Award--0757339

Contributions within Discipline

How have your findings, techniques you developed or extended, or other products from your project *contributed to the principal disciplinary field(s) of the project*? Please enter or update as appropriate.

A CETR UMT Tribometer machine is modified to facilitate micro laser assisted machining (µ-LAM) process. This demonstrates a method of building a µ-LAM system using a simple commercial system.

The indentation and scratch tests were carried out on two materials, Si and SiC using µ-LAM process using the system built in the laboratory. While Silicon is irreplaceable in microelectronics, the significance of the possible applications for SiC in high temperature electronics and applied optics were the key reasons for the selection of these materials. Atomic Force Microscopy (AFM) and the white-light interferometry were used to determine the profiles of the scratches. This clearly shows the ductile regime nanomachining of these two important semiconductors.

In a separate study, the effect of laser heating on the mechanical properties of specimens especially the hardness of the indentations and scratches was determined. These studies proven the fact that the laser softens the material and help to achieve deeper grooves. There was almost 40% reduction in hardness, while using the laser heating. It was noted that the thrust force is constant, while the cutting force has been reduced for a particular depth of cut. This greatly reduced the cutting tool wear and improved the surface roughness. These results will be presented in the NAMRI/SME's NAMRC 37 conference, May 2009 in Greenville, SC, and International MSEC 2009 conference in West Lafayette, IN.

The major contributions of these studies lie in the ductile regime machining of the semiconductors and using highly focused laser beams to achieve heating and thermal softening.

Contributions to Other Disciplines

How have your findings, techniques you developed or extended, or other products from your project contributed to disciplines other than your own (or disciplines of colleagues and associates not covered under "Contributions within Discipline")? Please enter or update as appropriate.

The optical properties of the semiconductors at atmospheric pressure were studied to determine the effect of laser heating and pressure (during machining). The understanding of variation of optical properties of materials like silicon carbide and silicon at ultra-high pressure and high temperatures (by laser heating) is of interest to physicists and geologists. As it requires synchrotron radiation, we submitted a research proposal to Advanced Photon Source (APS) through a general user proposal system, which has been recently approved after peer review process. These experiments will be conducted in August 2009 at APS in Chicago, IL

The optical alignment of the laser through the cutting diamond tool is under investigation and it is a promising tool to control the amount of heating energy needed in the specified cutting region. It also improves the efficiency of laser heating while using medium power and continuous wave laser compared to laser ablation methods. These results will be presented in a paper at the MSEC Conference, Oct. 2009 in West Lafayette, IN.

Investigation of methods to reduce the back reflection of laser beam from cutting surface of the diamond tool has also been performed during this period. The team has worked on a customized anti-reflection (AR) coating, which initially has shown that it is possible to reduce the laser beam back reflection up to 20%.

The ongoing work on µ-LAM machining will contribute to eventual manufacturing of these high temperature high power semiconductor (SiC) devices used in wind turbines and hybrid vehicles.

Contributions to Human Resource Development

How have results from your project contributed to human resource development in science, engineering, and technology? Please enter or update as appropriate.

- Training Engineering students to use the UMT tribometer, Wyko optical profiler, and atomic force microscope (AFM)

- Training students to use the software packages to simulate the machining processes semiconductors

- Training students on optical alignment and beam profiling techniques

- Training Engineers and technicians on the design and assembly of optical components in Namiki, Japan

Contributions to Resources for Research and Education

How have results from your project contributed to physical, institutional, and information resources for research and education (beyond producing specific products reported elsewhere)? Please enter or update as appropriate.

The research on thermal paints to determine the surface temperature of semiconductor

Studying the semiconductors by XRD to get the orientation distribution function (ODF) and pole figures, and getting orientation imaging microscopy (OIM) to determine the preferred cutting orientation in the single crystal semiconductors

Characterization of phase transformations of Si and SiC using micro Raman spectroscopy before and after the machining operation (over very small selected regions).

Analysis of the machined surface for any undersurface damage using acoustic emission microscopy.

Study, analysis and tabulation of important optical and mechanical properties of the silicon carbide polytypes

Proposed work at ANL/APS to study laser heating in a diamond anvil cell will result in new knowledge and understanding about the high temperature-high pressure behavior of SiC; this information will be useful for our research program to document the behavior of SiC under these extreme conditions (P&T)

Contributions Beyond Science and Engineering

How have results from your project contributed to the public welfare beyond science and engineering (e.g., by inspiring commercialized technology or informing regulatory policy)? Please enter or update as appropriate.

