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The Effect of Laser Heating on the Ductile to Brittle Transition in Silicon

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ABSTRACT

Advanced ceramics and semiconductors (i.e. SiC, Si, Quartz, 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. Often times, severe fracture can result when trying to achieve high material removal rates when machining ceramics and semiconductors due to their low fracture toughness. 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 a single point diamond tool tip. To further augment the ductile response of the nominally brittle e materials, traditional scratch/single point diamond turning (SPDT) tests are coupled with a micro-laser assisted machining (µ-LAM) technique. In this research, a study is done to compare the results of scratch tests done on single crystal Silicon, with and without laser heating. The effects of laser heating were studied by verifying the depths of cuts for scratch tests carried out on single crystal Silicon with increasing loads (thrust force) to wherein the scratch shows both ductile and brittle response (with a ductile to brittle transition (DBT) region within the scratch). Cutting forces and three-dimensional cutting profiles using a white light interferometer were investigated. Laser heating was successful in enhancing the ductile response of the material by yielding in a greater ductile to brittle transition depth.

I. INTRODUCTION

Semiconductors and ceramics share common characteristics of being nominally hard and brittle, which stems 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 [1]. 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 during machining and material removal has been a major obstacle that limited the wider application of these materials [1]. 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 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 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 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 and brittle fracture. In order to develop a suitable process, ductile regime machining, considered to be one of the satisfactory precision machining techniques, has been continuously studied in the last two decades [3-11]. Laser assisted micro/nano machining is another important development in this direction [12, 13].

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terial 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 Fig.1. This hybrid method could potentially increase the critical depth of cut (larger DBT depth) in ductile regime machining, resulting in a higher material removal rate.

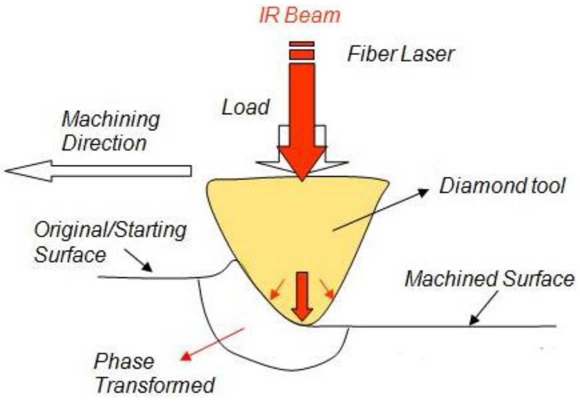

Fig. 1: A schematic cross-section of the μ-LAM process.

The objective of the current study is to determine the effect of laser heating on the DBT of single crystal Silicon (Si) using scratch testing. The scratch tests were carried out to examine the effect of temperature in thermal softening of the high pressure phases formed under the diamond tip. These scratch tests were also used to evaluate the difference between with and without irradiation of the laser beam at a constant loading (constant thrust force) and cutting speed. The effects of laser heating were studied by verifying the depths of cuts for scratch tests carried out on single crystal Si with increasing loads (thrust force) to make sure the scratch shows both ductile and brittle response (with a DBT region within the scratch). Cutting forces and three-dimensional cutting profiles (using a white light interferometer) were investigated.

II. 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 applied by the user to obtain the desired depth of cut (based on the tool geometry and workpiece material properties). The equipment is equipped with a dual-axis load cell that is capable of constantly monitoring 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 Si wafer. All cuts were performed on the {100} plane along the <110> 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 were depicted in Figure 3 (a and b). An infrared (IR) diode laser (λ=1480nm and P_{max}=400mW,) with a Gaussian profile with a beam diameter of ~10μm was 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 system is configured in such a way that the laser beam passes through the diamond tip (tool) and impinges on the Si work piece material at the tool work piece interface (contact). The laser emerges from a 90° conical single crystal diamond tip with 5μm radius spherical end.

