EMO 2015
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TOWARDS MULTISCALE MANUFACTURING

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WORKSHOP: FUTURE TRENDS IN MACHINE TOOLS AND MANUFACTURING

OUTLINE

Introduction

Micro-manufacturing processes for engineered surfaces

- Micro-cutting
- Micro-laser processing
  - Laser ablation
  - Laser Induced Micromachining
- Micro-forming
  - Micro-incremental forming
  - Micro-rolling

Conclusions

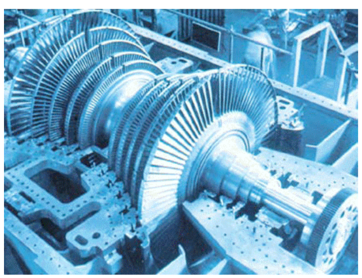
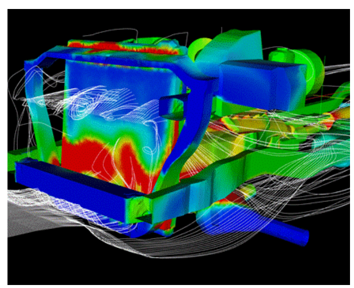
MOTIVATION - Imagine Surfaces:

that never get icy…

1998, 2005 and 2007 ice storm in NE of US, each cost about $4-6B

that inhibit fouling …

Billions of $ in loss of productivity in agriculture and $56M fuel cost for US destroyers only

that increase heat exchange rates by 10X …

95% electricity in the US is generated by steam engines; a slight efficiency increase can make a huge impact.


that never "wear"…

1/3 of energy consumption in mechanical systems is to overcome friction and replace worn materials.

Role of Surfaces

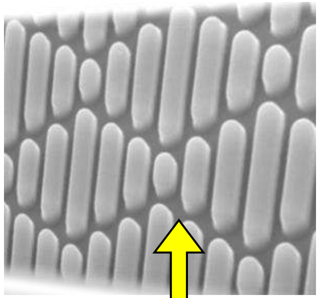
Both pragmatic and experimental evidence clearly support the fact that surface properties (texture and integrity) are among the dominant factors that define the functional performance of engineered systems.

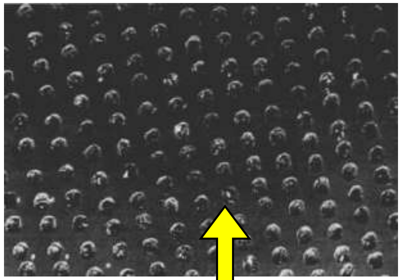
HOWEVER, there are at least four (4) major issues associated with their use:

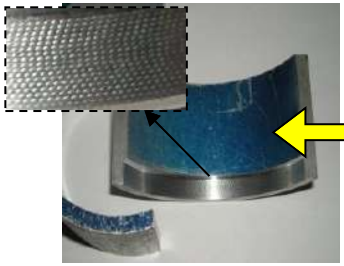
- **What type of surface to choose?**
- **What are the fundamental relations between the surface properties and their functional responses?**
- **How much is to be gained?**
- ***How to produce the desired surface?***

