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The Effects of Laser Heating on the Ductile to Brittle Transition (DBT) of Silicon Carbide

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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 proven that ductile regime machining of these materials is possible due to the high pressure phase transformation occurring in the material caused by the high compressive stresses induced by the single point diamond tool tip. To further augment the ductile response of the machined material, these traditional scratch/single point diamond turning tests are coupled with a micro-laser assisted machining (μ-LAM) technique. Micro Laser Assisted Machining, (μ-LAM), has the potential to positively impact, i.e., lessen, the brittle fracture behavior of semiconductors and ceramics during manufacture. The μ-LAM process has been used to heat and thermally soften these materials (Si and SiC) leading to enhanced ductility (plastic deformation) and ease of machining of these nominally brittle materials. The μ-LAM process will be evaluated for its ability to also provide for reduced fracture damage during machining, as a result of reduced brittleness, due to the laser heating and thermal softening effect.

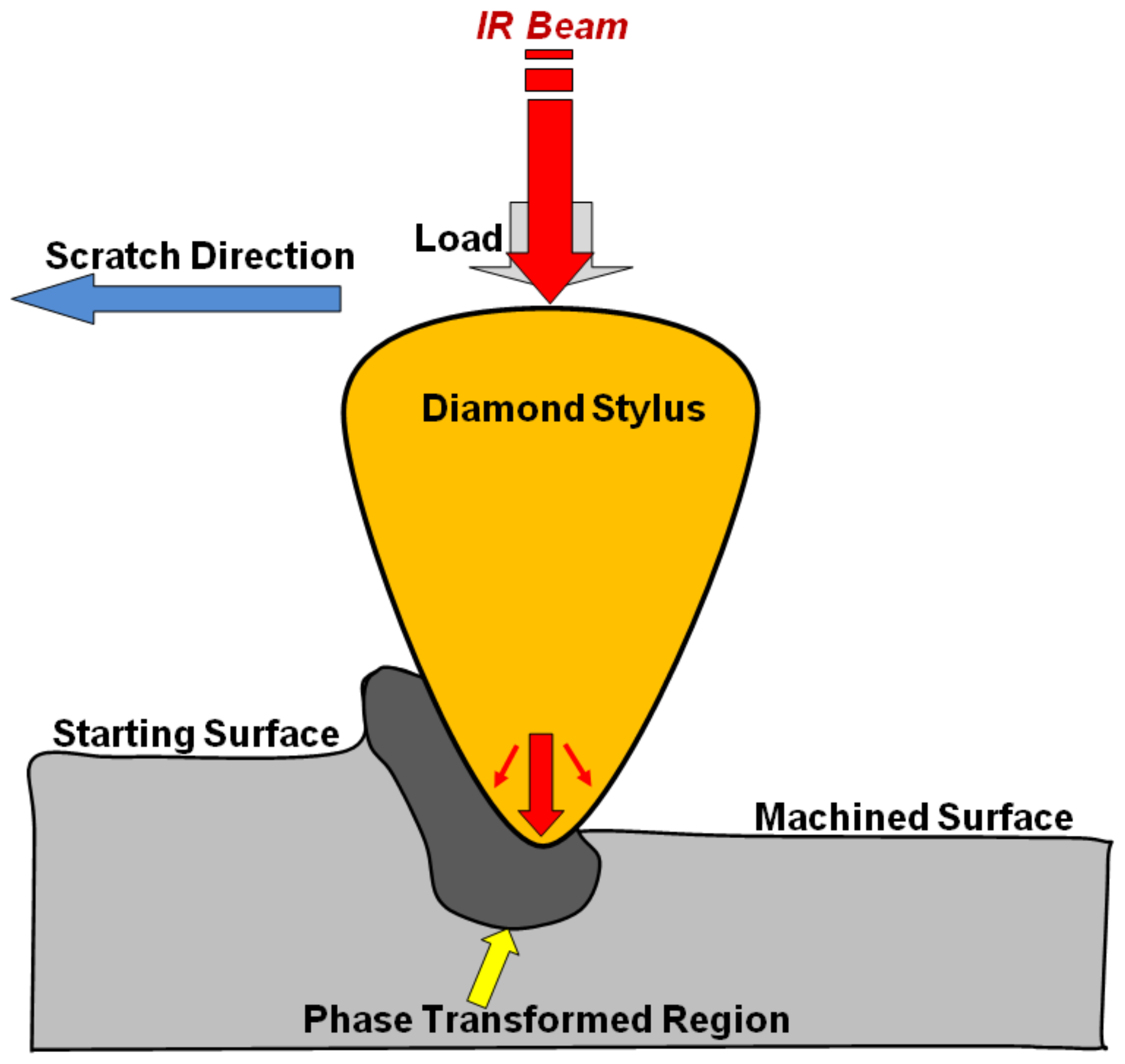


FIGURE 1. A SCHEMATIC CROSS SECTION OF THE μ-LAM PROCESS.

The IR diode laser used in this investigation is a Furukawa 1480nm 400mW IR fiber laser with a Gaussian profile and beam diameter of 10μm. The IR laser beam is guided from the diode laser through a 10μm fiber optic cable to the ferrule, which is attached to the diamond stylus. In this setup, the IR laser beam passes through the diamond tip (tool) and impinges on the single crystal 4H-SiC work piece material (Figure 1).

