystal Silicon (Si) and 4H-Silicon Carbide (SiC) using scratch testing. The scratch tests were carried out to examine the effect of elevated temperature in thermal softening of the high pressure phases formed under the diamond tip. Scratch tests were chosen to be the principle material removal 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, such as cutting force.

There were two studies done from these scratch experiments: studying the laser heating effect on the DBT of the material and evaluating the thermal softening and relative hardness as a result of irradiation of the laser beam at a constant cutting speed. The effect of laser heating was studied by verifying the depths of cuts and the nature of the scratches (i.e. ductile, DBT or brittle) for diamond stylus and tool scratch tests carried out on single crystal Si and SiC with increasing loads (thrust force). The load range was selected such that the scratches show both ductile and brittle response (with a DBT region within the scratch). Cutting forces and three-dimensional cutting surface profiles (using a white light interferometer) were investigated.

In addition to experimental analysis, numerical simulations were also carried out to determine the effect of temperature on the hardness of SiC. The FEM software AdvantEdge, developed by Thirdwave Systems Inc has been used in these studies.

2. Experimental Procedure: An infrared (IR) diode fiber laser ($\lambda=1480\text{nm}$ and $P_{\text{max}}=400\text{mW}$) with a Gaussian profile and a beam diameter of $\sim 10\mu\text{m}$ was used in this study. The laser beam is guided through a $10\mu\text{m}$ fiber optic cable to the ferrule, which is attached to the diamond stylus or cutting tool. The μ -LAM system is designed in such that the laser beam passes through the diamond tip and impinges on the work piece material at the tool work piece interface.

The thermal softening effect on Si and SiC has been investigated using two different. The first was a 90° conical single crystal diamond tip with $5\mu\text{m}$ radius spherical end, as shown in Figures 3(a) and (b). The second single crystal diamond tool used was a 1.4mm nose radius tool with a -45 degree rake angle and a 5 degree clearance angle (only used to experiment on Si).

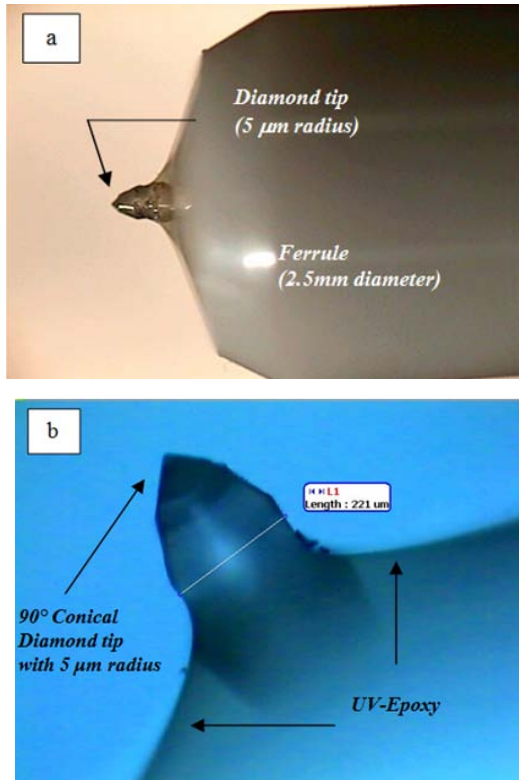


Figure 3: Diamond tip attachment: (a) 5 μ m radius diamond tip attached on the end of the ferrule using epoxy, (b) Close up on diamond tip embedded in the solidified epoxy.

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 1 μ m/sec at nanometric cutting depths. The tribometer is a load controlled device where the required thrust force (F_z) is applied by the user to obtain the desired depth of cut (based on the tool geometry and workpiece material properties). The equipment includes a dual-axis load cell that is capable of constantly monitoring the thrust and cutting forces, (F_x , obtained as an output parameter from the cutting experiment). A typical scratch test setup along with the μ -LAM system is shown in Figure 4.