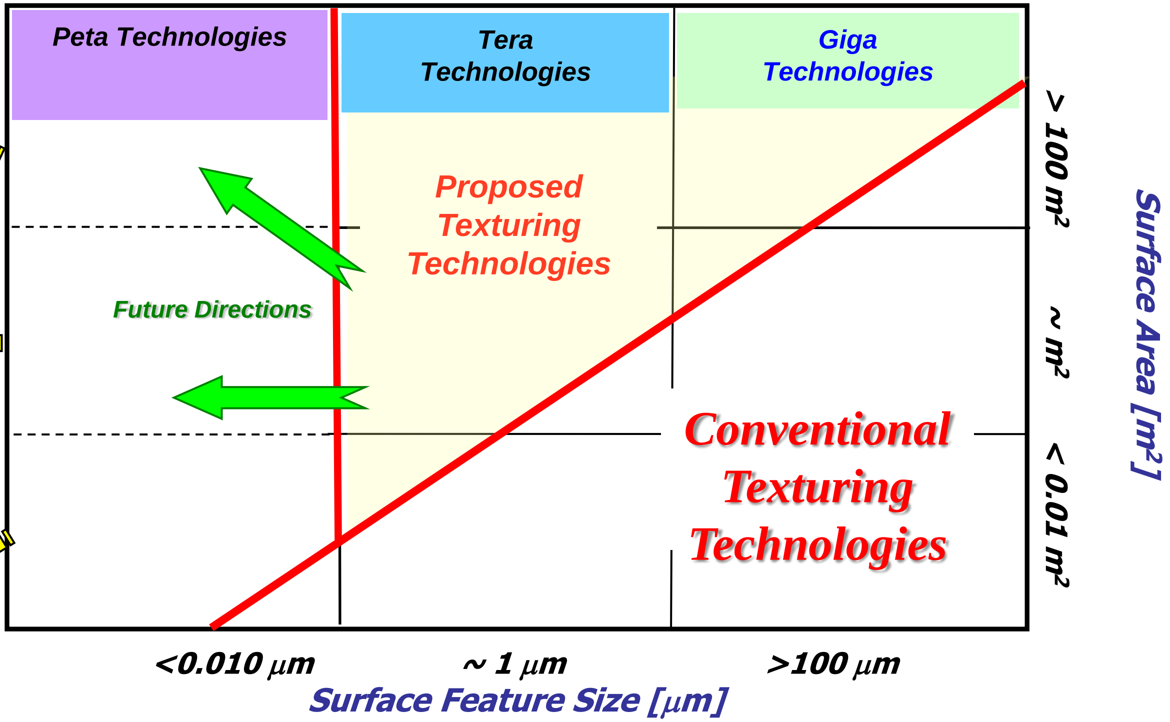
Definition of Surface Texturing Domain

Application areas of large-area textured surfaces on hard materials



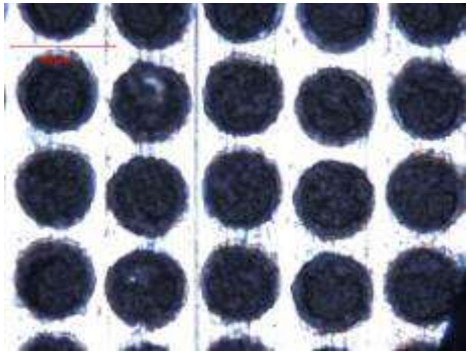






X-Technology: X = Surface features / m^2

Processing Times by Different Texturing Methods



Dimple array with 100 μm distance in both directions

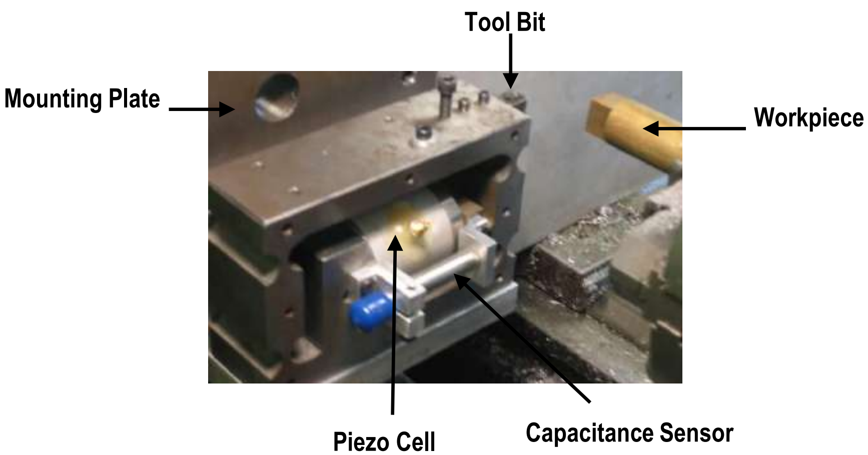
Processes	Time (per m^2)	Assumptions
Vibro/ultrasonic - machining	1 hour	Working at 28 kHz
Laser ablation	115 days	Each dimple takes 0.1s
Micro-rolling	50s	Rolling speed: 20mm/s
Micro-milling	1.5 years	Each dimple takes 0.5s