TABLE 1. SCRATCH CONDITIONS

Scratch Number	Load Range (Fz)	Machining Condition	Cutting Speed	Laser Power
1	2-70mN	*No Laser*	1μm/sec	0
2	2-70mN	*With Laser*	1μm/sec	350mW*

**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).*

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 single crystal 4H-SiC wafer specimen. The loads were increased linearly with time from 2 mN to 70 mN along the scratch.

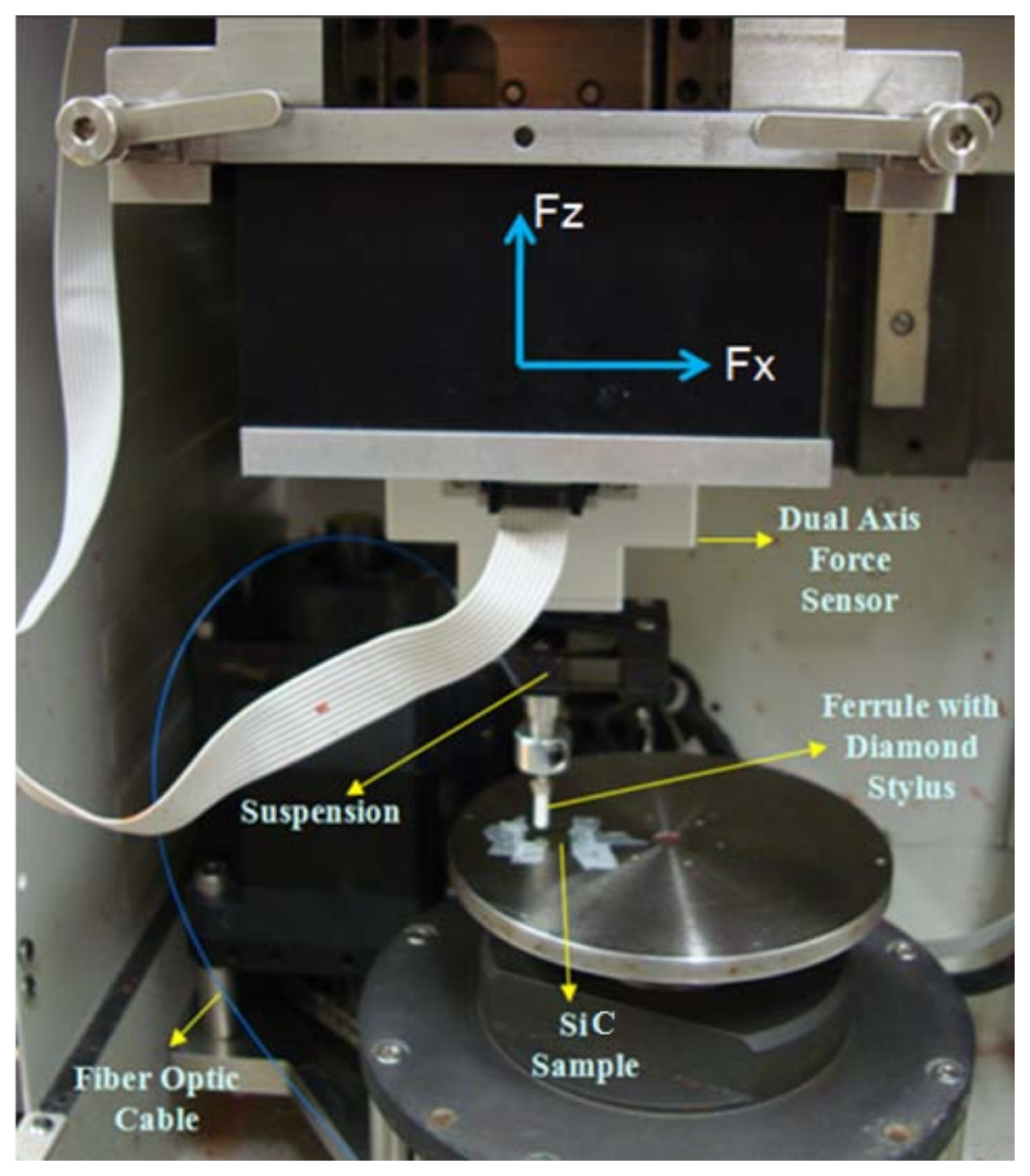


FIGURE 2. μ-LAM SETUP USED IN EXPERIMENTS.

The μ-LAM experimental setup is shown in Figure 2. 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 1μm/sec at nanometric cutting depths.

