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

Deepak Ravindra & Bogac Poyraz
Manufacturing Research Center
Western* Michigan *University

Dr.John Patten
Director -Manufacturing Research Center
Western Michigan University

WESTERN MICHIGAN UNIVERSITY
College of Engineering and Applied Sciences

© Deepak Ravindra. All rights reserved

Presentation Overview

- Brief intro on ceramics
- Research Background
  - Concept of Ductile Regime Machining
  - Micro Laser Assisted Machining (µ-LAM)
- Research Objective
- Experimental Setup
  - Scratch Test Setup
  - Testing/Experimental Parameters
- Results & Discussion
  - Comparing scratch with and without laser
  - Summary of results
- Ongoing & Upcoming work

© Deepak Ravindra. All rights reserved

Ceramics & Semiconductors

- Advantages
  - Extreme hardness (SiC = 26GPa, Si = 12GPa)
  - High wear resistance
  - High temperature operation
  - Good optical properties (large range)
  - Light weight

- Disadvantages
  - Extreme hardness (SiC = 26GPa, Si = 12GPa)
  - Low fracture toughness (Si ≈1 Mpa.m$^{0.5}$) – poor machinability
  - Extremely abrasive – results in significant tool wear

Motivation

- Increasing industrial demand in high quality, mirror-like and optically smooth surfaces
- High machining cost and long machining time of semiconductors and ceramics
- Reduce the tool wear generated when machining abrasive ceramics
- Reduce the cost in precision machining of hard and brittle materials (semiconductors and ceramics)

Ductile Regime Machining

- Plastic flow of material in the form of severely sheared machining chips occur

- Possible due to High Pressure Phase Transformation (HPPT) or direct amorphization

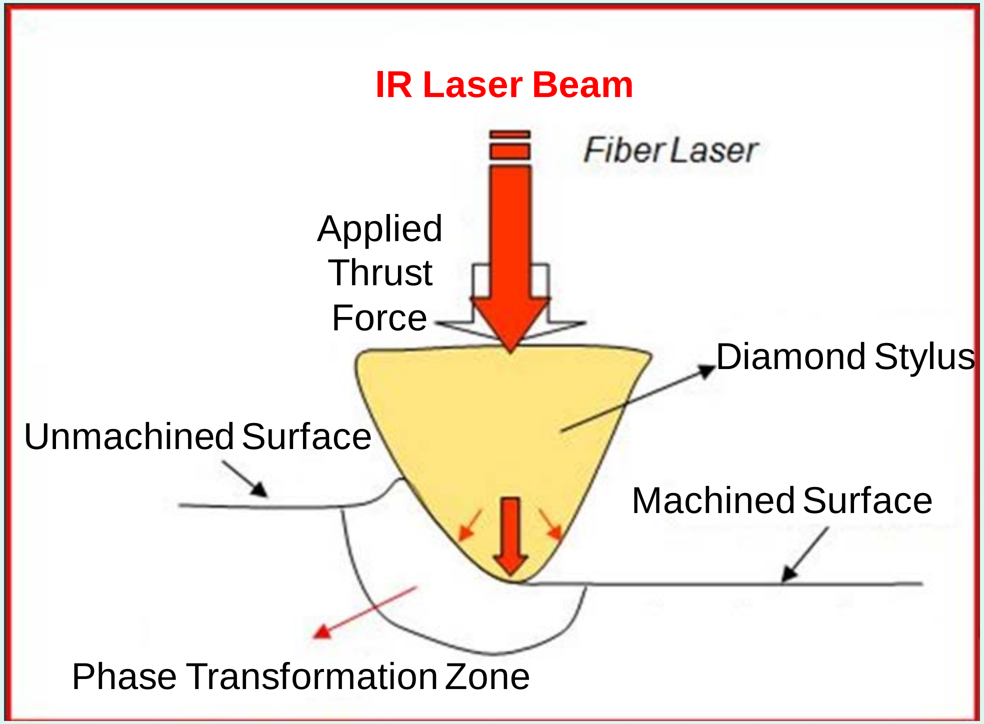
- Plastic deformation caused from highly localized contact pressure and shear stresses.

