THE EFFECT OF LASER HEATING ON THE DUCTILE TO BRITTLE TRANSITION OF SILICON CARBIDE

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INTRODUCTION

Semiconductors and ceramics, such as silicon carbide, share common characteristics of being nominally hard and brittle, which stems from their covalent chemical bonding and crystal structure. These materials are important in many engineering applications, and are particularly difficult to machine in traditional manufacturing processes due to their extreme hardness and brittleness [1]. Silicon carbide (SiC) has many desirable properties, such as excellent wear resistance, chemical stability, and high strength even at elevated temperatures. All of these properties make it an ideal candidate for tribological, semiconductor, MEMS and optoelectronic applications. In spite of all these characteristics, the difficulty during machining and material removal has been a major obstacle that limits the wider application of this material [1]. The plastic deformation of SiC 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 generally subsequently removed in lapping and polishing processes, which significantly increases the machining time and cost. 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 final product cost [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 from 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 low 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, i.e., cracks and brittle fracture. Ductile regime machining of nominally brittle semiconductors and ceramics has been continuously studied and developed in the last two decades [3-11, 20]. Laser assisted micro/nano machining is another important development in ductile regime machining of brittle materials [12, 13].

In past research, it has been demonstrated that ductile regime machining of these materials is possible due to the high pressure phase transformation (HPPT) occurring in the material caused by the high compressive and shear stresses induced by the single point diamond tool tip [14, 15]. To further augment the ductile response of these materials, traditional scratch/single point diamond turning 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 can 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. μ-LAM was previously successfully carried out on single crystal Si yielding a significantly greater DBT (for the scratch performed with laser heating) [18].

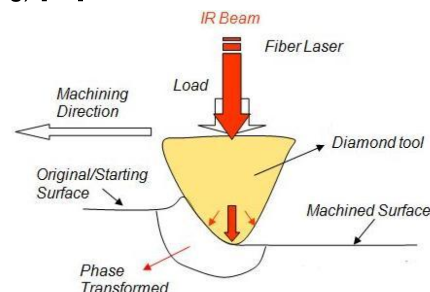

Figure 1. A schematic cross-section of the μ-LAM process.

The objective of the current study is to determine the effect of laser heating (using the μ-LAM process) on the DBT of single crystal 4H-Silicon Carbide (SiC) using scratch testing. The scratch tests were carried out to examine the effect of laser heating and thermal softening of the high pressure phases formed under the diamond tip. The effects of laser heating were studied by verifying the depths of cuts and the nature of the scratches (i.e. ductile, DBT or brittle) for diamond stylus scratch tests carried out on single crystal 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 profiles were investigated.

EXPERIMENTAL PROCESS

The scratch tests were performed on a Universal Micro-Tribometer (UMT) which is produced by 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. The tribometer is a load controlled device where the required thrust force (Fz) is programmed by the user to obtain the desired DoC (based on the tool geometry and work piece material properties). The equipment includes a dual-axis load cell that is capable of continuously monitoring and recording the thrust and cutting forces, Fx, (obtained as an output parameter from the cutting experiment). A typical scratch test setup along with the μ-LAM system is shown in Figure 2. All scratch tests were performed on a single crystal 4H-SiC wafer. All cuts were performed on the {1010} plane along the <1010> direction.

A 90° conical single crystal diamond stylus (with a spherical end tip radius of 5μm) was used as the scratch tool. The details of the diamond tip attachment are depicted in Figure 3. An infrared (IR) diode fiber laser (λ=1480nm and P_{max}=400mW) with a Gaussian profile with a beam diameter of ~10μm was used in this study. The laser beam is guided through a 10μm fiber optic cable to the ferrule, which is attached to the diamond stylus. The μ-LAM system is configured in such a way that the laser beam passes through the diamond tip and impinges on the work piece material at the tool work piece interface . [19]

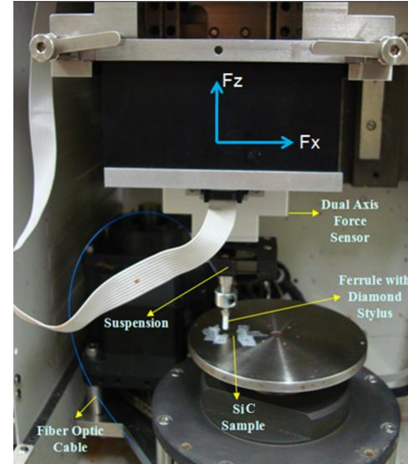

Figure 2. μ-LAM setup.

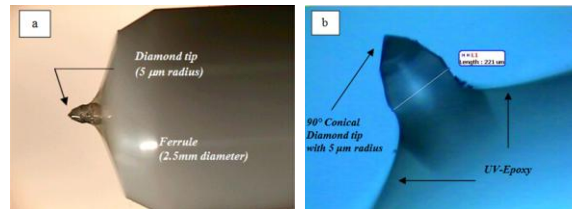

Figure 3. Diamond tip attachment: (a) 5μm radius diamond tip attached on the end of the ferrule using epoxy, (b) Close up on diamond tip embedded in the solidified epoxy [19].