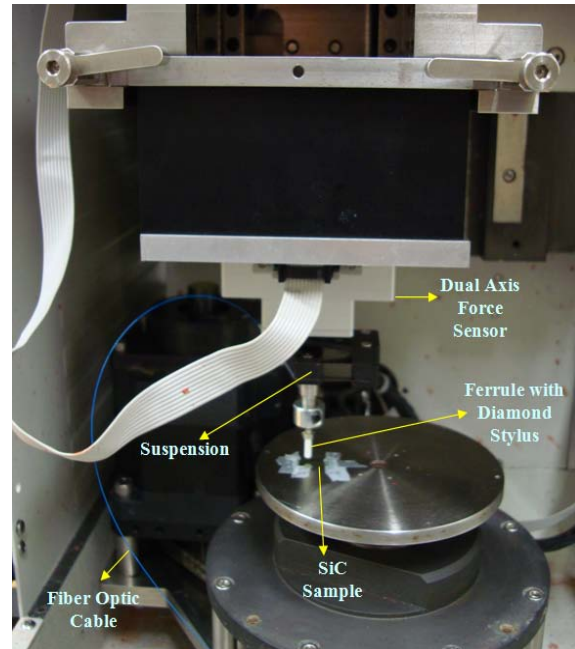


Figure 4: μ -LAM setup on the universal micro Tribometer (a similar setup was used for all scratch testing experiments).

The specimens are single crystal 4H-SiC or Si wafers. The primary flat of the SiC wafer is the {1010} plane with the flat face parallel to the $\langle 1120 \rangle$ 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 $\langle 1010 \rangle$ direction. For the DBT scratch tests on Si, all cuts were performed on the {100} plane along the $\langle 110 \rangle$ direction.

2.1. Effects of Laser Heating on Si:

2.1.1. 5 μ m Tip Radius Diamond Stylus: In this part of the study, scratch tests were performed with and without laser heating. The scratches were carried out at low cutting speeds (1 μ m/sec) in order to maximize the thermal softening of the material during the laser heating. Scratch lengths of 500 μ m were produced on the Si wafer. The loads were increased linearly with time from 20 mN to 70 mN along the 500 μ m scratch length. The scratch test parameters are summarized in Table 1.

Table 1: Parameters used for the DBT tests on Si.

Scratch #	Load Range (mN)	Machining Condition	Cutting Speed (μ m/sec)	Laser Power (mW)
1	20-70	no laser	1	0
2	20-70	with laser	1	350*

*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.

2.1.2. 1.4mm Nose Radius Diamond Cutting Tool: In this experiment, scratches were performed with and without laser heating using an actual cutting tool similar to that used for SPDT. The loads (F_z) used for the scratch tests are 1g (~10mN), 1.5g (~15mN), 2g (~20mN), 2.5g (~25mN) and 5g (~50mN) with a cutting speed of 1 μ m/sec. Scratch lengths of 300 μ m were produced on a single crystal Si wafer. The scratch test parameters are summarized in Table 2.

Table 2: Parameters used for the scratch tests on Si.

Load, F_z (mN)	Machining Conditions	Cutting Speed (μ m/sec)	Laser Power (mW)
10	With/Without Laser	1	0/350*
15	With/Without Laser	1	0/350*
20	With/Without Laser	1	0/350*
25	With/Without Laser	1	0/350*
50	With/Without Laser	1	0/350*

*Only applicable for the scratches with laser heating. 350mW is the laser power, approximately 254mW is actually delivered to the work piece material, the remaining laser power is lost due to scattering and reflections.

Only low loads were used in this study to maximize the laser heating; the laser beam size of approximately 10 μ m matched the lower applied loads, which yielded relatively shallow cuts with narrow widths (on the same size scale as the laser beam).

2.2. Effects of Laser Heating on SiC: In this case, the scratches were carried out at low cutting speeds (1 μ m/sec) as explained in previous sections. The loads were increased linearly with time from 2 mN to 70 mN along the scratch. This particular load range was chosen as it would exhibit a ductile, DBT and brittle region. The scratch test parameters are summarized in Table 3.

Table 3: Parameters for the DBT tests on SiC.

Scratch #	Load Range, (mN)	Machining Condition	Cutting Speed (μ m/sec)	Laser Power (mW)
1	2-70	no laser	1	0
2	2-70	with laser	1	350*

*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.