Micro-cutting Processes

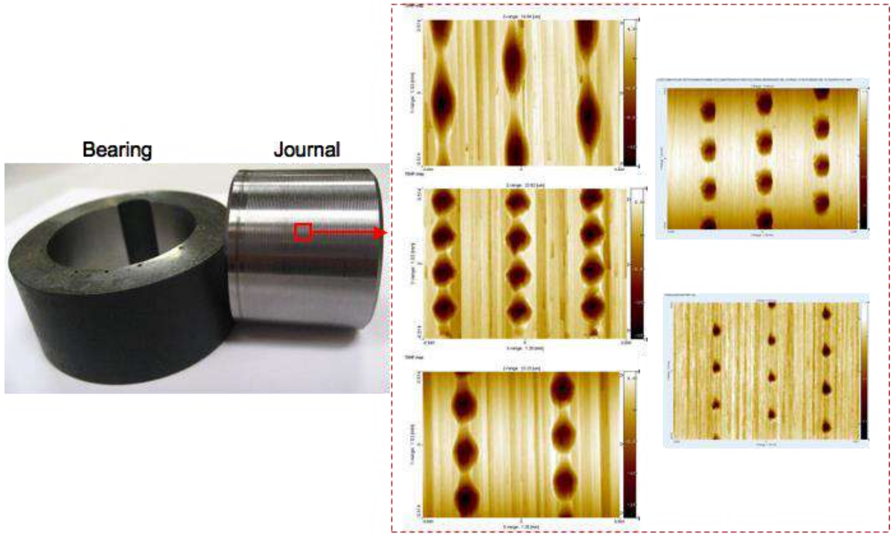
Surface Texture Development

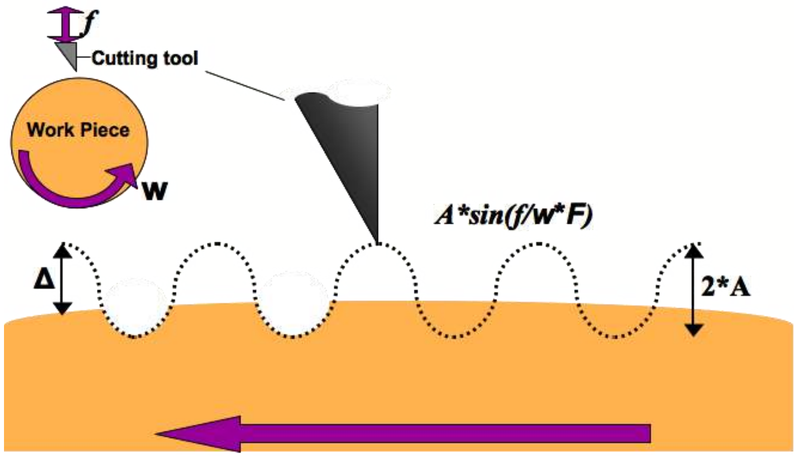
Vibro-mechanical Texturing Method

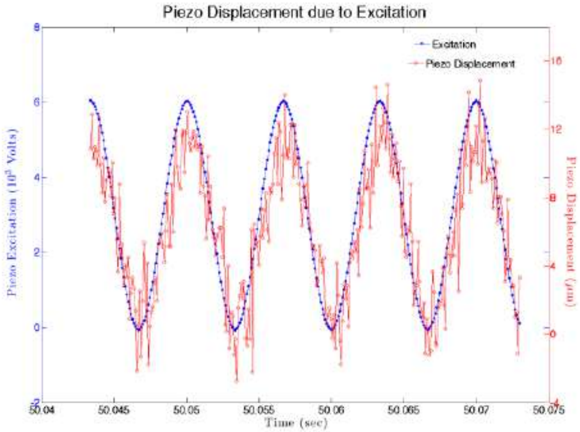
Surface Texturing Method



Texture Designs



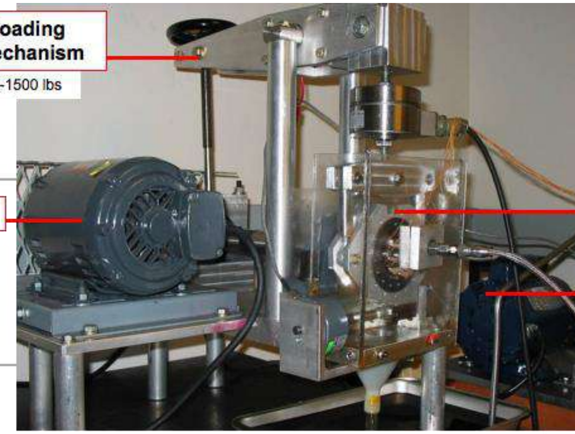


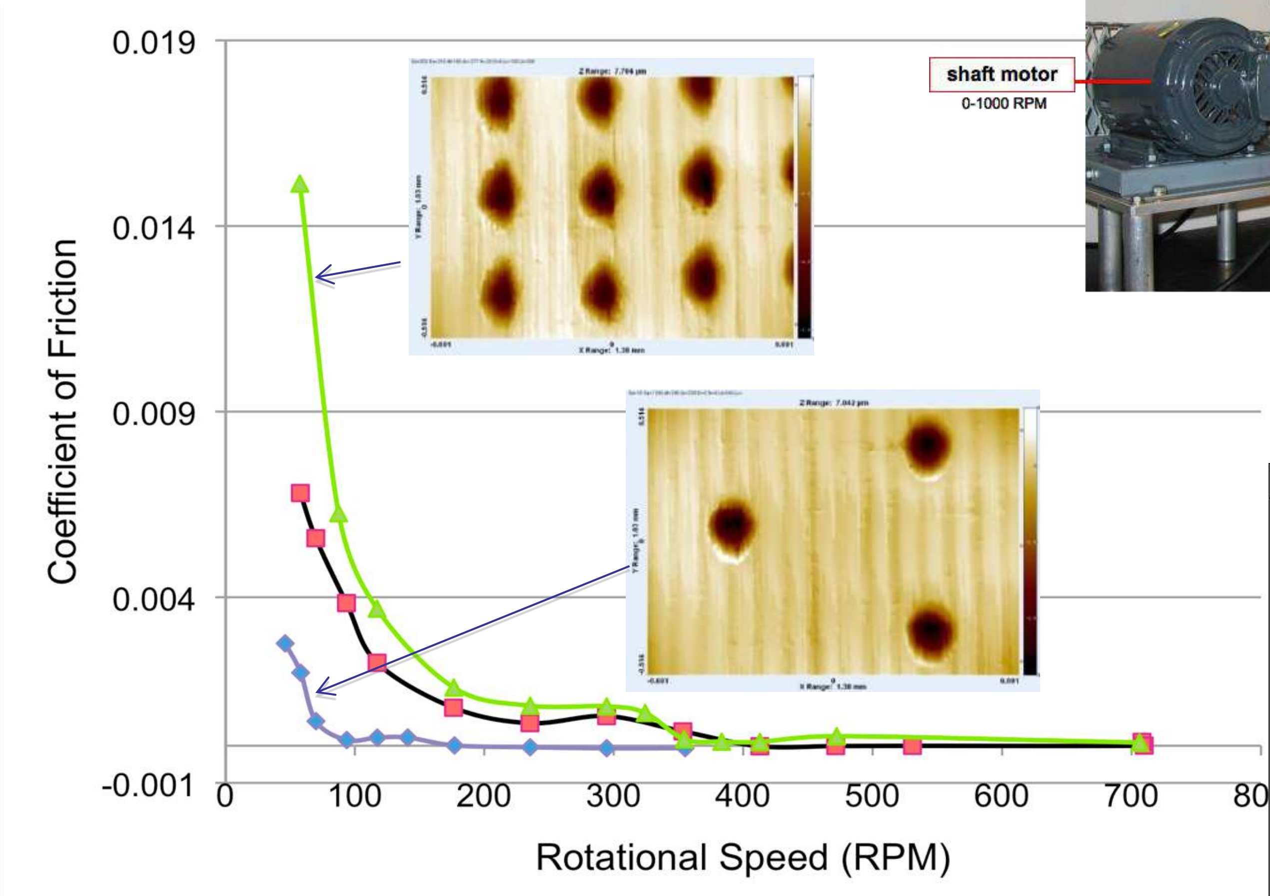


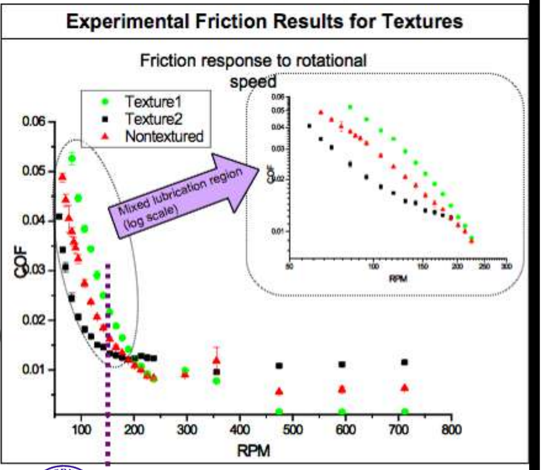
Prof. Ehmann, Wang

Northwestern University