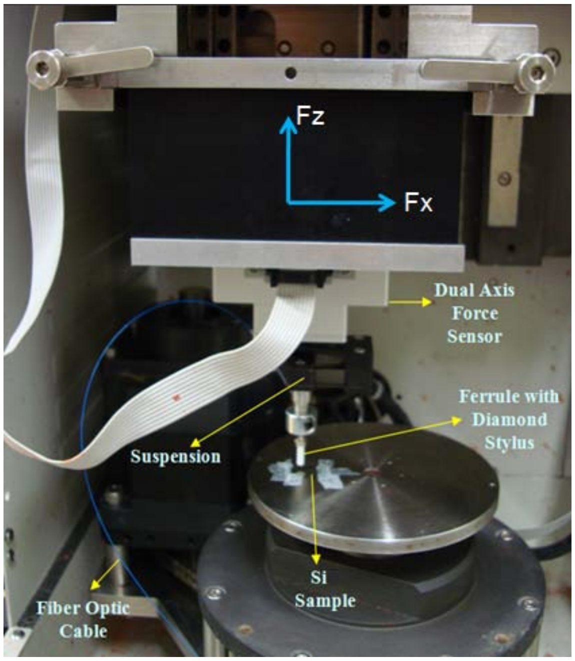

Fig. 2: μ-LAM system used in the experiments.

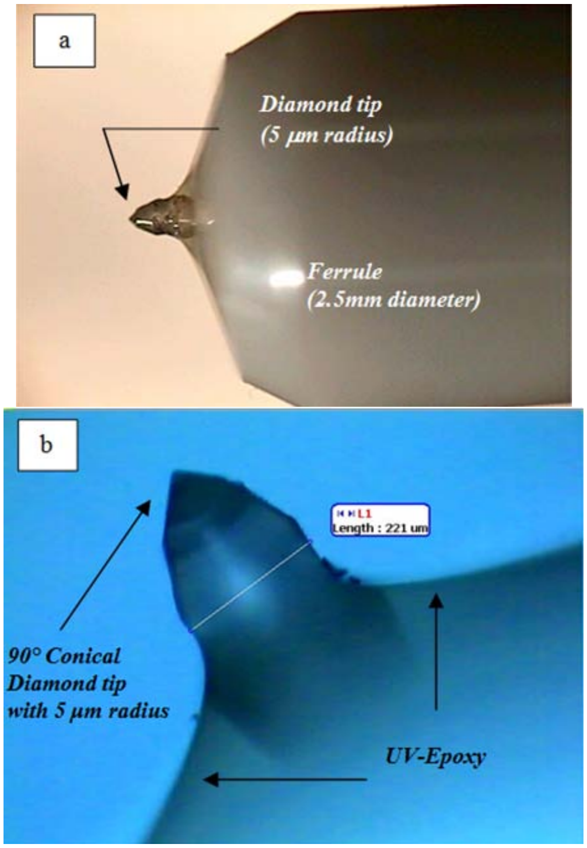

Fig. 3: Diamond tip attachment: (a) 5µm radius diamond tip attached on the end of the ferrule using epoxy, (b) Close up on diamond tip embedded in the solidified epoxy.

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 Si wafer specimen pieces. The loads were increased linearly with time from 20 mN to 90 mN along a 500 µm scratch length. 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	*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.*

III. RESULTS

Figure 4 shows two scratches that represent the two conditions: without heating (scratch 1) and with laser heating (scratch 2). The load range (20-70 mN) performed on these scratches were ideal for this study as it had both the ductile and brittle regime along the same scratch. The 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 5 shows a high magnification optical microscope image used to identify brittle fracture along the scratch. It is seen in Figure 5 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 5 as it is outside the field of view.

Fig. 4: Scratches done with (2) and without laser heating (1).