Supporting 3 doctoral students and 1 Masters student to carry on with their path of excellence in pedagogical path; informing the community of the environmental issues and providing improved manufacturing routes for SiC based high power and high temperature electronic devices used in wind turbines and hybrid vehicles

Outreach Activities

What **outreach activities** have you undertaken to increase public understanding of, and participation in, science and technology?

To provide public awareness on the importance of renewable energy usage and the value of green energy technologies that incorporate high temperature/high power electronic components made from SiC.

Presentation of the µ-LAM machining process by Dr. John Patten in East Lansing, MI (date, time and the title of the talk)

Presentation of the recent research results at the Department of Manufacturing, Purdue University, (date, time and title of the talk)

Presentation at Hannover University (Germany) about the project (April 30, 2009), provides for international exposure of work.

Training and Development

What **research and teaching skills and experience** has the project helped provide to those who worked on the project?

- Training students to use the tribometer, metrology and optics lab devices
- Training students to use the software packages for simulation of the semiconductors machining process
- 3 Ph.D, 1 Masters 1 Undergraduate and 1REU students are currently being trained on various aspects of this project.

Project Activities and Findings

(1) What have been your major **research and education activities (experiments, observations**, simulations, presentations, etc.)?

Part A. Research activities:

A.1. Experiments and Observations:

1. Pressure and temperature effects in micro-laser assisted machining (μ-LAM) of silicon carbide (4H-SiC)

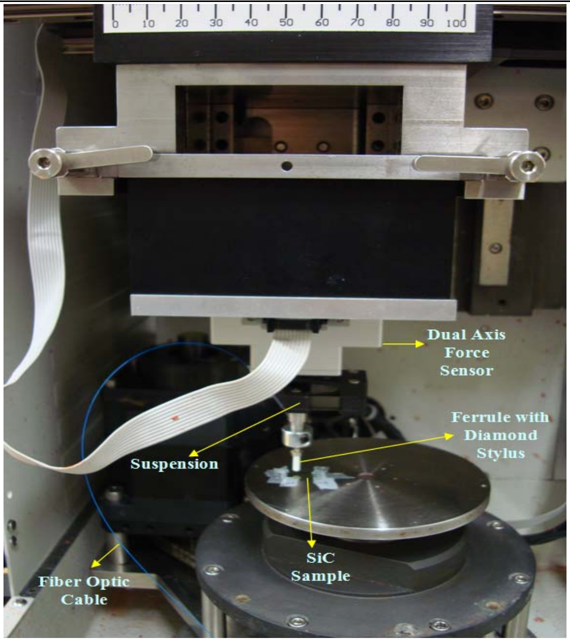
These investigations were focused on understanding the

- The effect of loading with and without laser heating at various cutting speeds
- The effect of laser preheat before applying any load

Details of the experimental conditions for different scratch tests:

Scratch No.	Loading g (mN)	Machining Condition	Cutting speed (μm/sec)	Laser Power (mW)
*1**	*2.5 (25)*	*w/o laser*	*305*	*0*
*2**	*2.5 (25)*	*w/ laser*	*305*	*350*
3	2.5 (25)	w/o laser	1	0
4	2.5 (25)	w/ laser	1	350

Figures 1 and 2 show the picture of experimental set-up used in the scratch tests and schematic configuration of the diamond tool and substrate surface respectively.



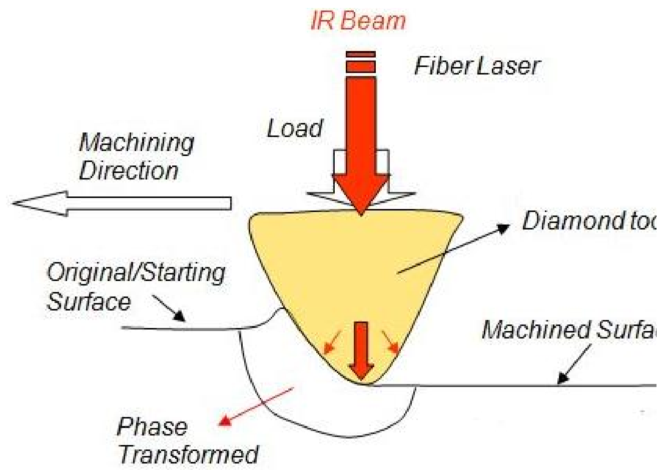
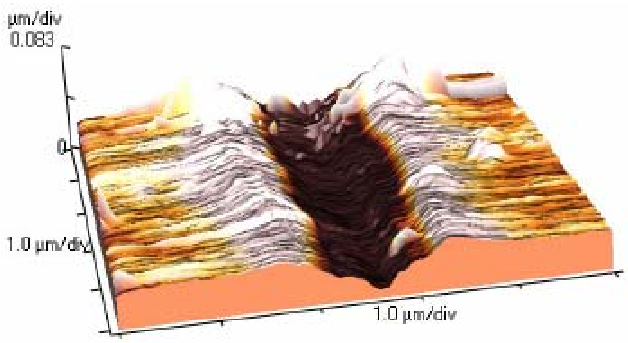