- Due to size effect, it happens at a relatively small depth

- High pressure (metallic) phase could be used to improve manufacturing processes and ductile response during machining.

© Deepak Ravindra. All rights reserved

Micro Laser Assisted Machining (µ-LAM)



- laser heating is coupled along with a ductile regime material removal process
- uses a laser as a heating source to thermally soften nominally hard and brittle materials (such as ceramics and semiconductors)
- the laser source preferentially heats the high pressure zone enhancing the ductile response of the material

Research Objective

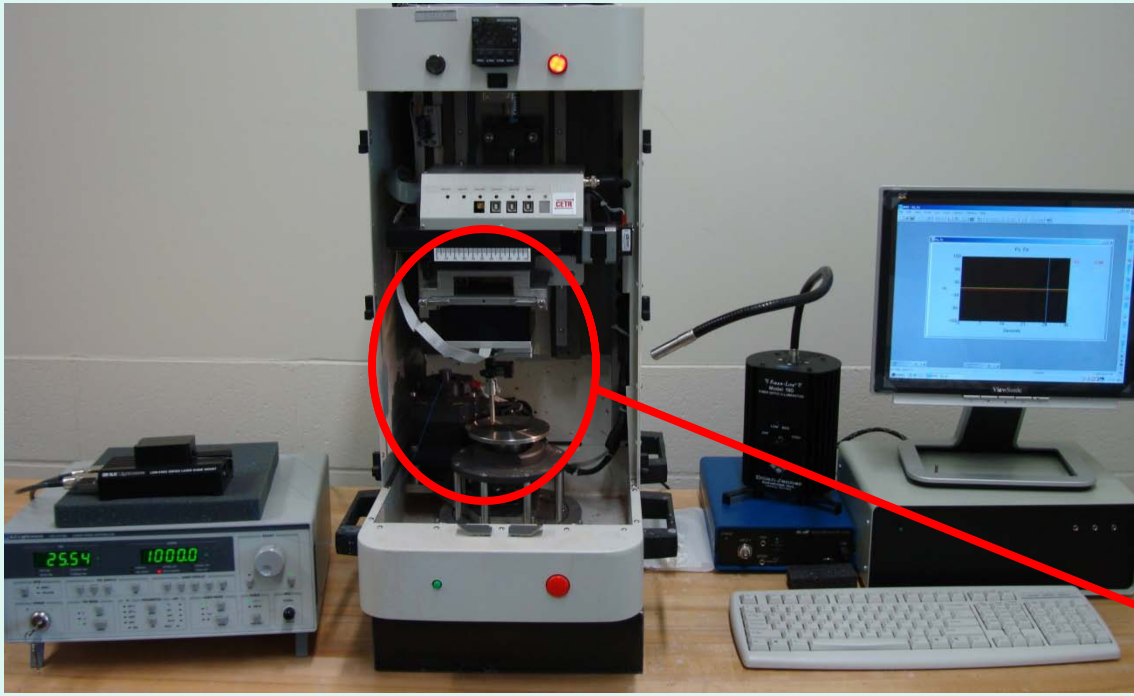
- The main objective is to study the effect of laser heating on the ductile to brittle transition (DBT) in Silicon
- The enhanced ductile response will be studied by carrying out scratch tests with increasing loads (with and without laser heating)
- The DBT depth will be compared for both conditions
- Cutting force data will be analyzed for both conditions