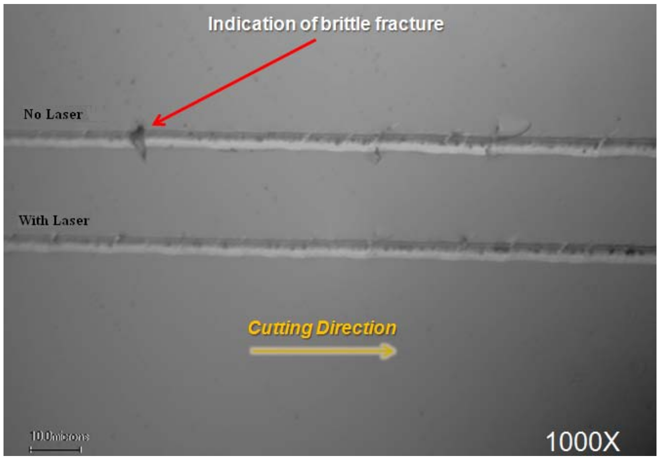

Fig. 5: Micrograph showing brittle fracture along the scratch.

In this study, there were two different analyses done based on the results obtained from the scratch tests.

The first analysis compares the depth of cut and cutting forces (Fx) for a constant thrust force (Fz) 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 2 show that for the same amount of applied thrust force (Fz = 20mN), the scratch performed with laser heating yielded in a greater depth of cut (400nm vs. 280nm). It is also evident that the scratch performed with laser heating yielded in 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 2: Scratch test results.

Machining Condition	Fz (mN)	Fx (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*	480	DBT
with laser	45	11.0*	710	DBT

*Just before the DBT occurs.

The second analysis done was to study the effects of laser heating on the DBT of the material. To determine this, two-dimensional scratch/groove profiles obtained using a white light interferometer were analyzed. Figure 6 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 (with a depth of 700nm) whereas the scratch done without laser heating indicates the DBT 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 7 illustrates a three-dimensional scratch profile that gives a clearer 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 is a good indication of ductile response of the material (as seen in the scratch performed with laser heating).

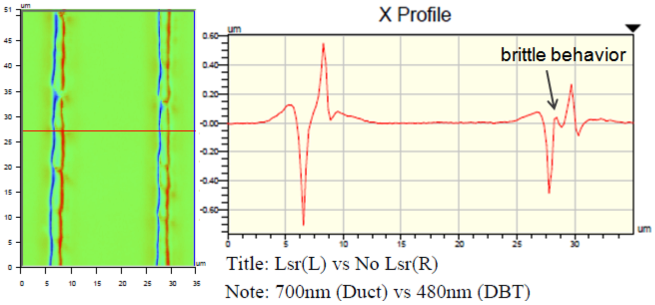

Fig. 6: Cross-section of scratches obtained from a white light interferometer.

Fig. 7: 3D scratch profiles of the scratches with and without laser heating.

Figure 8 shows the cross-section of the same two scratches taken at an equal thrust force of approximately 45mN. 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 230nm greater than the DBT depth of the scratch performed without laser heating.

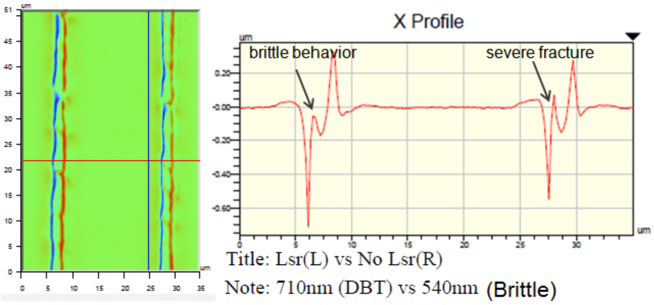

Fig. 8: Cross-section of scratches obtained from a white light interferometer.

IV. CONCLUSION

Micro-Laser assisted scratch tests were successful in demonstrating the enhanced thermal softening of the material resulting in 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 Silicon in the {100} plane along the <110> 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 depth of cut. Force analysis (thrust and cutting) ,optical microscopy and white light interferometry served as useful analysis methods to detect the enhanced ductile response and reduced brittle fracture as a result of preferential material heating. Results obtained from this study are promising to further implement micro-laser assisted machining (µ-LAM) in machining 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 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 in SiC will be researched in the future [16].

REFERENCES

[1] S. Jahanmir, L.K. Ives, A.W. Ruff and M.B. Peterson, “Ceramic Machining: Assessment of Current Practice and Research Needs in the United States”, *NIST Special Publication*, Vol. 834, p.102, 1992.