Figure 1 μ-LAM system used in experiements Figure 2. Schematic cross-section of μ-LAM

- Results of Experiments: The test scratches profiles were analyzed using AFM. Following figures 3 and 4 show the AFM images of the scratches made without and with laser heating respectively.



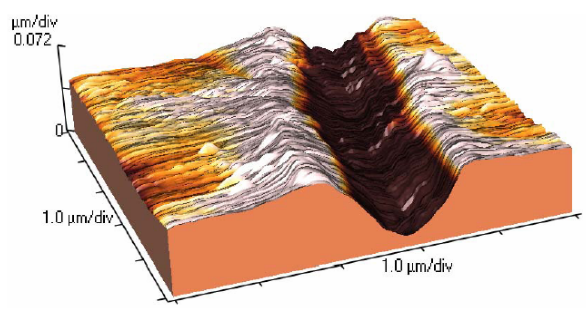


Figure 3. AFM image of the scratch without laser heating

Figure 4. AFM image of the scratch with laser heating

(Both scratches were carried out at 25 mN load, with a scratch speed of 1 μm/s speed)

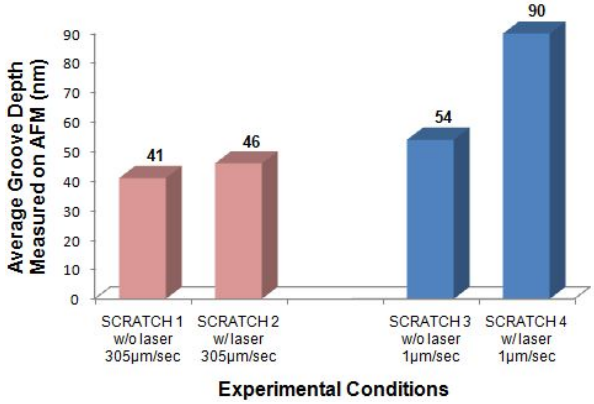


Figure 5. Average groove depth measured with AFM in (nm) at two different speeds and w/ and w/o laser heating

Conclusion:

Effect of laser heating is successfully demonstrated as evidenced by the significant increase in groove depth. Reduced hardness is indicative of enhanced thermal softening. AFM measurements of the laser-heat assisted scratch grooves show deeper and wider grooves as compared to scratches made without the laser heating assisted methods.

2. Force analysis, mechanical energy and laser heating evaluation of scratch tests on silicon carbide (4H-SiC) in micro-laser assisted machining (μ-LAM) process

- Force analysis was carried out to understand the laser heating effect on the cutting forces and the measured depth of cut.

-Evaluated the mechanical work, specific energy, and determined the effect of laser heating on the cutting process.

Details of experimental parameters for the scratches made on the 4H-SiC:

Scratch No.	Loading (mN)	Machining condition	Cutting speed (μm/sec)	Laser power (mW)
1	25	w/Laser	1	350
2	25	No Laser	1	0
3	50	No Laser	1	0
4	70	No Laser	1	0

Results: AFM and Optical profiler were used to measure groove depth profiles. Figure.6 shows the profile of a scratch made with laser.