Influence of Surface Texture on the Coefficient of Friction

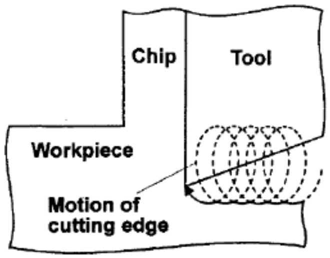




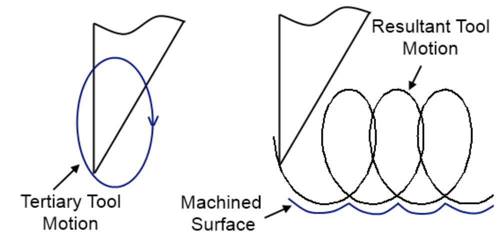


Prof. Wang

Elliptical Vibration Texturing



Elliptical Vibration Cutting



Elliptical Vibration Texturing

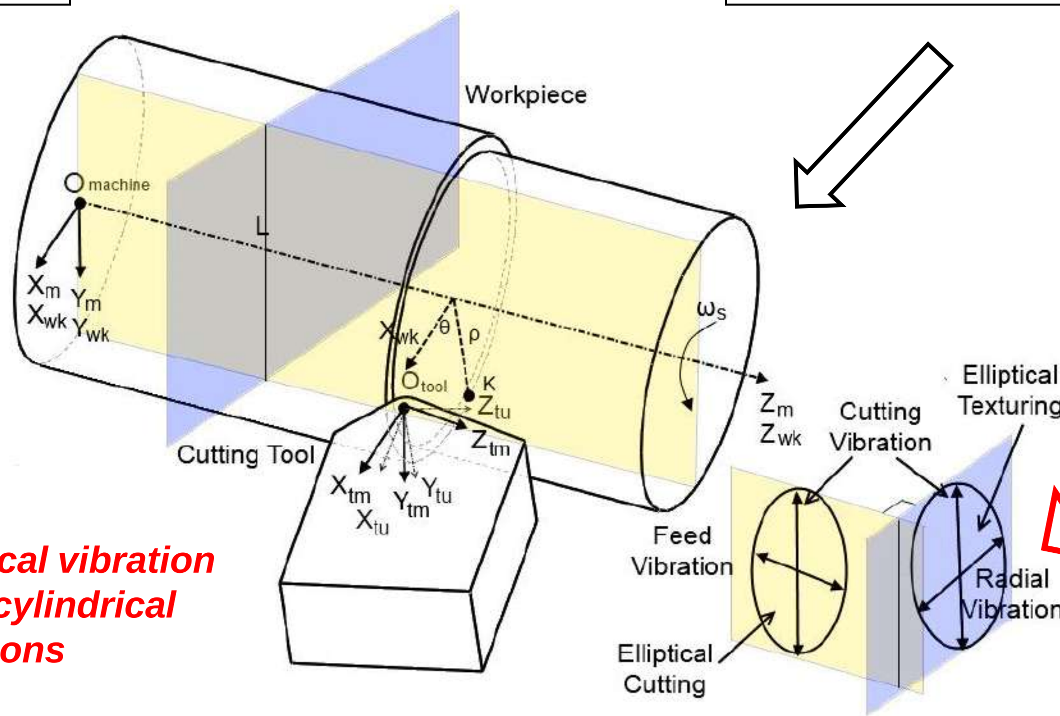
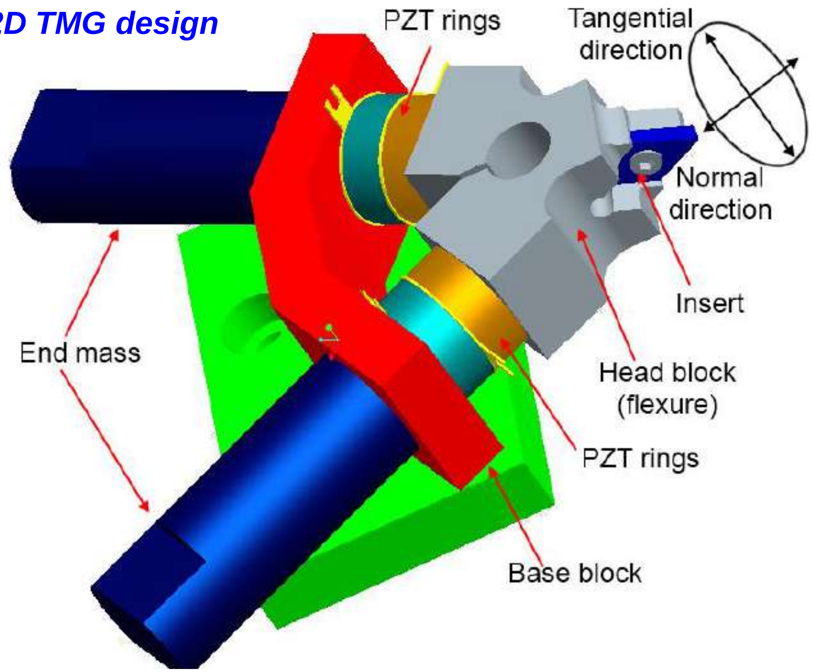
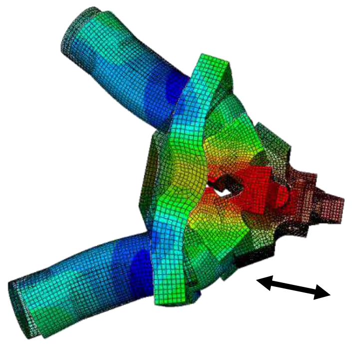


Illustration of the elliptical vibration texturing process in cylindrical turning operations