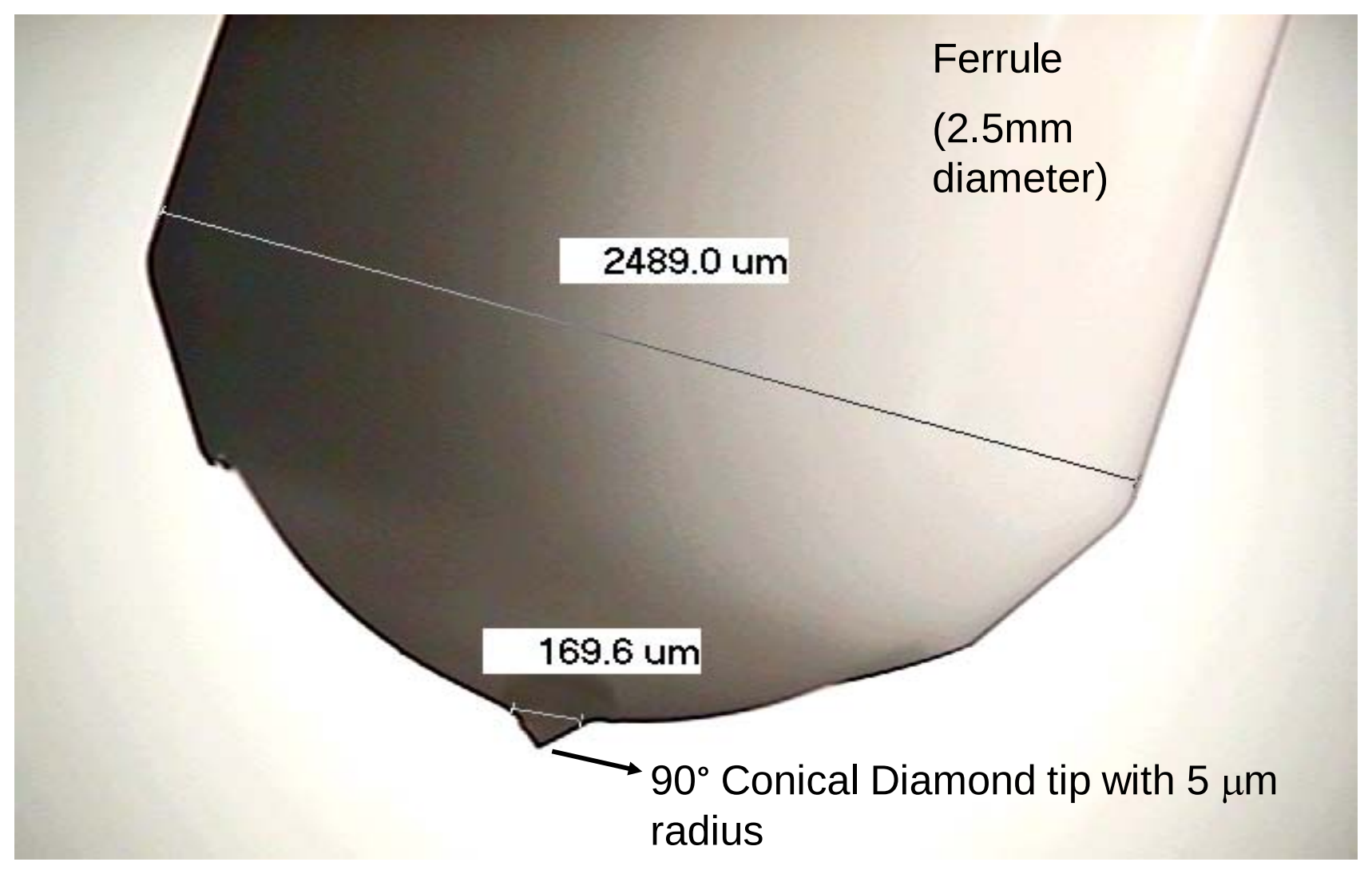


FIGURE 3. 5 μm RADIUS DIAMOND TIP ATTACHED ON THE END OF THE FERRULE USING EPOXY.