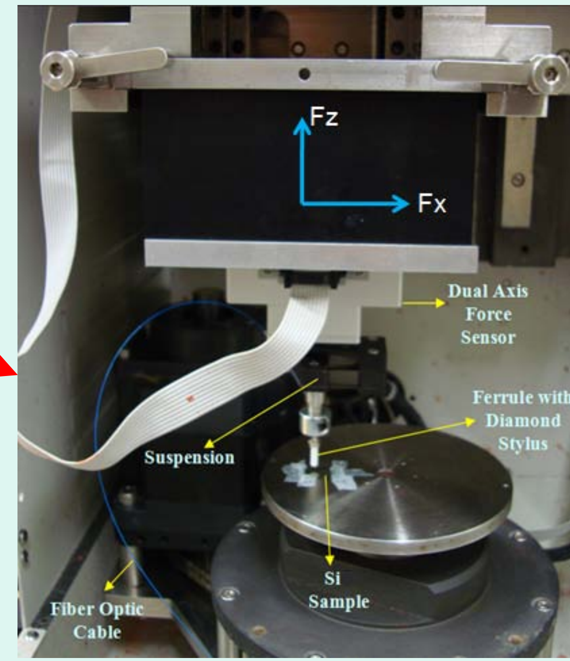
© Deepak Ravindra. All rights reserved

Scratch Test Parameters

- **Scratch Conditions** : With & without laser heating (Increasing loads, $F_z = 10 – 80mN$)
- **Cutting Speed** : 1 μm/sec
- **Scratch Length** : 500 μm
- **Cutting Stylus** : 90° conical single crystal diamond tip with 5μm radius spherical end
- **Laser Wavelength (λ)** : 1480 nm *(only applicable for the scratches w/ laser heating)*
- **Laser Power** : 350 mW *(only applicable for the scratches w/ laser heating)*
- **Workpiece** : Single Crystal Silicon Wafer
- **Crystal Plane** : {100}
- **Cutting Direction** : <110>