3. Results and Discussion:

3.1 Effect of Laser Heating on Si:

3.1.1 5 μ m Tip Radius Diamond Stylus: Figure 5 shows two scratches with and without laser heating (scratches 2 and 1) respectively. The load range (20-70 mN) performed on these scratches exhibited both, the ductile and brittle regime (with a DBT zone) along the same scratch. The ductile to brittle transition is identified somewhere between the ductile and brittle regime of the scratch using optical microscopy, white light interferometry and force analysis (from variations in cutting forces). Figure 6 shows a high magnification optical microscope image used to identify brittle fracture along the scratch. It is seen in Figure 6 that the scratch performed without laser heating exhibits brittle fracture along the cut much before the scratch performed with laser heating. The indication of brittle fracture for the scratch done with laser heating is not seen in Figure 6 as it is outside the field of view.



Figure 5: Scratches done with (2) and without laser heating (1).

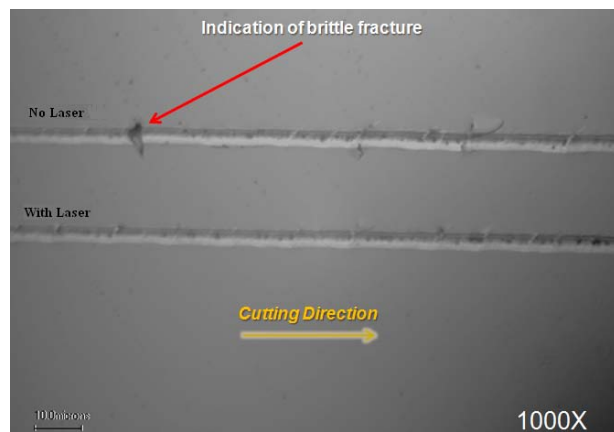


Figure 6: Micrograph showing brittle fracture along the scratch in Si

In this study, there were two different analyses done based on the results obtained from the scratch tests. The first analysis compares the depth of cut and cutting forces (F_x) for a constant thrust force (F_z) for both cutting conditions (with and without laser heating). For this analysis, scratches analyzed for both conditions were in the ductile regime. The results summarized in

Table 4 show that for the same amount of applied thrust force ($F_z = 20\text{mN}$), the scratch performed with laser heating yielded a greater depth of cut (400nm vs. 280nm). It is also evident that the scratch performed with laser heating yielded a slightly lower cutting force for an equal applied thrust force (although the scratch performed with laser heating was significantly deeper). A scratch without laser heating done at higher loads, to result in a depth of cut of 400nm, will most definitely result in higher cutting forces due to the hardness of the material [16, 17].

Table 4: Scratch test results for Si.

Machining Condition	F_z (mN)	F_x (mN)	Depth of Cut (nm)	Scratch Nature
no laser	20	6.0	280	Ductile
with laser	20	5.5	400	Ductile
no laser	35	9.0*	450*	DBT
with laser	42	8.0*	710*	DBT

*Just before the DBT occurs.

Investigations were also carried out to understand the effects of laser heating on the DBT of the material. During these studies, the scratches were examined using a white light interferometer. Figure 7 shows the cross-section of the two scratches taken at an equal thrust force of approximately 35mN. It can be seen in Figure 7 that the scratch performed with laser heating (left) exhibits a perfectly ductile behavior (with a depth of 700nm) whereas the scratch done without laser heating indicates the onset of fracture at a depth of 480nm. The brittle behavior is identified by the imperfect pattern of the groove edge which is a representation of the stylus imprint on the material. Figure 8 illustrates a three-dimensional scratch profile that gives a clear graphical illustration of the nature of the scratch: i.e., ductile or brittle. Here, it can be clearly identified that the scratch performed with laser heating still exhibits ductile behavior whereas the scratch performed with no laser heating shows brittle behavior for similar thrust forces. The clear and defined edges that depict the stylus imprint are a good indication of ductile response of the material (as seen in the scratch performed with laser heating).

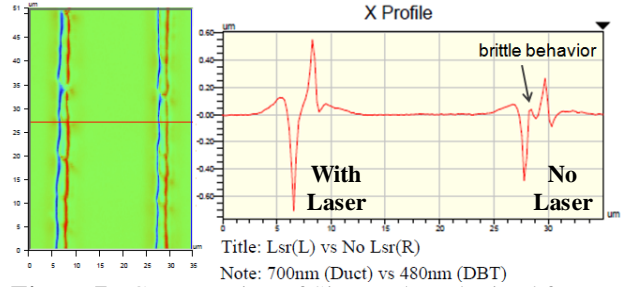


Figure 7: Cross-section of Si scratches obtained from a white light interferometer.