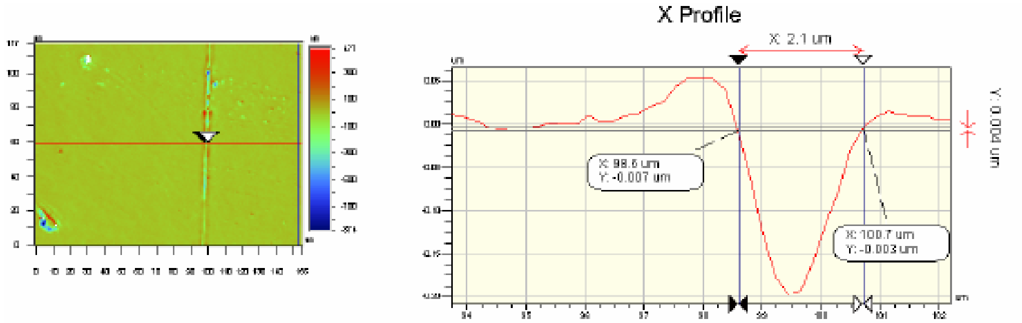


Figure 6. Wyko optical interferometer profile of the scratch w/ laser

Force and groove parameters for scratches on 4H-SiC at cutting speed of 1μm/sec

Scratch No.	Machining condition	Fn Thrust Force (mN)	Fc Cutting Force (mN)	dc Depth of cut (nm)	w Width of scratch (μm)
1	w/Laser	25	8.0	90	1.9
2	No Laser	25	7.5	55	1.1
3	No Laser	50	16.4	70	1.5
4	No Laser	70	27.3	95	1.7

The variation of mechanical enegy with laser heating is shown in figure. 7. Our calculations showed that increasing the temperature of the 4H-SiC to its melting point resulted in lowering the required amount of mechanical energy, which reaches zero at around 3000°C and required heat increases to almost 1nW.

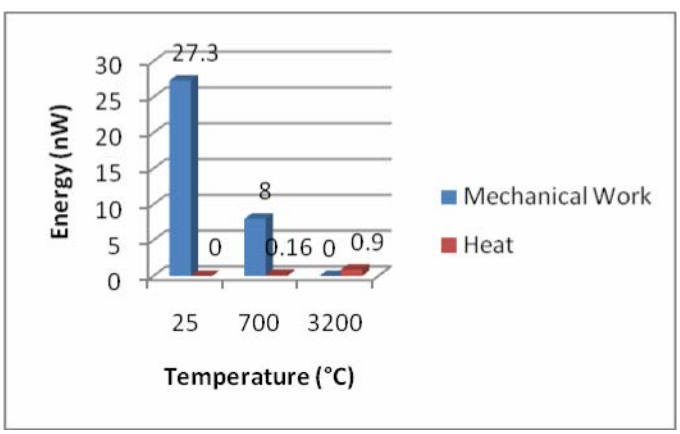


Figure 7. Plot of mechanical energy and heat versus temperature

Conclusion:

Laser heating was successfully demonstrated as evidenced by the significant increase in groove depth, i.e., reduced hardness, indicative of enhanced thermal softening. AFM and optical profiler measurements of the laser-heat assisted scratch grooves showed deeper and wider grooves compared to scratches made without the laser heating assisted methods.

A.2. Simulation Results:

1. Numerical simulations and analysis of the thermal effects on silicon carbide during micro-laser assisted machining

Simulation studies were performed using AdvantEdge software from Third Wave Systems. Initially, thermal softening curve is plotted from the results reported in the literature. Mechanical properties of SiC were also compiled as shown in Table below.

Thermal softening behavior: This curve is plotted based on the values reported in the literature. It starts at 2000°C as shown in figure. 8.

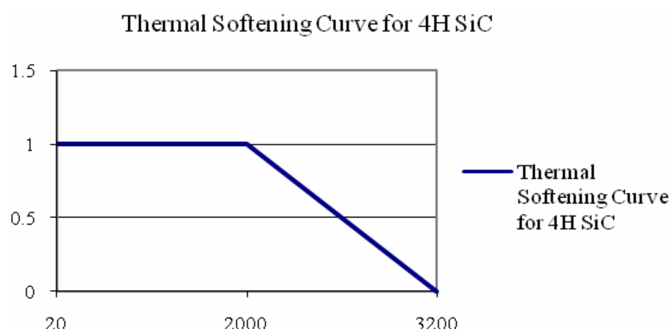


Figure 8. Thermal softening curve for 4H-SiC

Important material properties of SiC:

Material properties	Value	Units
Elastic Modulus, E	330	GPa
Poisson's ratio	0.212	-
Hardness, H	26	GPa
Initial yield stress, σ_0	16.25	GPa
Reference plastic strain, ε_0^p	σ_0/E	-
Accumulated plastic strain, ε^p	1	-
Strain hardening exponent, n	50	-
Low strain rate sensitivity exponent, m1	100	-
High strain rate sensitivity exponent, m2	100	-
Threshold strain rate, $\dot{\varepsilon}_t^p$	1E7	sec^{-1}

Figure.9 shows the workpiece and tool configuration modeled in the simulation.