µ-LAM Experimental Setup

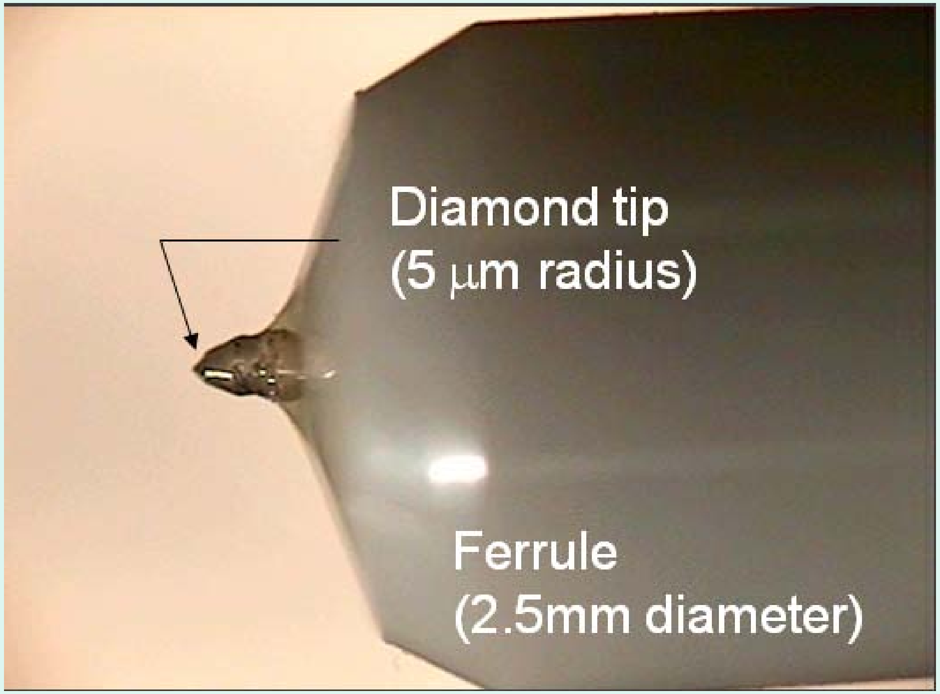




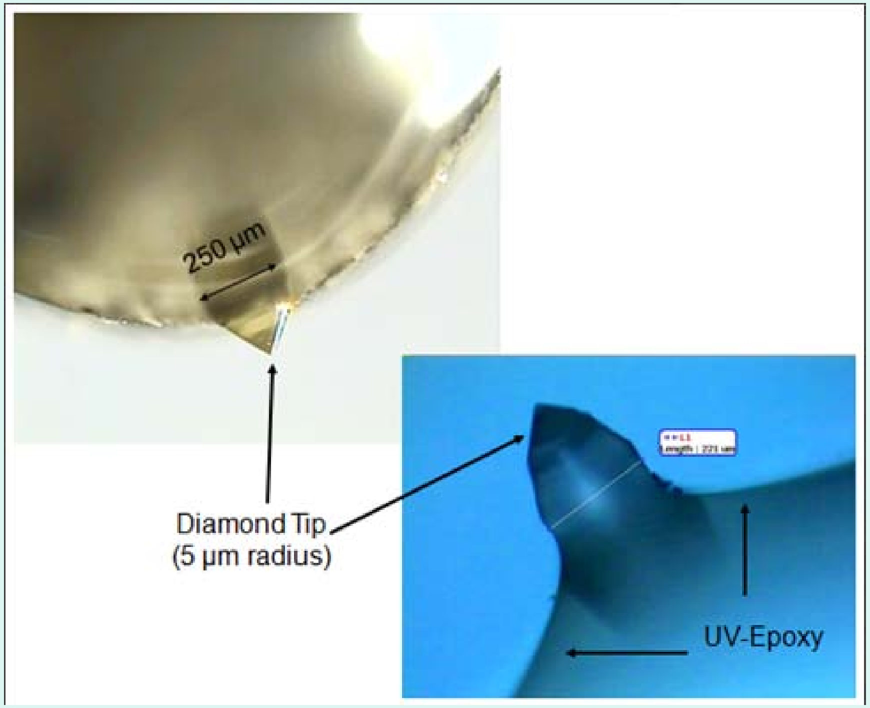
- **A 400mW IR diode laser system (Furukawa) is coupled with a Universal Microtribometer (CETR Inc.)**
- **A continuous beam with a wavelength of 1480nm was used**
- **The tribometer has a dual axis load cell, measuring cutting (Fx) and thrust forces (Fz).**

© Deepak Ravindra. All rights reserved

Diamond Tip Attachment



(a)



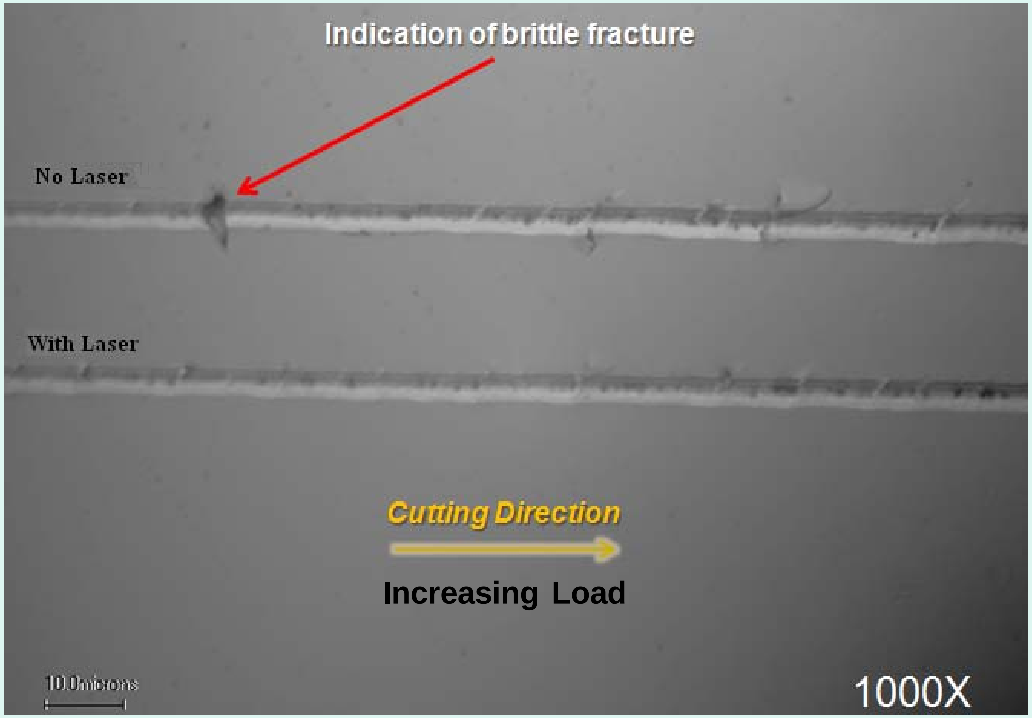
(b)