Figure 8: 3D scratch profiles of the Si scratches with and without laser heating (related to the same area imaged in Figure 7).

Figure 9 shows the cross-section of these same scratches taken at an equal thrust force of approximately 42mN. It can be seen that the scratch performed with laser heating (left) indicates a ductile to brittle transition at a depth of 710nm. At this load, the scratch performed with no laser heating shows signs of severe fracture. In comparison, the DBT depth of the scratch performed with laser heating was approximately 260nm greater than the DBT depth of the scratch performed without laser heating.

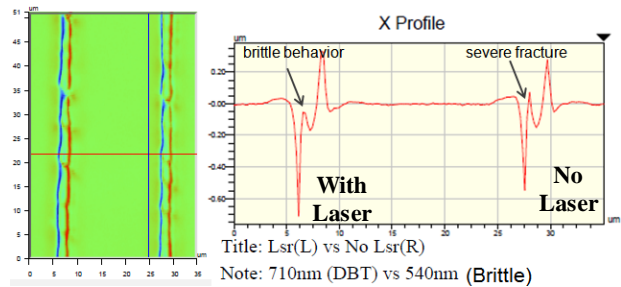


Figure 9: Cross-section of Si scratches obtained from a white light interferometer.

Figure 10 shows the cutting force comparison for the scratch with and without laser heating for a linearly increasing thrust force/load. Force data analysis is yet another method used to confirm the DBT and identify the onset of fracture behavior in the material. As seen in the cutting force data (blue and red lines), instability (large peaks and valleys on a linearly increasing line) in cutting forces are usually correlated to fracture occurrence along the scratch. Another advantage of

force analysis is that fracture can be observed in-situ via the instability observed in the cutting forces (blue and red lines) during the scratch experiments. This is an important tool while attempting ductile mode machining of brittle materials as the force data will indicate the onset of brittle behavior (during the cutting process: in-situ) allowing the machinist to reduce the depth of cut of thrust force avoiding fracture or even catastrophic failure in the material. From the force data in Figure 10, it is clear that the cutting forces for the scratch performed with laser heating are lower than the cutting forces for the scratch with no laser heating (although scratch with laser heating yields a greater depth of cut) for a similar applied thrust force.

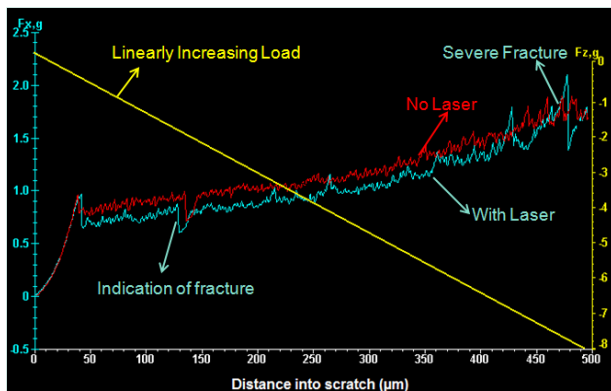


Figure 10: Force data (F_x =cutting force and F_z = thrust force) comparing the Si scratch with and without laser heating for equal loads (linearly increasing thrust force).

3.1.2 1.4mm Nose Radius Diamond Cutting Tool:

All scratches were imaged using an optical microscope to ensure that there were no surface cracks or any form of brittle fracture. Figure 11 shows fully ductile cuts comparing both conditions (with and without laser heating). From these images, there are no obvious differences between the cuts (the purpose of optical microscopy here was only to look for evidence of brittle fracture, if any).



Figure 11: Region of the Si scratches, with and without laser heating, done with a 20mN (2g) thrust force.

Figure 12 compares the depth of cut with the applied thrust force for both testing conditions: with and without laser heating. From the figure it is clear that there is an

increase in the depth of cut with laser heating for all applied loads experimented (i.e. 10mN, 15mN, 20mN, etc.). This is due to the enhanced ductility or reduced hardness due to the thermal softening of the material.