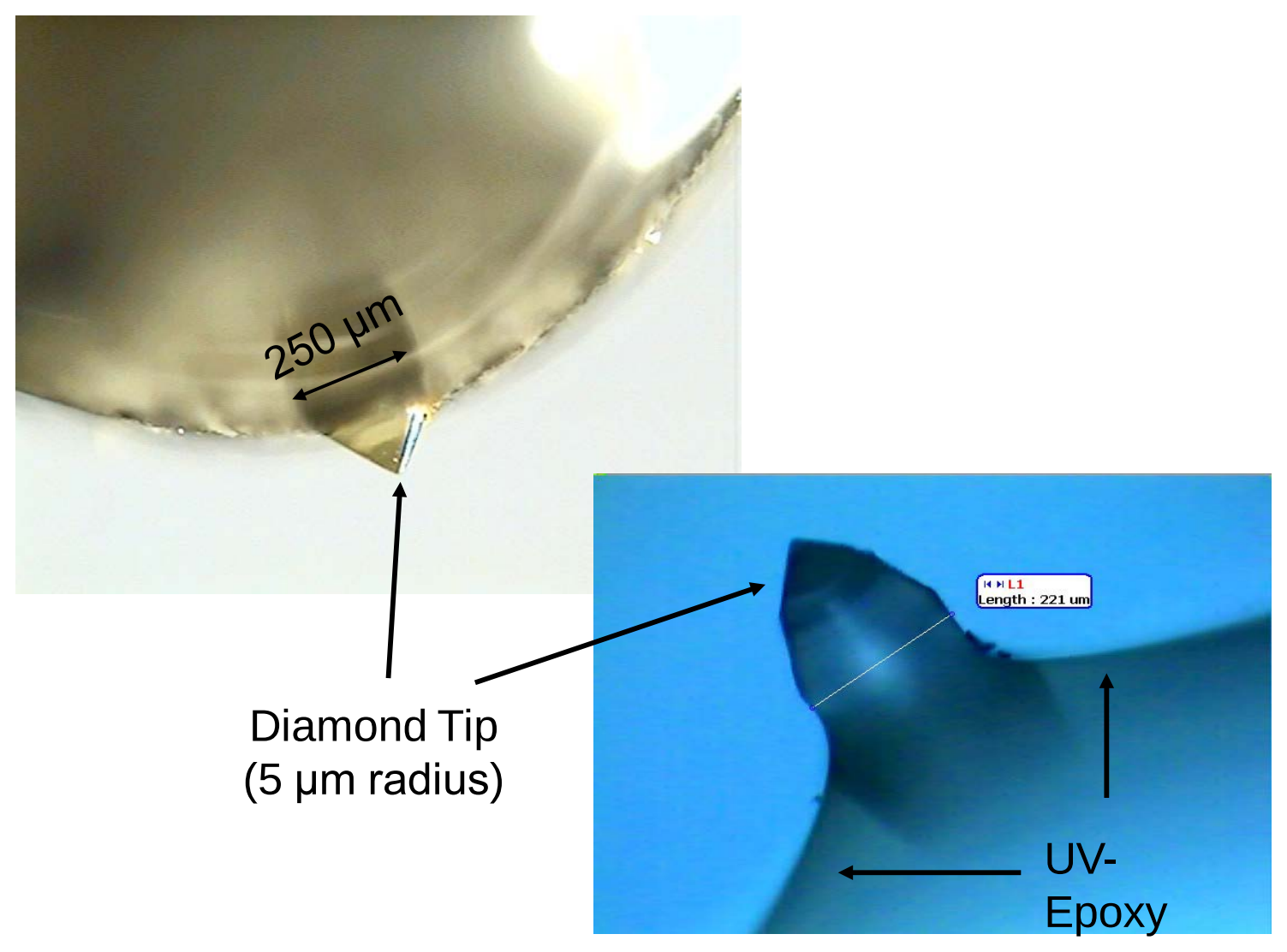


FIGURE 4. CLOSE UP ON DIAMOND TIP EMBEDDED IN THE SOLIDIFIED EPOXY.

A 5μm radius single crystal diamond tip is attached to the facet of a laser ferrule using UV-cured epoxy (refer to Figures 3 and 4). The diamond tip is partially embedded in the epoxy for the laser heating experiments. The laser emerges from a 90° conical single crystal diamond tip with 5μm radius spherical end, as shown in Figure 3 and 4.