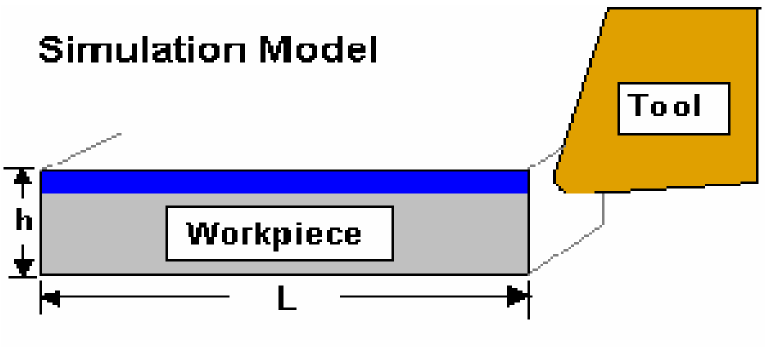


Figure 9. Simulation model

Simulation Results for the micro-LAM machining process:

Figures. 10 to 14 depicts the simulation results especially with respect to chip formation at different temperatures from 20°C to 3100°C. These clearly depict the differences in chip formation, as temperatures are increased.

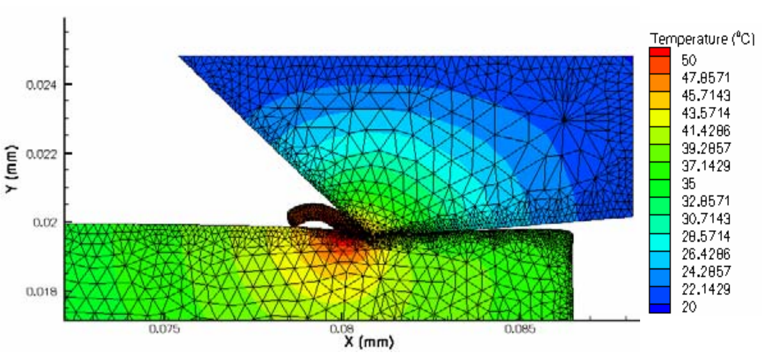


Figure 10. Simulation results at 20°C

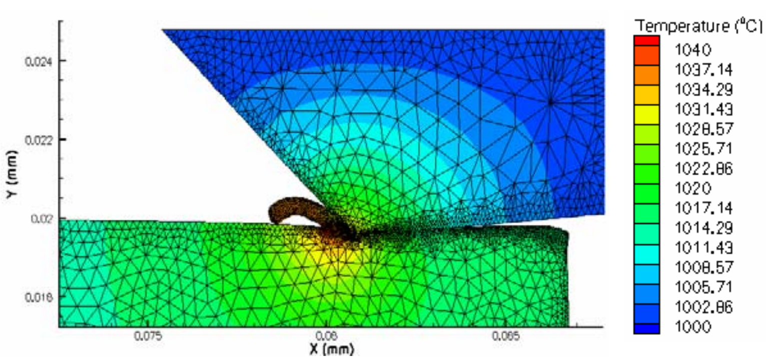


Figure 11. Simulation results at 1000°C

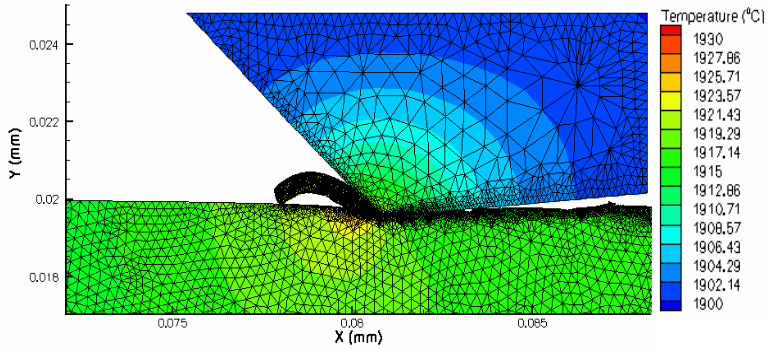


Figure 12. Simulation results at 1900°C

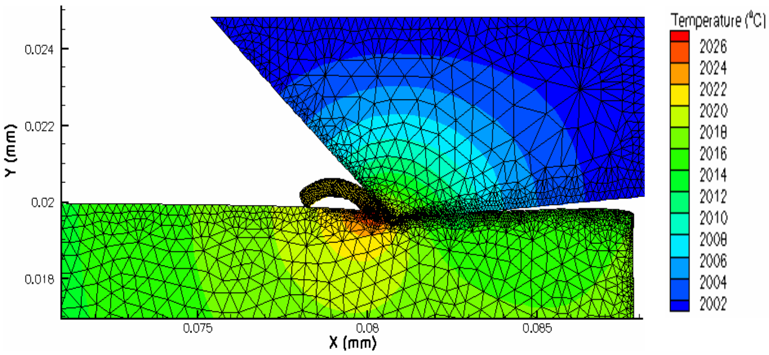