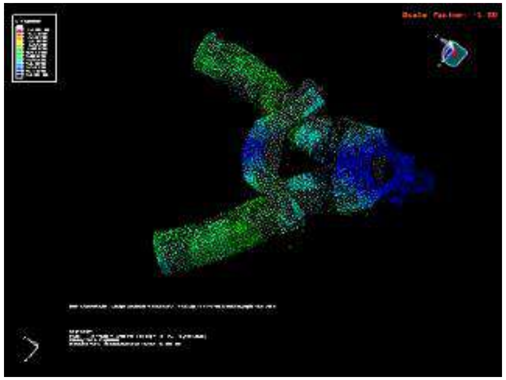
Tertiary Motion Generator

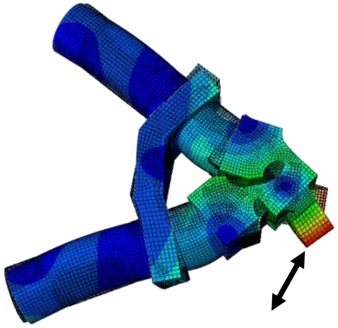
Resonant-mode 2D TMG design



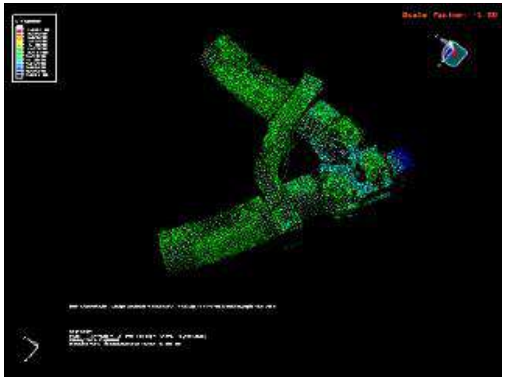


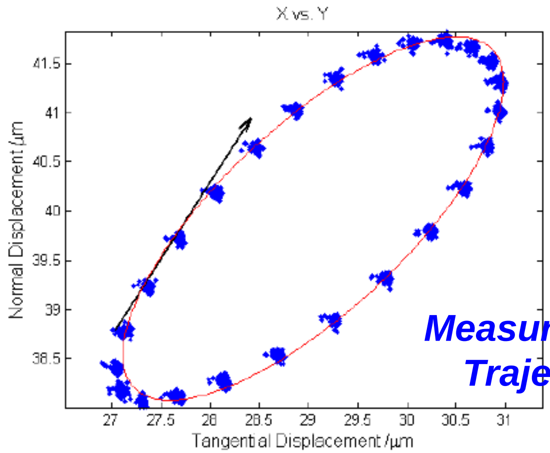
Normal Mode





Tangential Mode

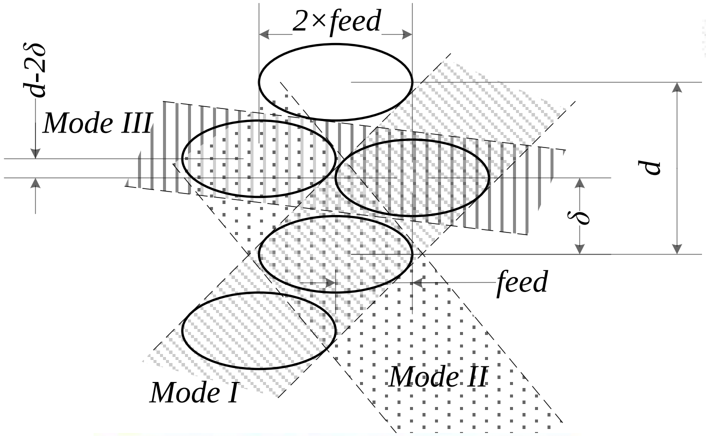


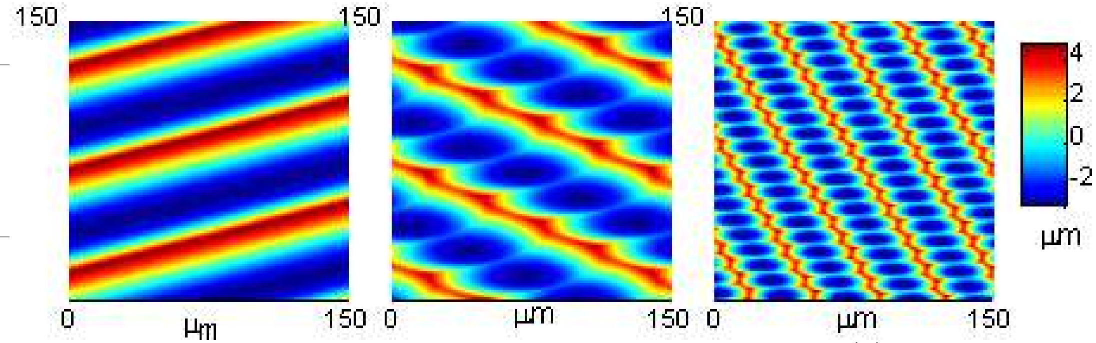


Measured Tool Vibration Trajectory @ 28 kHz

P. Guo et al., "Development of a tertiary motion generator for elliptical vibration texturing," Precision Engineering, 2013; 37: 364-371.

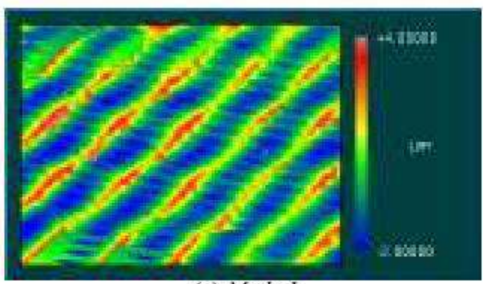
Micro-channel Generation



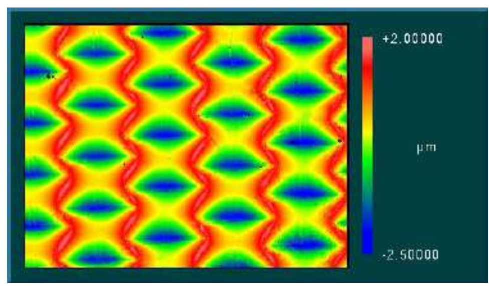


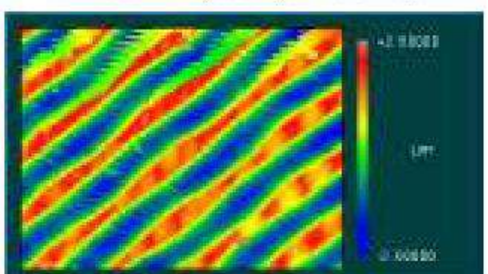
(a) (b) (c)

Influences of the principal overlapping ratio and the minor overlapping ratio

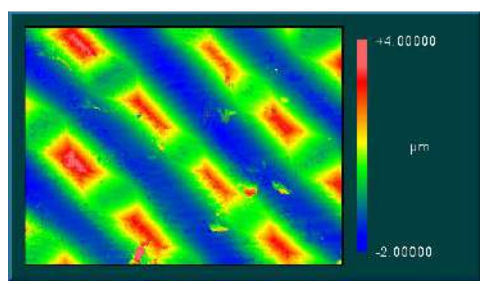


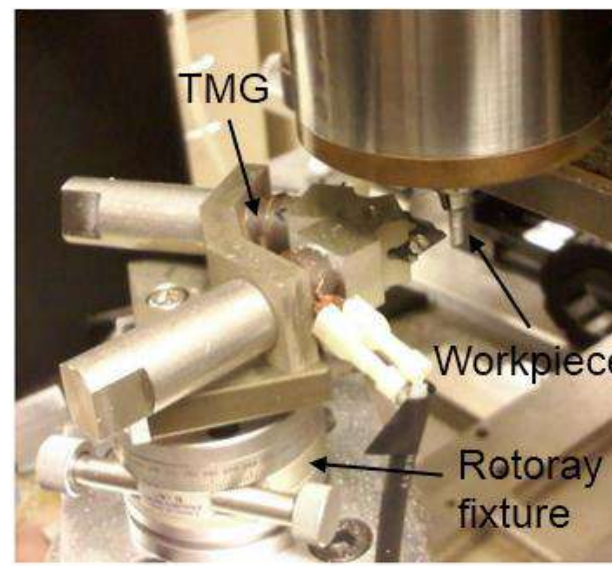
(a) *Mode I*
N=22660 RPM *feed*=4 μm *DOC*=10 μm