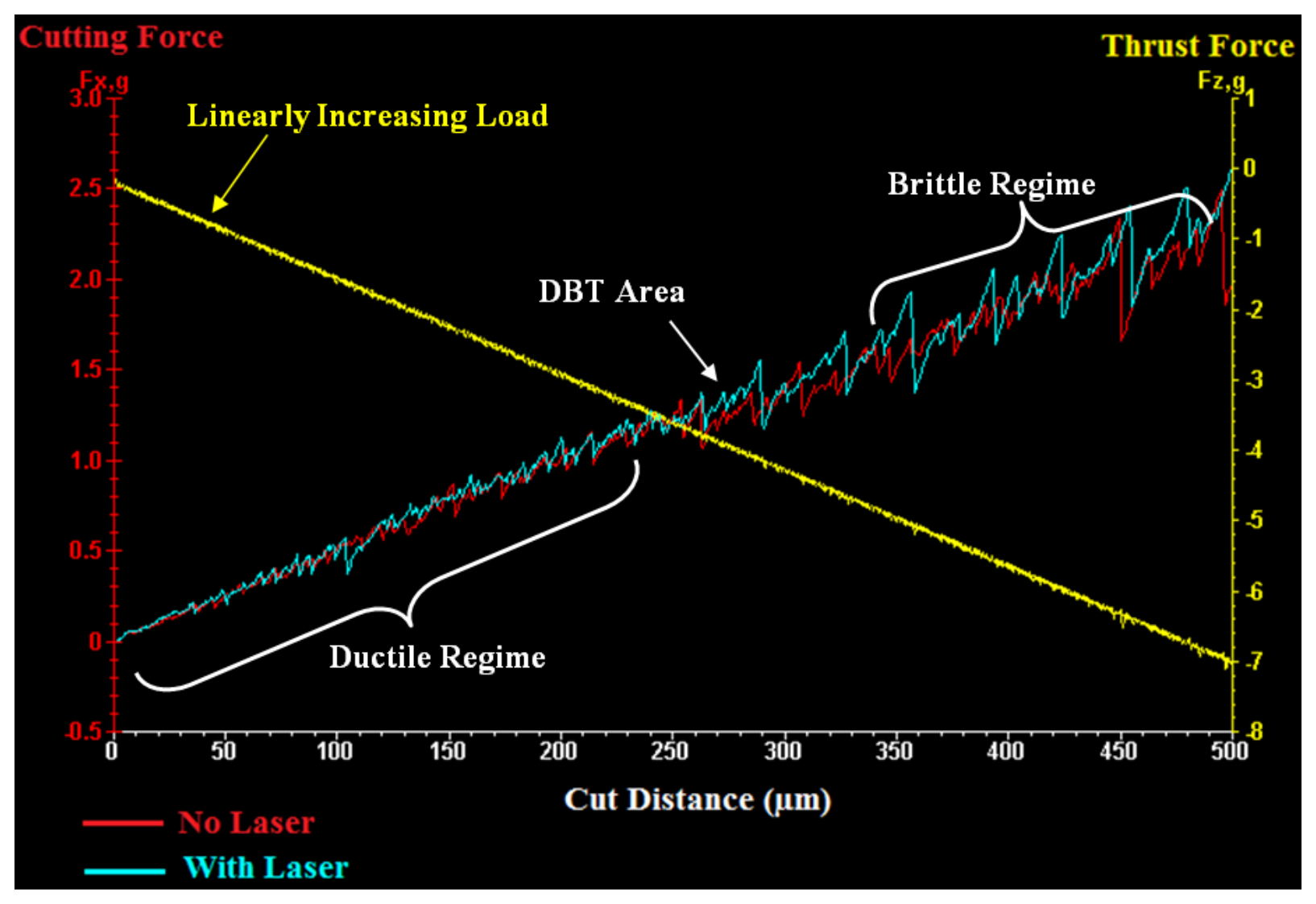
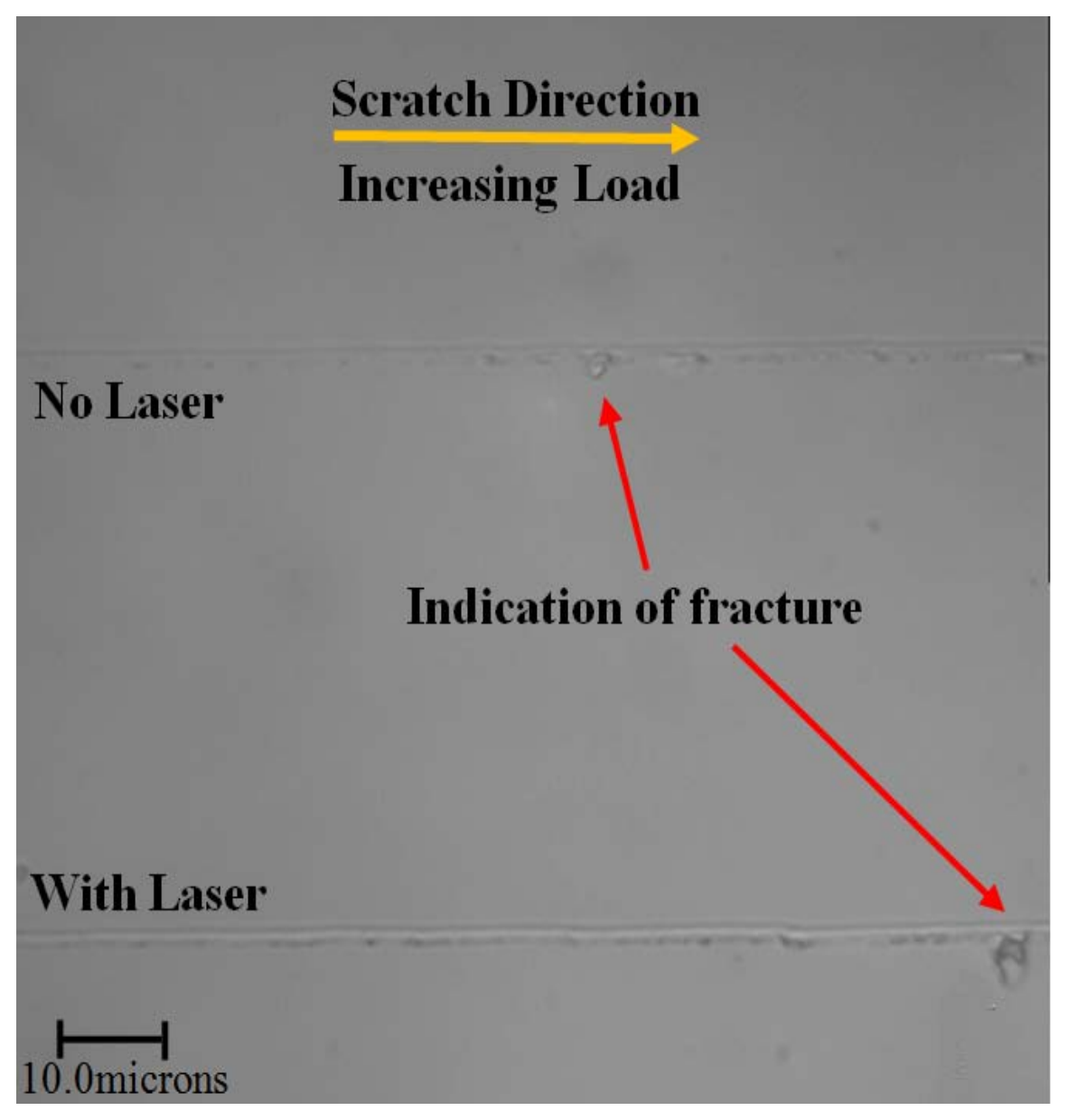