[2] H.G. Wobker and H.K. Tonshoff, “High Efficiency Grinding of Structural Ceramics”, International Conference on Machining of Advanced Materials, *NIST Special Publication 847*, Gaithersburg, MD, 455-463, 1993.

[3] P.N. Blake and R.O. Scattergood “Precision Machining of Ceramic Materials”, *Journal of the American Ceramic Society*, 73(4), 949-957, 1990.

[4] W.S. Blackley and R.O. Scattergood "Chip Topography for Ductile-Regime Machining for Germanium", *Journal of Engineering for Industry*, 116, 263-266, 1994.

[5] J.C. Morris, D.L. Callahan, J. Kulik, J.A. Patten and R. Scattergood, “Origins of The Ductile Regime in Single-Point Diamond Turning of Semiconductors”, *Journal of American Ceramic Society*, 78(8), 2015-2020, 1995.

[6] T.P. Leung, W.B. Lee and X.M. Lu, “Diamond Turning of Silicon Substrates in Ductile-Regime”, *Journal of Materials Processing Technology*, 73, 42-48, 1998.

[7] Sreejith P.S. and Ngoi B.K.A., “Material Removal Mechanisms in Precision Machining of New Materials”, *International Journal of Machine Tools & Manufacture*, v.41, 1831-1843, 2001.

[8] J.W. Yan, K. Syoji and T. Kuriyagawa, “Ductile Regime Turning at Large Tool Feed”, *J. MATER PROCESS TECH*, 121(2-3): 363-372, 2002.

[9] J.W. Yan, K. Maekawa, J. Tamaki et al., “Experimental Study on the Ultra-Precision Ductile Machinability of Single-Crystal Germanium”, *JSME INT J C-MECH SY* 47(1): 29-36, 2004.

[10] J.A. Patten, R. Fesperman, S. Kumar, S. McSpadden, J. Qu, M. Lance, R. Nemanich and J. Huening, “High-Pressure Phase Transformation of Silicon Nitride”, *Applied Physics Letters*, 83(23), 4740-4742, 2003.

[11] J.A. Patten, W. Gao and K. Yasuto, “Ductile Regime Nanomachining of Single-Crystal Silicon Carbide”, *J. MANUF. SCI E-T ASME*, 127(3), 522-532, 2005.

[12] L. Dong and J.A. Patten, "Real Time Infrared (IR) Thermal Imaging of Laser-Heated High Pressure Phase of Silicon", *Advanced Laser Applications Conference & Expo (ALAC 2007)*, September 24-25, Boston, MA, 2007.

[13] P.A. Rebro, F.E. Pfefferkorn, Y.C. Shin and F.P. Incropera, "Comparative Assessment of Laser-Assisted Machining of Various Ceramics", Transactions of NAMRI, Vol. 30, pp. 153-160, 2002.

[14] Deepak Ravindra et al., “Single Point Diamond Turning Effects on Surface Quality and Subsurface Damage in Ceramics,” *Proceedings of the ASME International Manufacturing Science and Engineering Conference*, Paper #84113, 2009.

[15] Deepak Ravindra et al., “Improving the surface roughness of a CVD coated SiC disk by performing ductile regime single point diamond turning,” *Proceedings of the ASME International Manufacturing Science and Engineering Conference*, Paper #72145, 2008.

[16] A.R. Shayan., H.B. Poyraz, D. Ravindra, M. Ghantasala and J.A. Patten, “Force analysis, mechanical energy and laser heating evaluation of scratch tests on silicon carbide (4H-SiC) in micro-laser assisted machining (µ-LAM) process”, *Proceedings of the ASME International Manufacturing Science and Engineering Conference*, Paper# 84207 2009.

[17] Shayan, A.R., Poyraz, H. B., Ravindra, D. and Patten, J.A., “Pressure and Temperature Effects in Micro-Laser Assisted Machining (µ-LAM) of Silicon Carbide”, *Transactions NAMRI/SME*, v.37, pp. 75-80, 2009.