(c) *Mode I*
N=22665 RPM *feed*=8 μm *DOC*=0 μm

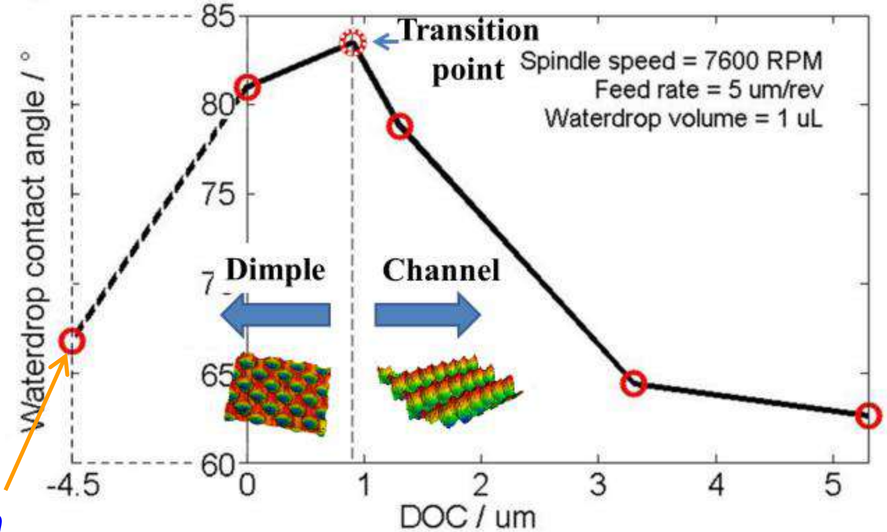




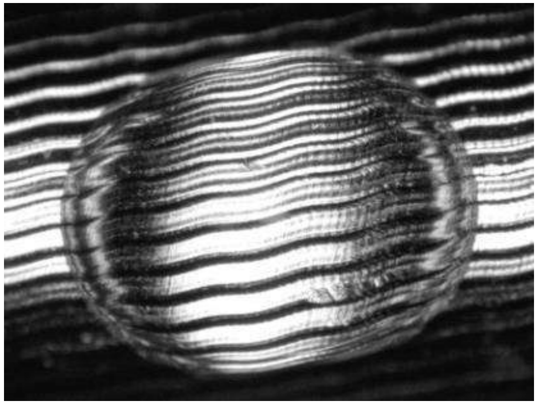
P. Guo and K. Ehmann, "An analysis of the surface generation mechanics of the elliptical vibration texturing process," International Journal of Machine Tools and Manufacture, 2013; 64: 85-95.