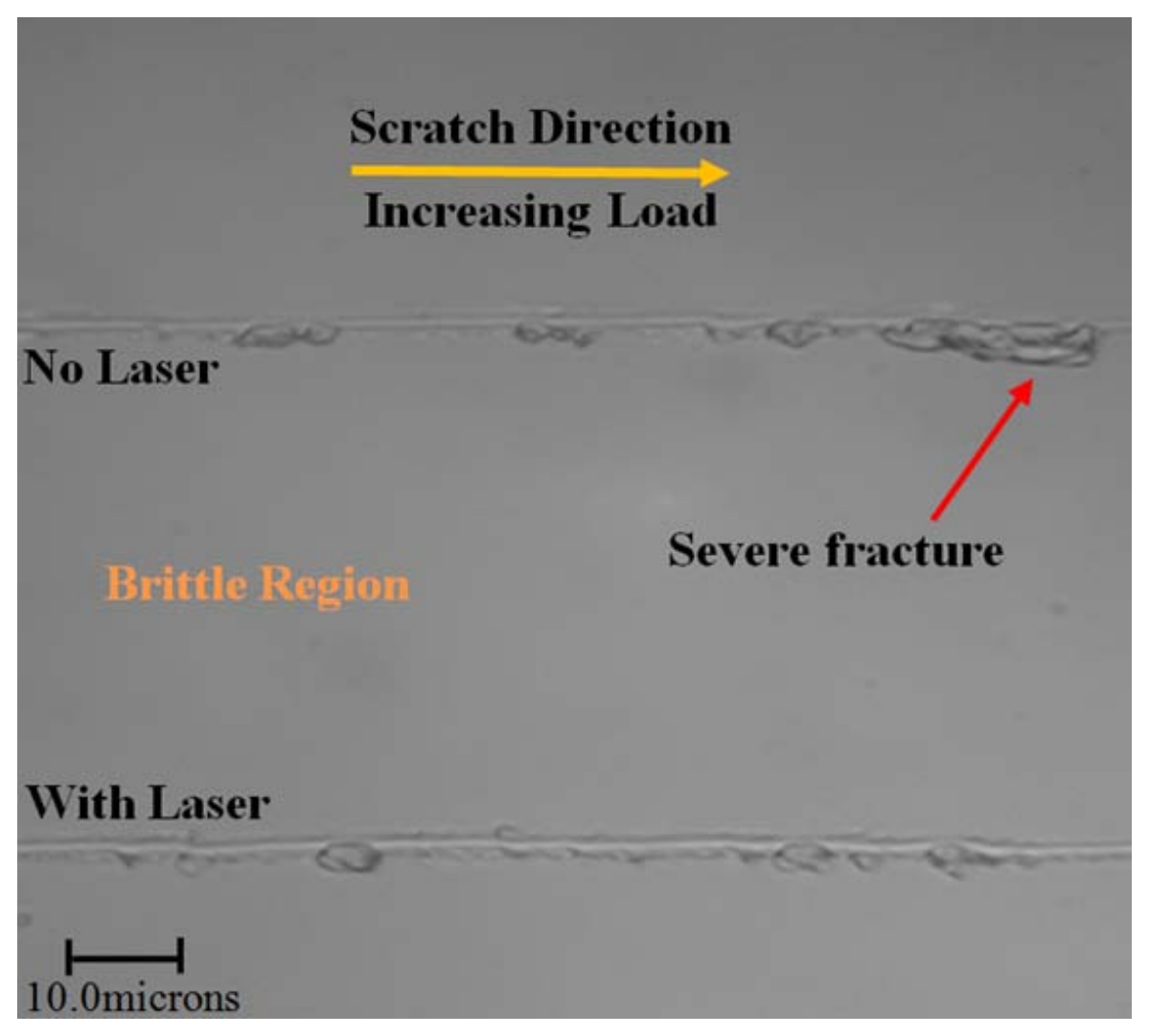
FIGURE 5. FORCE DATA FOR BOTH SCRATCH CONDITIONS

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 cutting forces as it is more sensitive towards brittle fracture) and can be identified by its instable behavior (higher standard deviation/ higher peaks-valleys in the force plots). Also, from Figure 5, it can be seen that the onset of brittle fracture is identified on the scratch performed with no laser heating. Monitoring the cutting forces during the material removal process is also an effective in-situ method to detect the onset of brittle regime machining (onset of fracture occurrence).



The onset of brittle fracture for both scratch conditions can be observed from the optical microscope image. From the image, it is evident that fracture occurs earlier (at a less load) for the scratch performed with no laser heating. The point of initial fracture can also be correlated to the force data where instability is first observed.

FIGURE 6. FRACTURE ONSET INDICATED ON BOTH SCRATCHES



The optical microscope image shows both scratch conditions in the brittle regime. Although both scratches are with the same load range, the extent of brittle fracture is much more severe for the scratch performed with no laser heating.