(a) 5 μm RADIUS DIAMOND TIP ATTACHED ON THE END OF THE FERRULE USING EPOXY

(b) CLOSE UP ON DIAMOND TIP EMBEDDED IN THE SOLIDIFIED EPOXY.

Optical Images of Scratches

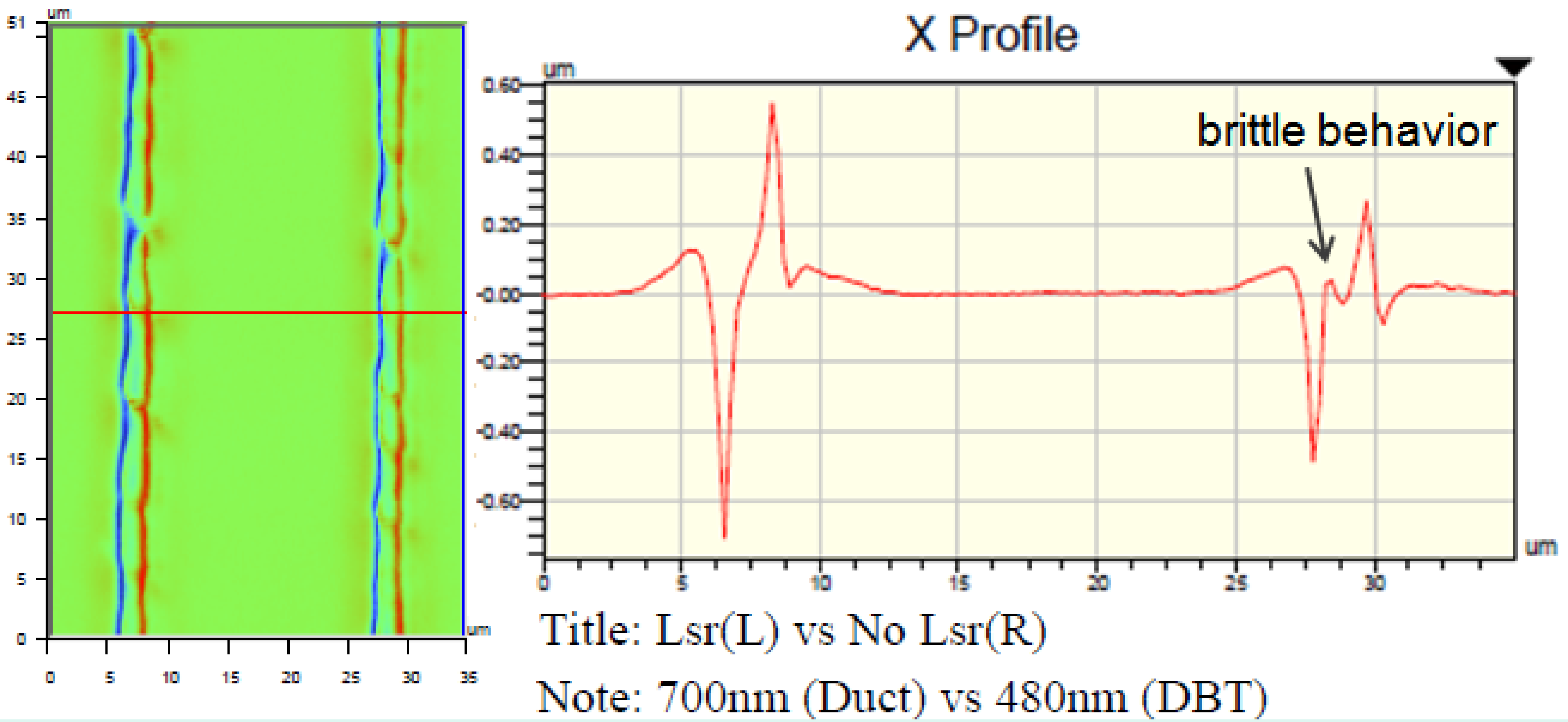
No Laser
With Laser



No Laser
With 350mW Laser

10-80 mN (1-8 g load)