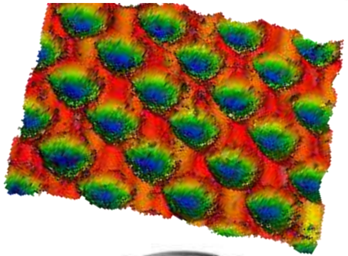
Case Study – Wettability Control

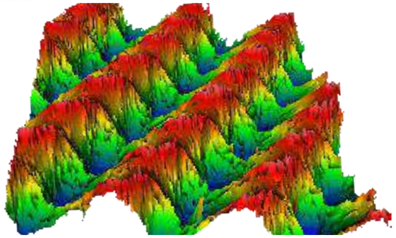
Depth-of-cut

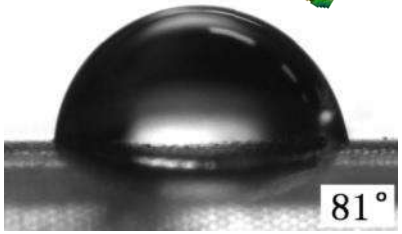


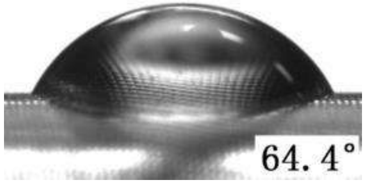
Smooth surface











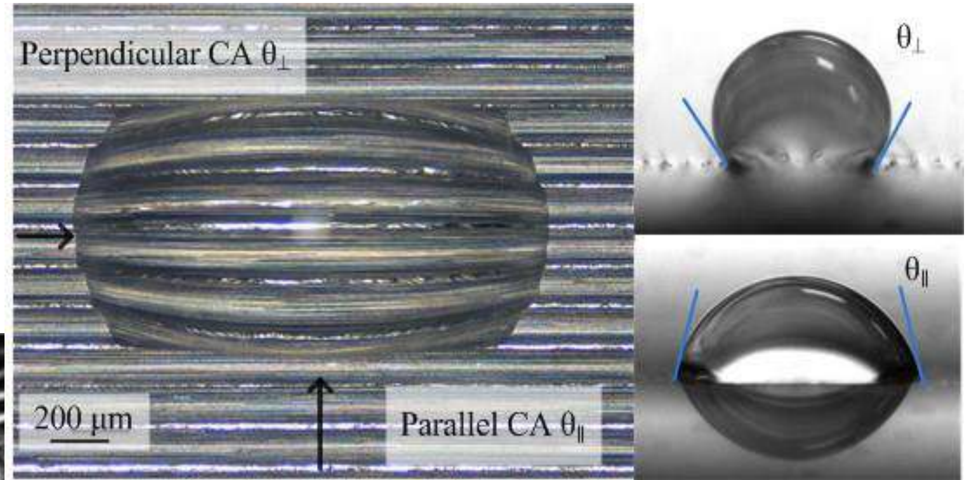
DOC = 0 μm

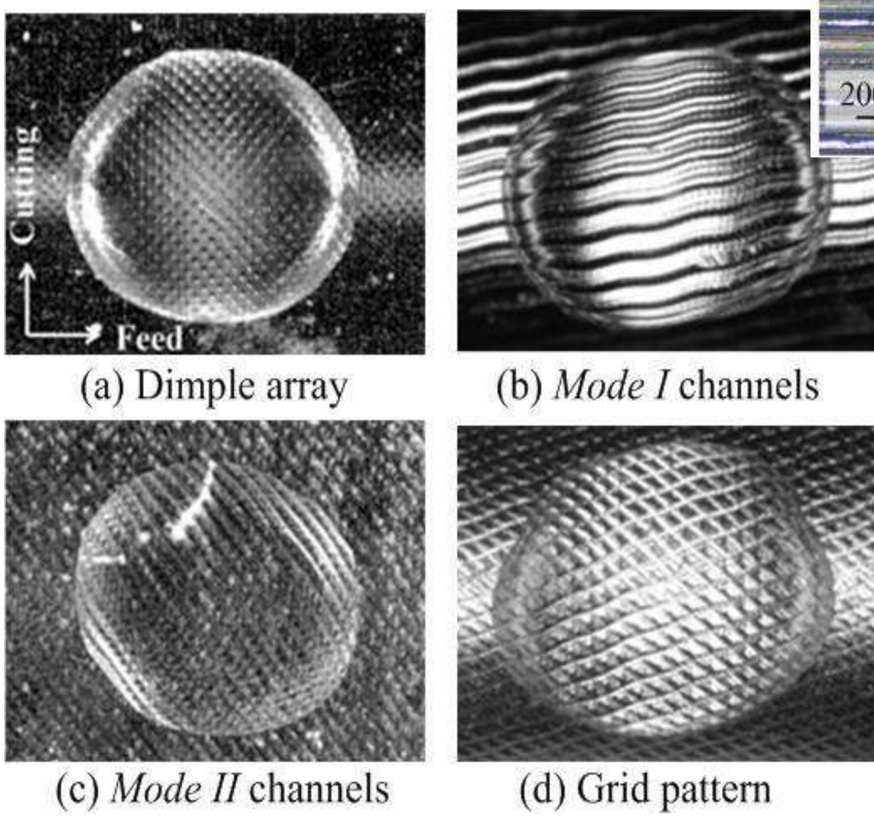
DOC = 3.5 μm

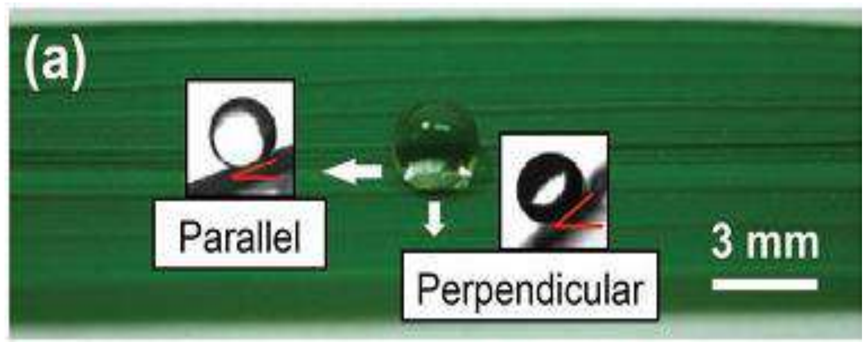
P. Guo et al., "Experimental Studies of Wettability Control on Cylindrical Surfaces by Elliptical Vibration Texturing," 2014, to be submitted

Multi-scale Structures on Flat Surfaces

Anisotropic water droplets





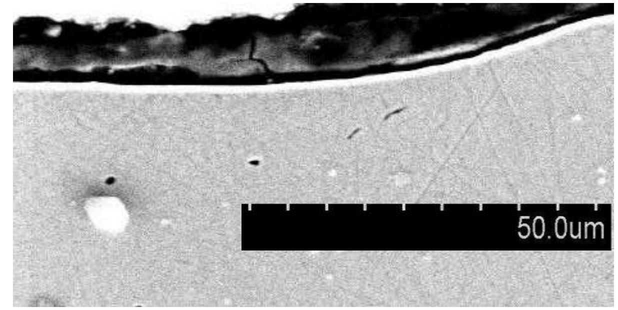


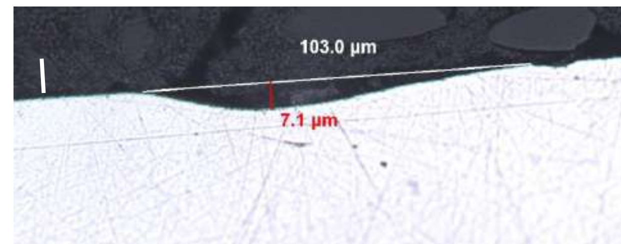
Directional rolling angles on a rice leaf[1]

Surface Integrity

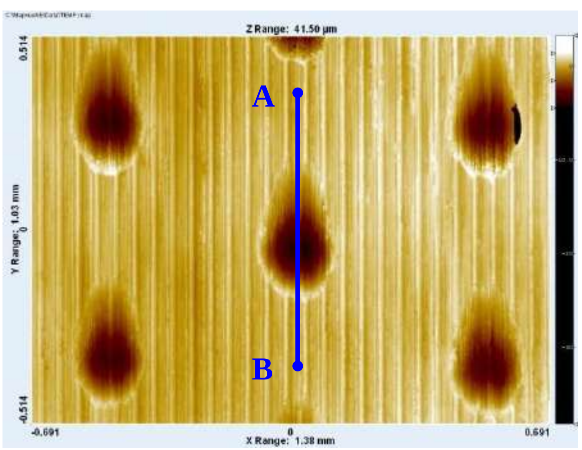
SEM

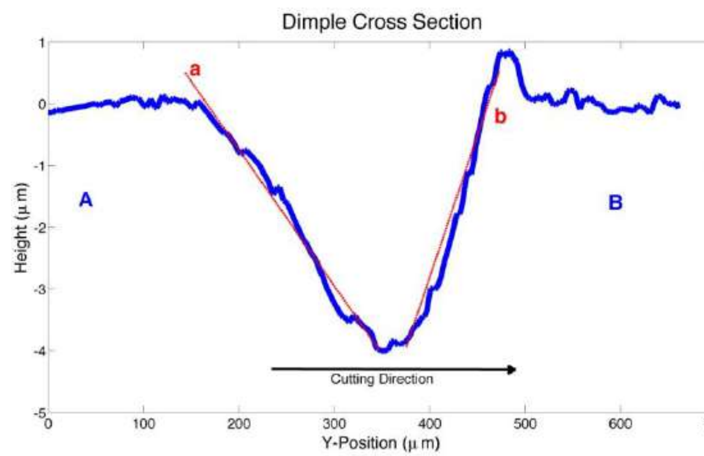
Optical 50X





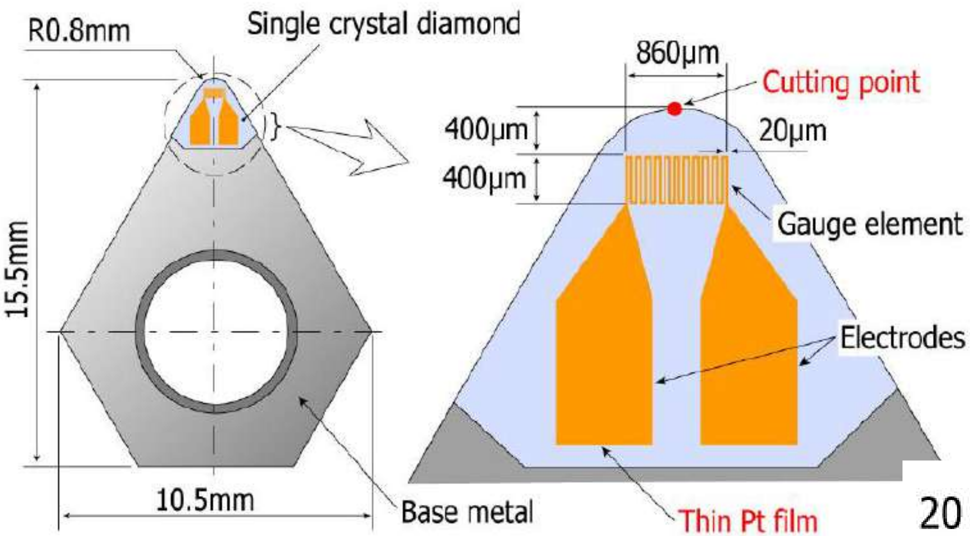
- 4715 Heat Treated Steel
- 55 HRC
- Dimple Dimensions – D= 7µm, dt = 97µm
- NO SURFACE CRACKS
- Signs of plastic shear flow