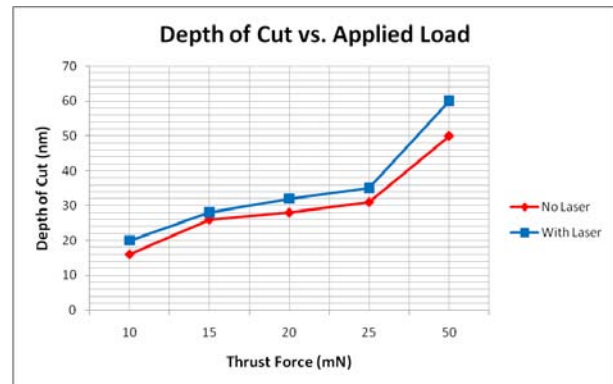


Figure 12: Depth of cut versus the applied load for five different loads comparing with and without laser heating conditions.

3.2 Effect of Laser Heating on SiC: Figure 13 shows two scratches, without (scratch 1) and with laser heating (scratch 2). The DBT is identified somewhere between the ductile and brittle regime of the scratch using optical microscopy, white light interferometry and force analysis (from variations in cutting forces). It is seen in Figure 13 that the scratch performed without laser heating exhibits brittle fracture along the cut before, i.e., at a shallower depth, than the scratch performed with laser heating.

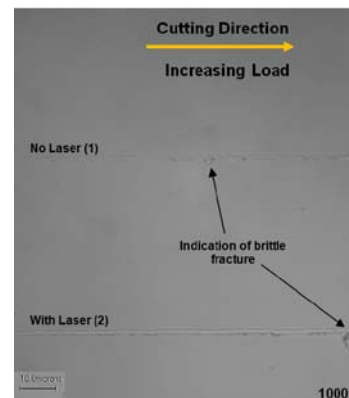


Figure 13: Micrograph showing brittle fracture of SiC along the scratch

In this study, there were two different analyses done based on the results obtained from the scratch tests. The first analysis compares the depth and cutting forces (F_x) for a constant thrust force (F_z) for both cutting conditions (with and without laser heating) to determine the effect of laser heating and thermal softening on the material. For this analysis, scratches analyzed for both conditions were in the ductile regime. The results

summarized in Table 5 show that for the same amount of applied thrust force ($F_z = 30\text{mN}$), the scratch performed with laser heating yielded a greater depth of cut (145nm vs. 95nm). It is also evident that cutting forces were equal for both these conditions for an equal applied thrust force (although the scratch performed with laser heating was significantly deeper). A scratch without laser heating at higher loads resulted in a depth of 145nm will most definitely result in higher cutting forces due to the hardness of the material [16, 17].

The subsequent analysis investigated the effects of laser heating on the DBT of the material. To determine this, two-dimensional scratch/groove profiles obtained using a white light interferometric profilometer were analyzed. Figure 14 shows the cross-section of the two scratches taken at an equal thrust force of approximately 35mN. It can be seen that the scratch performed with laser heating (left) exhibits a perfectly ductile behavior whereas the scratch without laser heating (right) indicates slight fracture (brittle behavior) of the material. The DBT depth identified for the scratch without laser heating just before the point of fracture is approximately 105nm. The brittle behavior is identified by the imperfect pattern of the groove edge which is a representation of the stylus imprint on the material. It is important to note from Figure 14, that the scratch performed without laser heating is (apparently) deeper (210nm vs. 113nm) as it is difficult to control the depth when the material removal mechanism is brittle (i.e. difficult to control the depth due to fracture of the material). The clear and defined edges that depict the stylus imprint are a good indication of ductile response of the material (as seen in the scratch performed with laser heating).

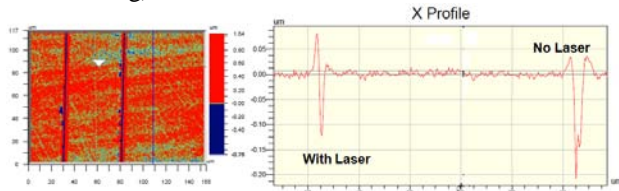


Figure 14: Cross-section of SiC scratches obtained from a white light interferometric profilometer

Figure 15 shows the cross-section of the same scratches at a different point taken at an equal thrust force of approximately 40mN. The DBT depth identified for the scratch performed with laser heating just before the point of fracture is approximately 240nm. At this load, the scratch performed with no laser heating shows signs of severe fracture. In comparison, the DBT depth of the scratch performed with laser heating was approximately 135nm greater (over twice as deep) than the DBT depth of the scratch performed without laser heating.