Cross Sectional Evaluation

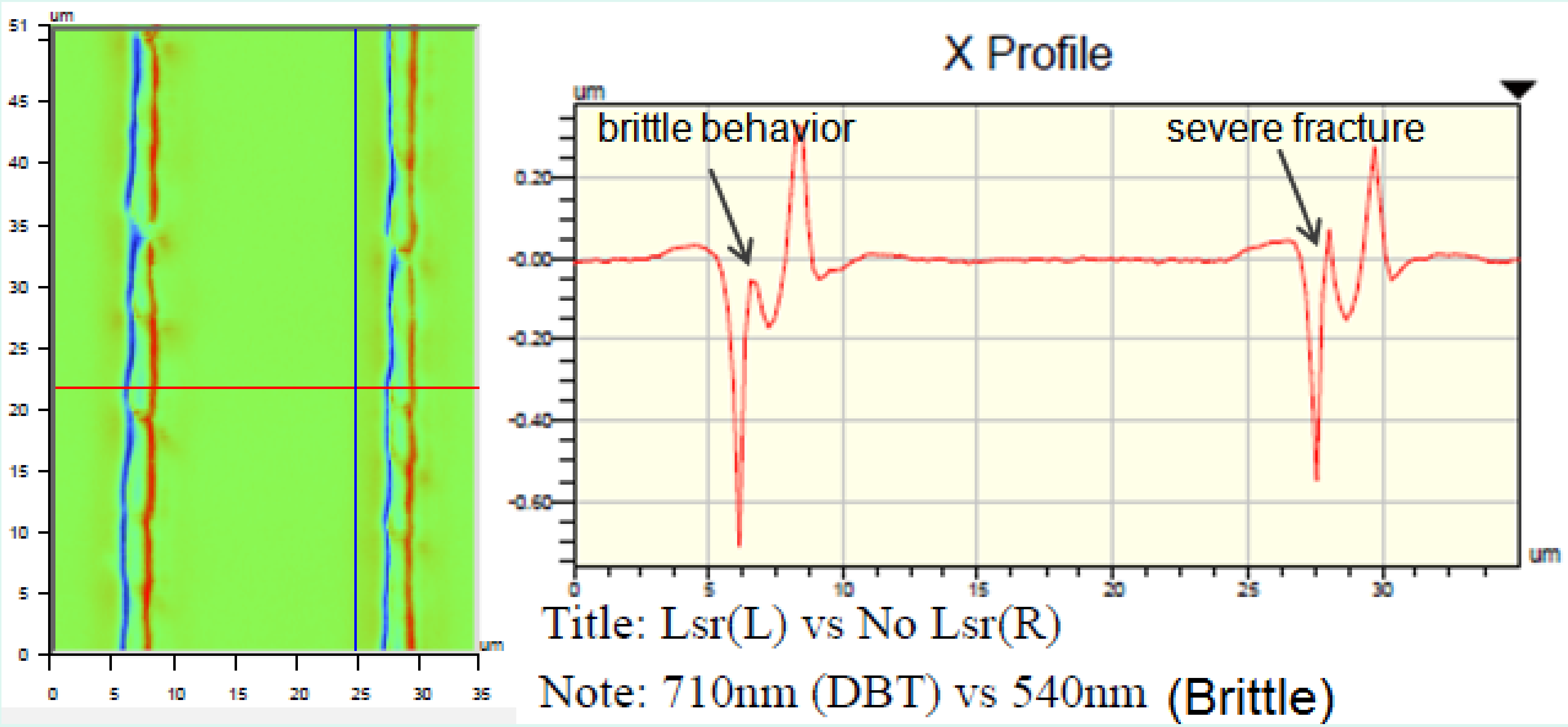


- Cross sections were evaluated using a white light interferometer
- The DBT of the scratch performed without laser heating is identified
- Peaks to the right of each scratch indicates material built up