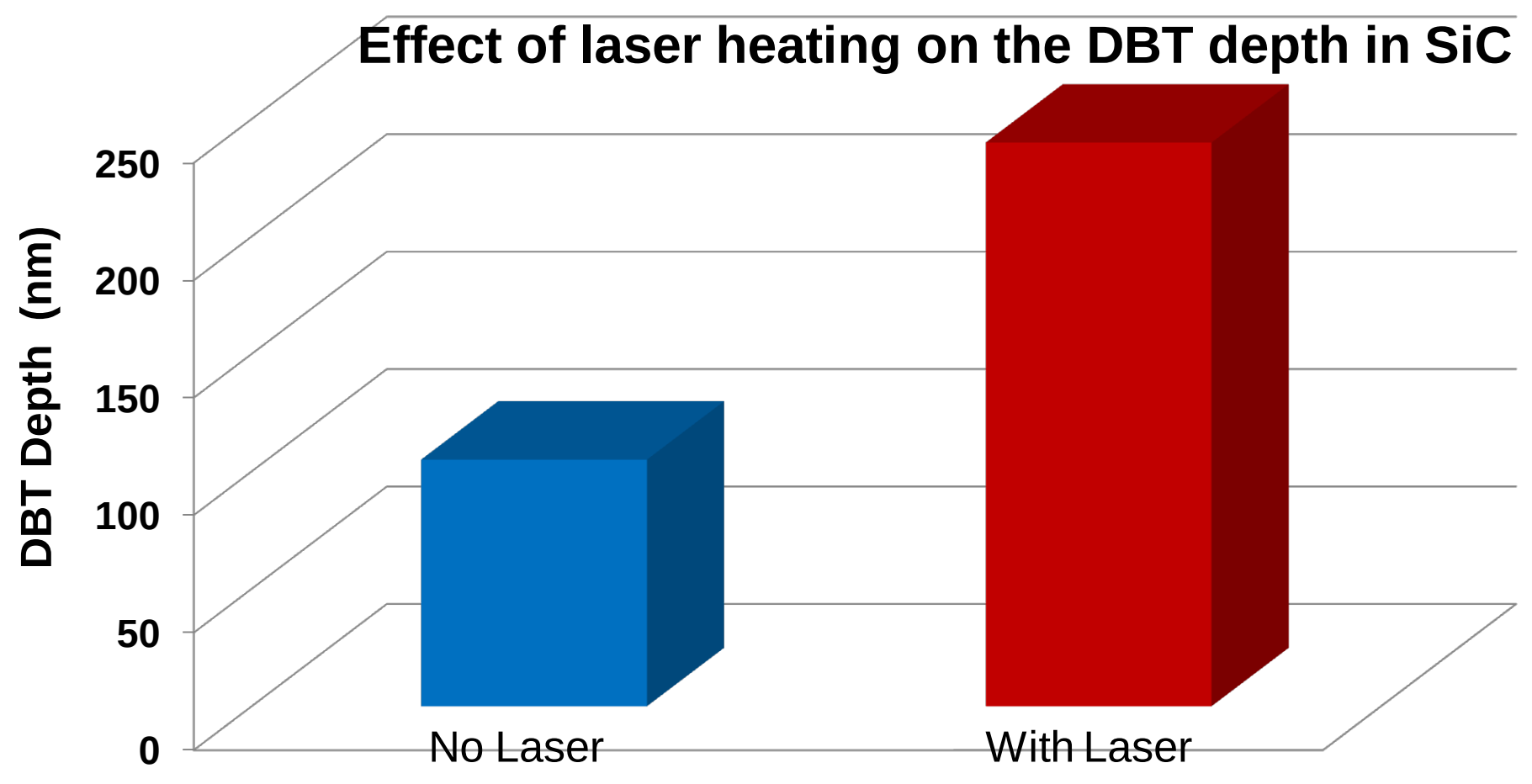
FIGURE 7. SCRATCHES INTO BRITTLE REGION AT HIGHER LOADS

For the thermal softening 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 = 30mN), 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 done at higher loads to result in a depth of 145nm will most definitely result in higher cutting forces due to the hardness of the material

TABLE 2. SCRATCH TEST RESULTS COMPARING WITH AND WITHOUT LASER HEATING.

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

Note: * Measurement taken just before the DBT occurs



The effects of laser heating on the DBT of the material was also analyzed. To determine this, two-dimensional scratch/groove profiles obtained using a white light interferometric profilometer were analyzed.