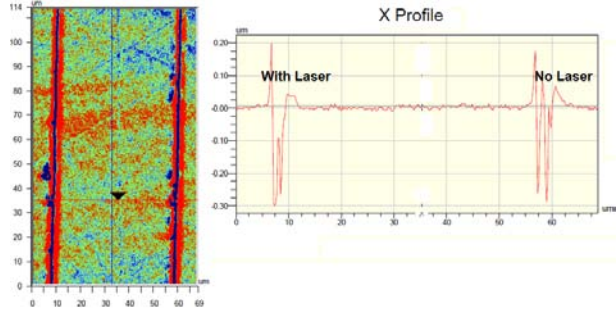


Figure 15: Cross-section of SiC scratches obtained from a white light interferometric profilometer

From Table 5, it is seen that the cut performed with laser heating yields a slightly higher cutting force at the DBT. This is due to the higher thrust force (40mN vs. 35mN) and larger depth of cut (240nm vs. 105nm).

Table 5: SiC scratch test results.

Machining Condition	Fz (mN)	Fx (mN)	Depth of Cut (nm)	Scratch Nature
No Laser	30	10	95	Ductile
With Laser	30	10	145	Ductile
No Laser	35	12 *	105*	DBT
With Laser	40	14 *	240*	DBT

*Just before the DBT occurs.

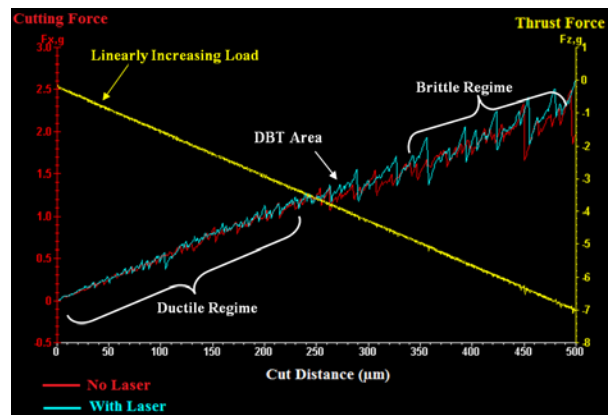


Figure 16: Plot shows cutting force and thrust force data for both SiC scratches.

Analyzing the force data after the scratch experiments helps in correlating the onset of brittle fracture along the scratches. Brittle mode material removal is usually seen in the force data (especially the cutting forces as they are more sensitive to brittle fracture) and can be identified by its unstable behavior (higher standard deviation/ higher peak-valleys in the force plots). Figure

16 shows the force data plot obtained from both scratching conditions (with and without laser heating).

4. Simulating the Effects of Thermal Softening on Ductile Mode Machining of SiC

The simulation results include the cutting and thrust forces that are used for comparison to evaluate the various machining conditions (primarily the workpiece temperature and the resultant thermal softening effect). The feed is 500nm and cutting edge radius on tool is 100 nm [26]. The simulations were carried out at various temperatures: 20° C, 700° C, 1500° C, 2200° C, and 2700° C, where 1500° C is the thermal cutoff temperature as shown in Figure 2. Beyond the thermal cutoff temperature, there is a linear decrease in the material strength until it reaches the melting point (2830° C).

The results at different temperatures are tabulated in Table 6. The simulations are run until the forces reach the steady state value, which does not necessarily cover the entire length of cut. The length of cut is selected such that the steady state is achieved before the tool runs through the entire length of workpiece.