3-D Scratch Profiles

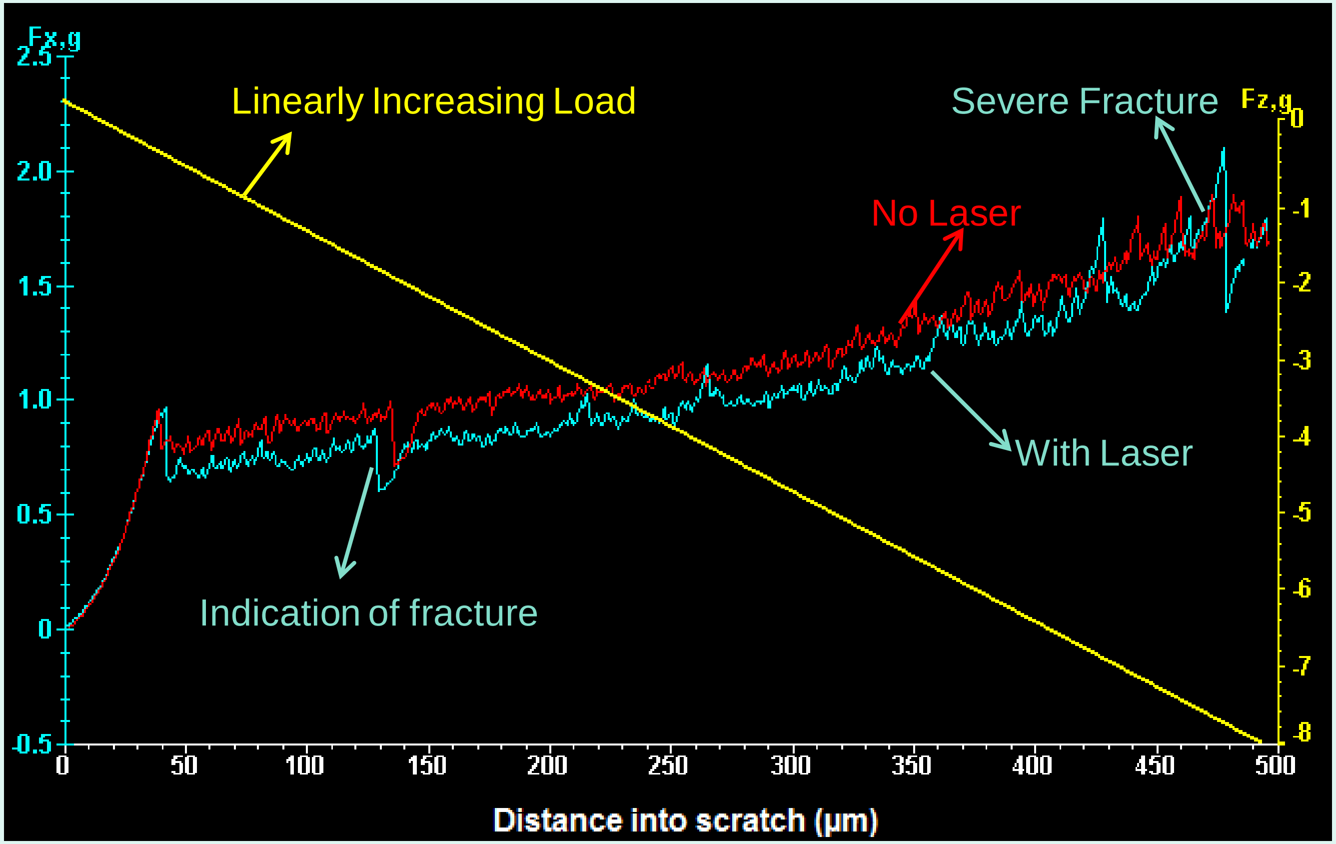
- Well defined groove edges seen in the scratch done with laser heating is a good indication of ductile response
- The tool/stylus imprint is not well defined in the groove seen in the scratch without laser heating.