Figure 13. Simulation results at 2000°C

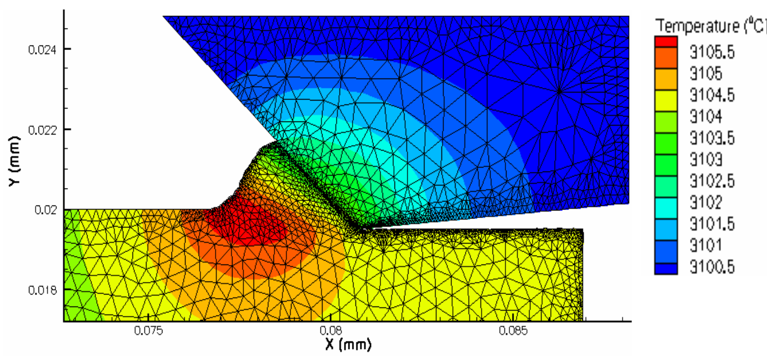


Figure 14. Simulation results at 3100°C

Figures. 15 and 16 are depicting the variation of forces and energy as shown below. The cutting forces and consequently the energy required for cutting also point to the fact that the thermal softening process start to occur at around 2000^{o}C. This fall rapidly as the temperature reaches the melting point.

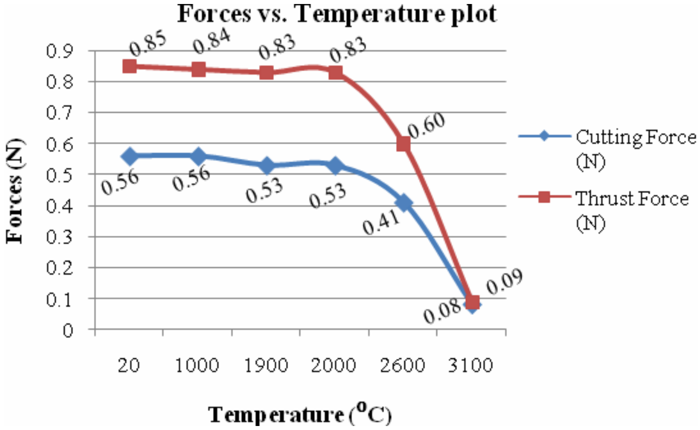


Figure 15. Plots of the cutting force and thrust force versus temperature

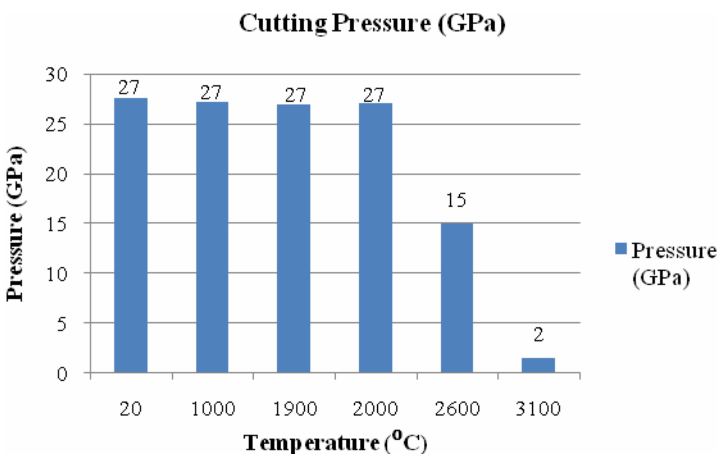


Figure 16. Plots of cutting pressure versus temperature

Conclusion:

From the summary of data it can be seen that there is considerable change in cutting and thrust forces. By comparing the simulations results, it indicates a decrease in cutting and thrust forces at 2600°C to those at 2000°C i.e. above and at the thermal softening temperature. The drop in cutting and thrust forces when the workpiece is heated above the thermal softening temperature 2000°C was significant (24% to 31%) as calculated by considering the values of the cutting and thrust forces at 2000 and 2600 °C. Below 2000°C the cutting and thrust forces remain almost constant as there is no thermal softening. The chip formation is also seen to change above the thermal softening temperature; above this temperature, the chip formation is quite ductile and hence the chip thickness also increases.

Part B. Education activities:
http://www.wmich.edu/mfe/mrc/index.php

B.1. Journal Papers:
- John A. Patten and Jerry Jacob, "Comparison between numerical simulations and experiments for single-point diamond turning of single-crystal silicon carbide", Volume 10, Issue 1, January 2008, Pages 28-33

B.2. Conference Papers and Presentations:
- Virkar S.R., Patten J.A., 2009 "Numerical simulations and analysis of the thermal effects on silicon carbide during micro-laser assisted machining", Submitted to ASME MSEC 2009 Conference West Lafayette, IN
- Patten J.A. Shayan A.R., Poyraz B.H., Ravindra D., and Ghantasala M., "Micro-Laser Assisted Machining (μ-LAM)", Submitted to the Proceedings of 2009 NSF Engineering Research and Innovation Conference, Honolulu, HI
- Shayan A.R. Poyraz B.H., Ravindra D., Patten J.A., and Ghantasala M., 2009 "Force analysis, mechanical energy and laser heating evaluation of scratch tests on silicon carbide (4H-SiC) in micro-laser assisted machining (μ-LAM) process", Submitted to ASME MSEC 2009 Conference West Lafayette, IN
-Shayan A.R., Poyraz B.H., Ravindra D., and Patten J.A., 2009 "Pressure and temperature effects in micro-laser assisted machining (μ-LAM) of silicon carbide", SME NAMRI's NAMRC 37, Greenville, SC
- Suthar K.J., Patten J.A., Dong L., and Abdel-Aal H., 2008 "Estimation of temperature distribution in silicon during micro laser assisted machining", ASME MSEC2008, Evanston, IL
- Micro-Laser Assisted Machining (μ-LAM): Scratch Tests on 4H-SiC 03/09
- Pressure and Temperature Effects in Micro-laser Assisted Machining (μ-LAM) of Silicon Carbide – 02/09
- Improving the Surface Roughness of a CVD coated SiC Disk by Performing Ductile Regime Single Point Diamond Turning by Deepak Ravindra (ASME-MSEC 2008) 10/08

B.3. Thesis and Dissertations:
- Deepak Ravindra, "Ductile-Regime Machining of Silicon Carbide and Quartz", 2008, Master's Thesis, College of Engineering and Applied Sciences, Western Michigan University, Thesis Advisor: Dr. John A. Patten

B.4. Software Simulations:
- Simulation with AdvantEdge software from Third Wave Systems

B.5. Presentations at Nanomanufacturing Group:
- OIM and XRD on SiC – Ravindra – 01/09

- μ-LAM – Depth of Cut, Width of Cut and Cutting Force Comparison – Ravindra – 11/08
- Fatigue Sensor – Gokanakonda – 10/08
- Scratch Test Results on 4H-SiC – Shayan, Poyraz – 10/08
- Laser Absorption % for Si & SiC – Shayan, Poyraz – 10/08
- Improving the Surface Roughness of a CVD Coated SiC Disk by Performing Ductile Regime Single Point Diamond Turning – Ravindra, Patten – 10/08
- Estimation of Temperature Distribution in Si during Micro Laser Assisted Machining – Suthar – 10/08

(Last) What are your major **findings** from the activities identified above?

The major finding from the above activities is that the μ-LAM machining process is capable of yielding significant results in implementing the hybrid system of machining with the laser heating to soften the semiconductor being machined while improving the efficiency of the process, rendering better surface integrity and reducing the wear on the cutting tool