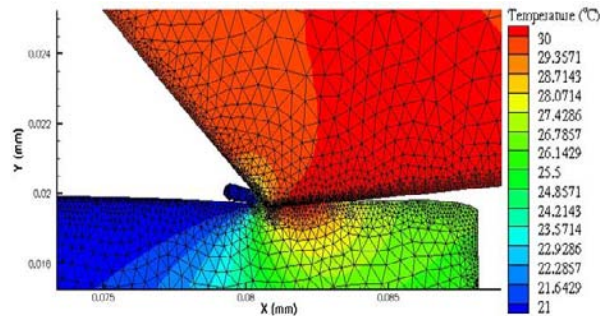


Figure 17: SiC simulation screenshot at 20° C

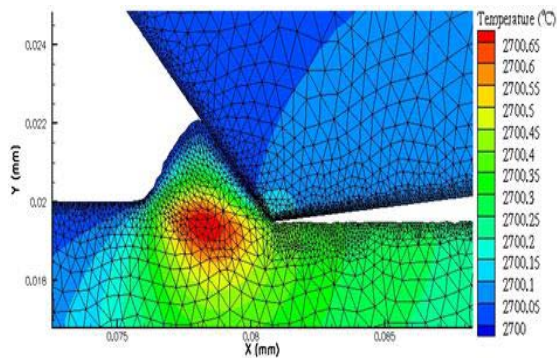


Figure 18: SiC simulation screenshot at 2700° C

Note that the temperature scale is different in Figures 17 and 18. At 20° C, there is a significant chip formation

and also the cutting pressure is high, as SiC retains its hardness at room temperature (Figure 17). At 2700° C, the hardness of the material is negligible and the material is simply ploughed by the tool (Figure 18).

Table 6 Summary of the simulation results for the machining of SiC

Boundary Condition	Temp. (° C)	Fx (mN)	Fz (mN)	Pressure (GPa)
Workpiece top surface	20	470	1040	47
	700	450	950	45
	1500	390	570	39
	2200	200	260	20
	2700	30	40	3

Table 6 clearly shows that the cutting and thrust forces (Fx and Fz respectively), and pressures are decreasing with an increase in temperature. This confirms the ability of the machining simulation software to model the thermal softening behavior due to laser heating, which reduces the hardness of the material.

5. Conclusion: Micro-Laser assisted scratch tests were successful in demonstrating the enhanced thermal softening and reduced brittleness of single crystal Si and 4H-SiC resulting in a greater ductility and a larger ductile to brittle transition depth. Laser heating was successfully demonstrated as evidenced by the significant increase in the ductile response of single crystal Silicon in the {100} plane along the <110> direction and single crystal 4H-Silicon Carbide in the {1010} plane along the <1010> direction. Laser heating (heating, thermal softening and reduced brittleness) during the material removal process resulted in greater depths of cuts (for equal applied loads when compared to cuts performed at room temperature), smaller cutting forces and a larger critical DoC (DBT). Force analysis (thrust and cutting), optical microscopy and white light interferometric profilometry served as useful analyses methods to detect the enhanced ductile response and reduced brittle fracture as a result of preferential material heating (of the high pressure phase transformed material).

For the simulation study, the boundary condition chosen successfully simulated the laser heating effect. The thermal softening effect begins above room temperature (20° C) as the hardness of the material decreases with an increase in temperature. Furthermore, the simulation results can be used to study behavior of the high pressure phase beyond the thermal cutoff point.

In general, results obtained from this study are promising to further implement micro-laser assisted machining (μ -LAM) in operations such as single point

diamond turning. Lower cutting forces obtained from the μ -LAM process are favorable to minimize tool wear while machining abrasive ceramics/semiconductors such as Quartz, Silicon and Silicon Carbide. The results from this study will also benefit the manufacture of brittle materials as laser heating is proven to decrease the brittle response in ceramics and semiconductors, which can result in high productivity rates (i.e. higher material removal rate). A similar analysis to study the effects of laser heating on other semiconductors/ceramics (i.e. Spinel, AlTiC, AlON and Sapphire) will be researched in the future.

6. Ongoing and Future Work:

6.1 Experimental Analysis: To further study the effects of high power laser heating on Si and SiC, an IPG fiber laser system (maximum power = 100W and $\lambda = 1070\text{nm}$) is currently being tested with a 1mm nose radius diamond cutting tool. The IPG laser system is coupled with a modular head component (beam delivery optics unit) which has beam delivery optics (from Laser Mechanisms, Inc.) that facilitates the diamond cutting tool (shown in Figure 19). The main objective is to study the material behavior with increased laser power (i.e. higher laser powers heat the surface more, resulting in enhanced ductility). Also, the machining parameters such as laser power, depth of cut and cutting speed will be optimized to obtain good surface finish with a higher material removal rate.