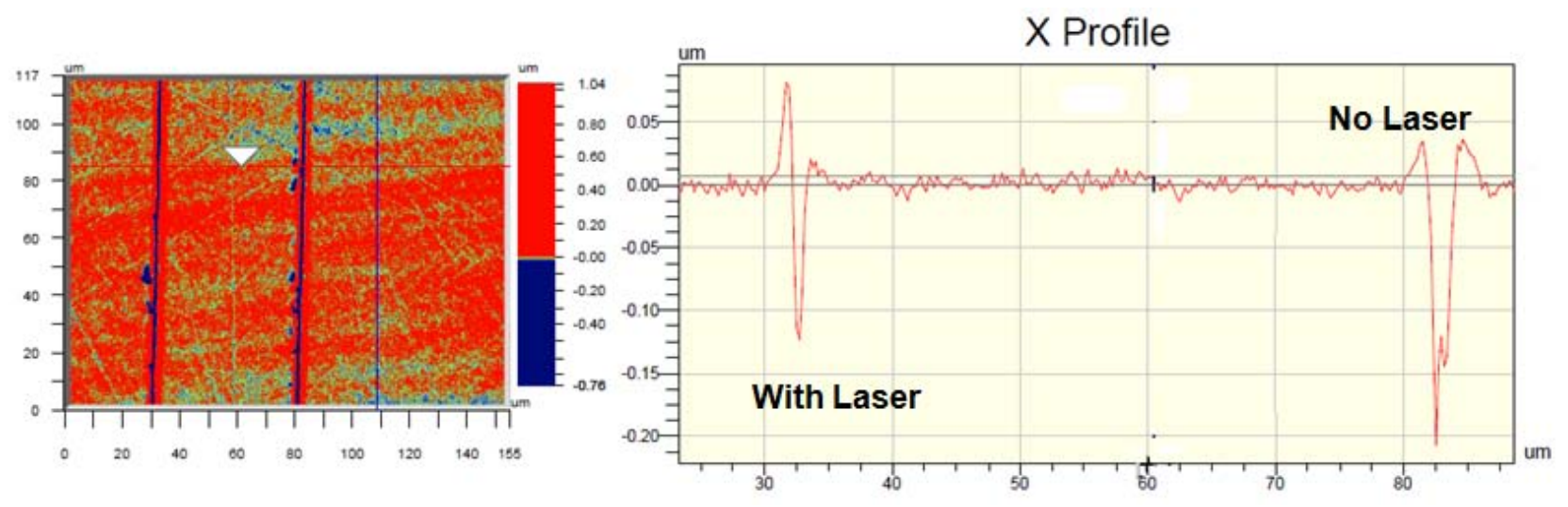


FIGURE 8. CROSS SECTION SHOWING THE ONSET OF BRITTLE BEHAVIOR FOR THE CUT WITH NO LASER

Figure 8 shows the cross-section of the two scratches taken at an equal thrust force of approximately 35mN. 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 brittle behavior is identified by the imperfect pattern of the groove edge which is a representation of the stylus imprint on the material. From Figure 8, 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 predict the depth due to fracture of the material). The clear and defined edges that depict the stylus imprint is a good indication of the ductile response of the material (as seen in the scratch performed with laser heating).

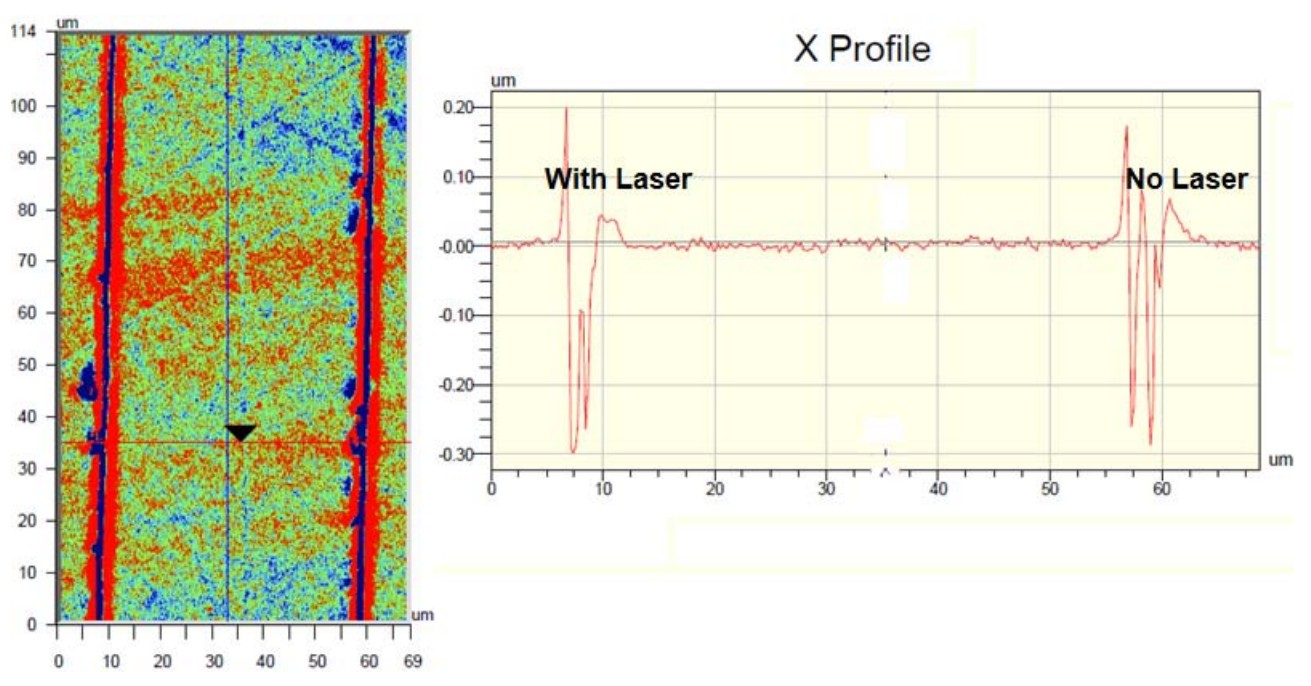


FIGURE 9. CROSS SECTION SHOWING THE ONSET OF BRITTLE BEHAVIOR FOR THE CUT WITH LASER HEATING. AT THIS POIINT SEVERE FRACTURE IS OBSERVED IN THE SCRATCH WITH NO LASER HEATING.

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 4H-Silicon Carbide in the {1010} plane along the <1010> direction. Laser assisted (heating, thermal softening and reduced brittleness) material removal resulted in 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 interferometry served as useful analysis 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 higher 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.