Scratch tests were chosen to be the principle method of investigation in this study as it is a better candidate for evaluating machining conditions than indenting because the mechanics during scratching are more applicable to the machining process such as single point diamond turning (SPDT). In this study, two conditions of scratches were performed: with and without laser heating. The scratches were carried out at low cutting speeds (1 μm/sec) in order to maximize the thermal softening of the material during the laser heating. Scratch lengths of 500 μm were produced on the SiC wafer specimen. The loads were increased linearly with time from 2 mN to 70 mN along the scratch. The scratch test parameters are summarized in Table 1.

Table 1. Scratch testing parameters.

Scratch No.	Loads (mN)	Machining Condition	Cutting Speed (μm/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.*

RESULTS

Figure 4 shows two scratches that represent the two conditions: without (scratch 1) and with laser heating (scratch 2). The load range (2-70 mN) performed on these scratches were ideal for this study as it had both the ductile and brittle regime along the same scratch. 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 4 that the scratch performed without laser heating exhibits brittle fracture along the cut much before the scratch performed with laser heating.

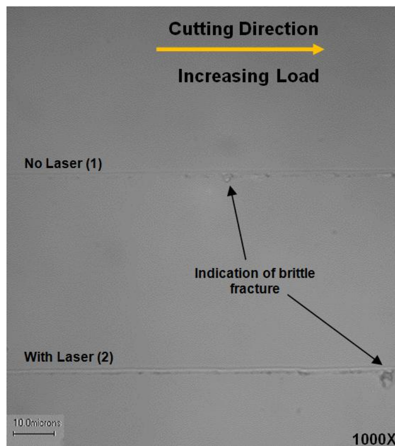

Figure 4. Micrograph showing brittle fracture along the scratch.

To study the effects of laser heating on the DBT of the material, two-dimensional scratch/groove profiles obtained using a white light interferometric profilometer were analyzed. Figure 5 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 done without laser heating (right) indicates slight fracture (brittle behavior) of the material. The DBT depth identified for the scratch performed 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 that from Figure 5, the scratch performed without laser heating is (apparently) deeper (210nm vs. 113nm) as it is difficult to control the DoC when the material removal mechanism is brittle (i.e. difficult to predict the DoC due to fracture of the material). The clear and defined edges that depict the stylus imprint is a good indication of ductile response of the material (as seen in the scratch performed with laser heating).

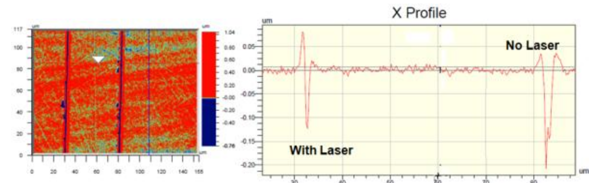

Figure 5. Cross-section of the scratches obtained from a white light interferometer profilometer.

Figure 6 shows the cross-section of the same two 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 than the DBT depth of the scratch performed without laser heating.

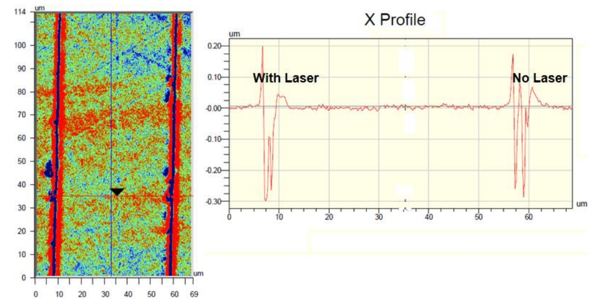

Figure 6.Cross-section of the scratches obtained from a white light interferometer profilometer.

From Table 2, it is seen that the cut performed with laser heating yields in a slightly higher cutting force. This is due to the higher thrust force (40mN vs. 35mN) and larger depth of cut (240nm vs. 105nm).

Table 2. Scratch test results.

Machining Condition	Fz (mN)	Fx (mN)	DoC (nm)	Scratch Nature
no laser	35	12*	105	DBT
with laser	40	14*	240	DBT

**Just before the first point of fracture.*

CONCLUSION

Micro-Laser assisted scratch tests were successful in demonstrating the enhanced

thermal softening of the material resulting and a greater ductile to brittle transition depth. Laser heating was successfully demonstrated as evidenced by the significant increase in the ductile response of single crystal 4H-Silicon Carbide in the {1010} plane along the <1010> direction. Laser assisted (heating, thermal softening and reduced brittleness) material removal resulted in a greater depths of cuts at less applied thrust forces, smaller cutting forces and a larger critical DoC. 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). 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 also will 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 on laser heating on other semiconductors/ceramics (i.e. Spinel, AlTiC, AlON and Sapphire) will be researched in the future.

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