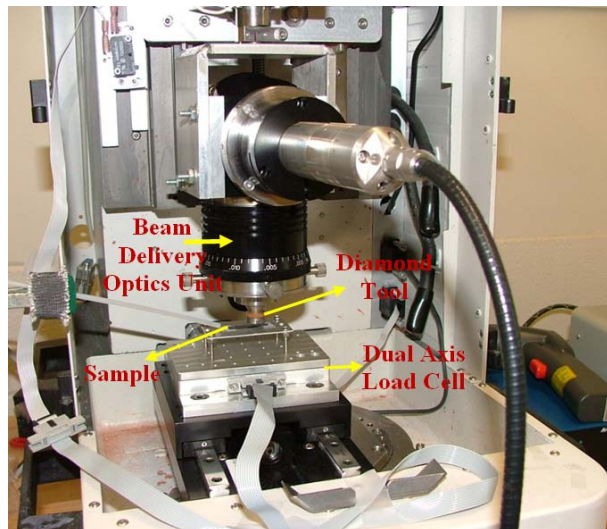


Figure 19: IPG Laser system coupled with a laser beam delivery optics unit.

Micro-Raman spectroscopy will be performed on the scratches/cuts to characterize the phases present along a scratch/cut to confirm the existence of a ductile mode material removal process. For the scratches/cuts performed to identify the DBT, three different regions

will be analyzed; the ductile region, the transition region and the brittle region. The spectrums of all three regions will be compared and new peaks (expected to be generated in the phase transformed region) will be identified as an evidence of ductile mode machining. Besides identifying new peaks or a shift in peaks, broadband peaks or amorphous broadening of the crystalline peaks is also expected in the machined surface (ductile mode material removal).

Preliminary Micro-Raman analysis has been carried out (at Argonne National Laboratory) successfully on cuts performed without laser heating on Si. In this preliminary analysis, two different laser excitation wavelengths were used; HeCd (442nm blue laser) and ArION (514nm green laser). Only results from the green laser are shown in this section as for this particular analysis, the results obtained from both wavelengths were identical. Figures 20(a) and (b) compare the Raman spectrum obtain from the original surface (unmachined) with the machined surface (ductile regime). The red circle in the figures represents the area investigated/characterized using Micro-Raman spectroscopy.

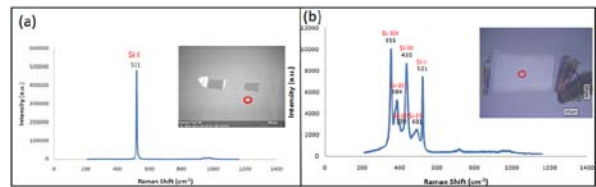


Figure 20: Micro-Raman spectrum using a 514nm wavelength excitation laser for (a) the unmachined surface and (b) ductile mode material removed surface

From Figure 20(b), it is seen that two new phases are identified (in the phase transformed region) in addition to the Si-I phase, which are Si-III and Si-XII. From previous research work, it is known that metallic Si-II is unstable below approximately 4GPa upon unloading and therefore transforming to other phases such as Si-I, Si-III and Si-XII, depending on the pressure release conditions [27].

Finally, high pressure and temperature tests were conducted at Argonne National Laboratory (ANL), Advanced Photon Source (APS) to determine the phase transition conditions and parameters of 4H, 6H and 3C SiC. The phase change in these SiC materials was seen over a pressure range of 66 - 88 GPa and at 1500 - 1600 K. It is believed (from preliminary results) that all three polytypes appear to form a dense cubic phase (3C) at these conditions. The data from these experiments is still being analyzed to determine the characteristics of the newly formed high pressure phase, such as optical

absorption over the wide range of wavelengths (UV through IR).

6.2 Simulation Study: The ongoing simulation work includes 3-D simulations of different depth of cuts as that of similar to the experiments and at room temperature to compare the cutting and thrust forces and cutting pressures. This comparison work will validate the simulation results. Further, 3D simulations will be conducted at elevated temperatures to compare with the experimental scratch tests done with the laser. Future work would also involve the study of the material behavior, i.e. thermal softening, beyond the thermal cutoff point up until the melting point. The experimental μ -LAM process will hopefully assist in determining those data points.

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