Cross Sectional Evaluation



- The DBT of the scratch performed with laser heating is identified
- At this point, the scratch carried out without laser heating shows signs of severe fracture
- The DBT depth of the scratch performed with laser heating was approximately 230nm greater than without laser

Force Data



- Initial fracture occurrence
  - No Laser: Fz = 35mN, Fx = 9mN (480nm depth)
  - With Laser: Fz = 42mN, Fx = 8mN (710nm depth)

Scratch Test Results Summary

Machining Condition	**Thrust Force (mN)**	**Cutting Force (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	42	8.0*	710	DBT

***Just before the DBT occurs.**

© Deepak Ravindra. All rights reserved

Conclusion

- μ-LAM scratch tests were successful in demonstrating the enhanced thermal softening of the material, resulting in a greater DBT depth and an apparent increase in fracture toughness.
- The DBT depth of single crystal Si increased from 480nm to 710nm in the {100} plane along the <110> cutting direction.
- The enhanced ductile response is promising to increase the material removal rate in machining processes such as single point diamond turning.
- Lesser tool wear is predicted due to the enhanced thermal softening of the material and lower cutting forces during the material removal process.
- Better product quality (improved surface finish) and lesser machining time is anticipated due to the decrease in brittle response in the material.

Future/Ongoing Developments

- The effects of laser heating on the DBT of the following materials:
  - Silicon Carbide
    - 4H Single Crystal
    - 6H Single Crystal
    - 3C Polycrystalline (CVD)
  - Quartz (Fused Silica)
  - Spinel ($MgAl_2O_4$)
  - AlTiC
  - Sapphire (synthetic)
  - AlON

- Micro Laser Assisted Machining (µLAM) coupled with Single Point Diamond Turning (SPDT)
  - Study the effect of heating (from laser)/softening of material when combined with SPDT
  - Evaluate fracture toughness and brittleness due to DBT as a result of thermal softening
  - Improve surface finish of ceramics & semiconductors via ductile mode machining
  - Minimize diamond tool wear as hardness of material is reduced

© Deepak Ravindra. All rights reserved

Thank you

Questions?

© Deepak Ravindra. All rights reserved

Energy (Specific & Mechanical)

Table.3 Specific energy, *S.E*, and relative calculated hardness, *H*, of the 90 nm and 95 nm deep scratches w/ and w/o laser; respectively, and cutting speed of 1 μm/sec

Scratch No.	Machining condition	S.E Specific energy (J/mm^3)	H Hardness (GPa)
1	w/Laser	60	18
3	No Laser	174	40

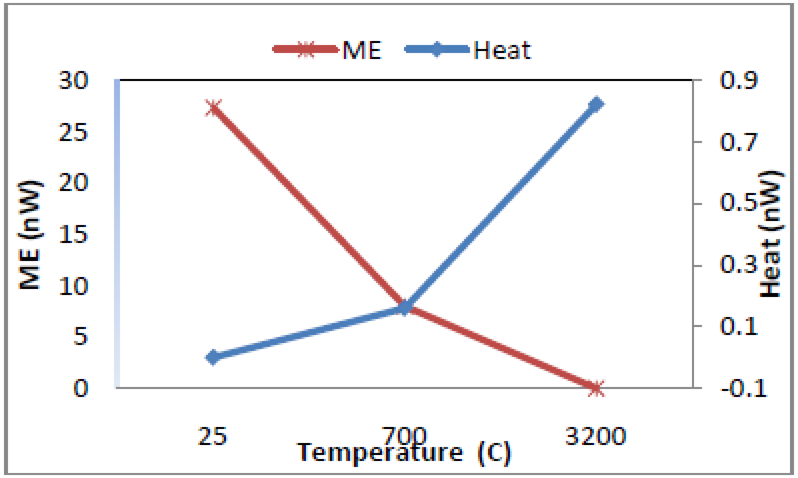


Figure.8 Plot of mechanical energy "ME" and heat vs. temperature