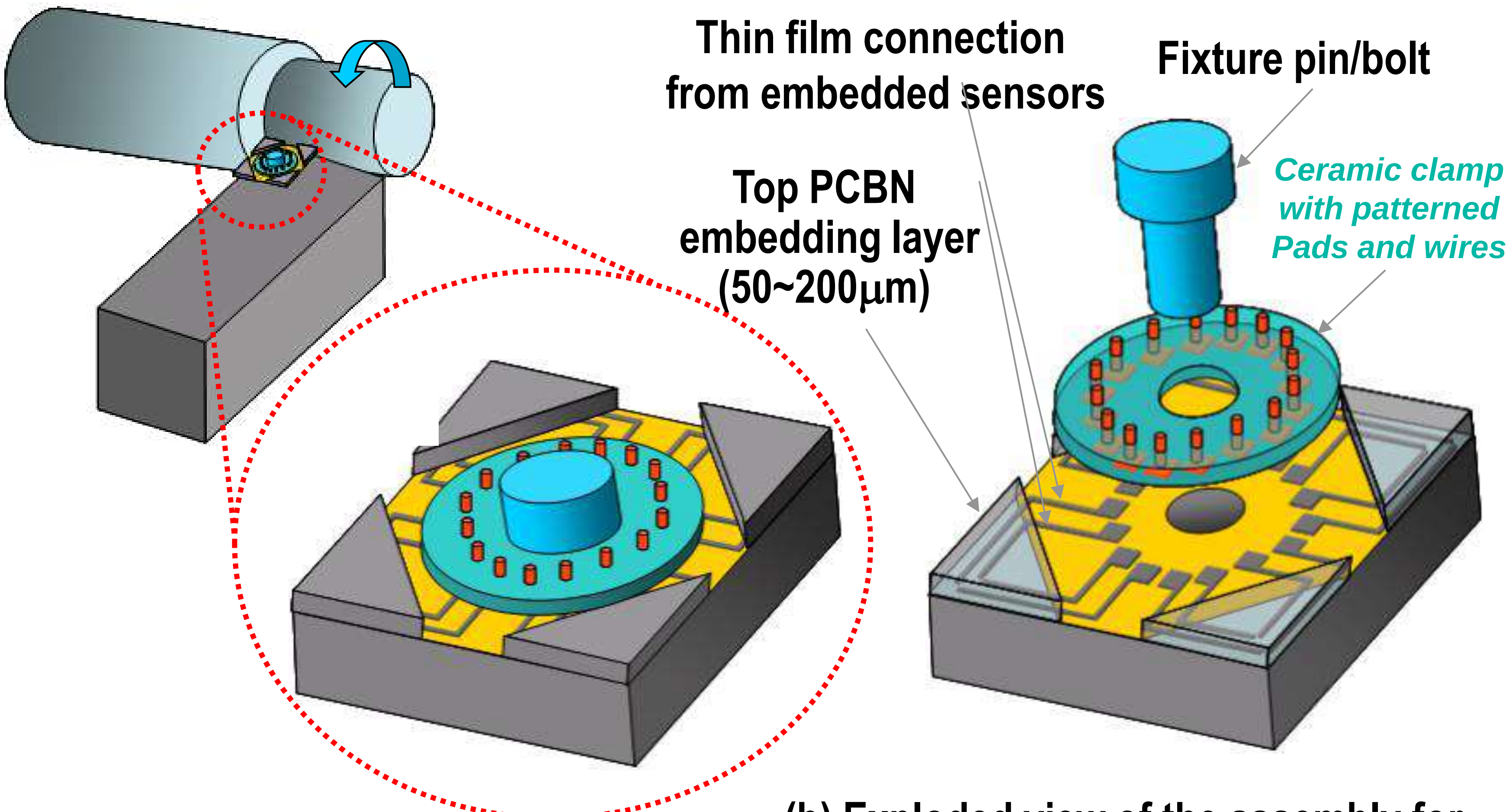
Cross section analysis of the dimple on the hardened steel surface

Surface Mounted TCs



Tool-mounted sensor and resulting temperature rise in adaptive tool temperature control [Hayashi, '08]

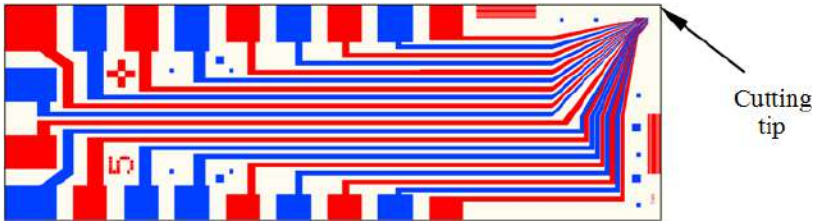
Sensors Embedded in Ceramic Tooling

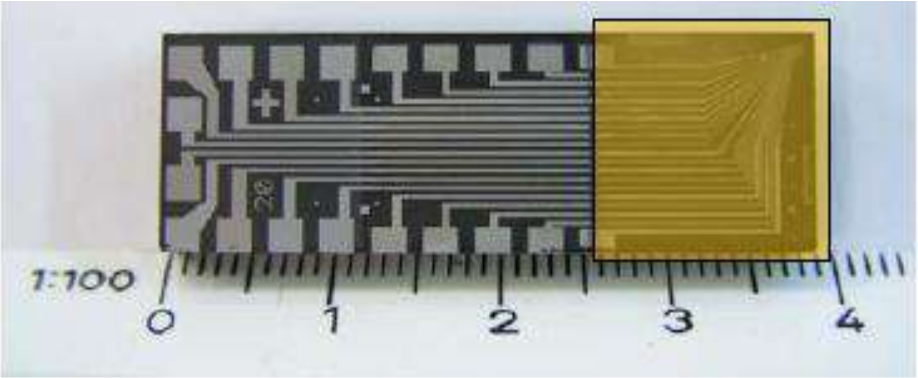


(a) Hard turning experimental setp with PCBN embedded sensors

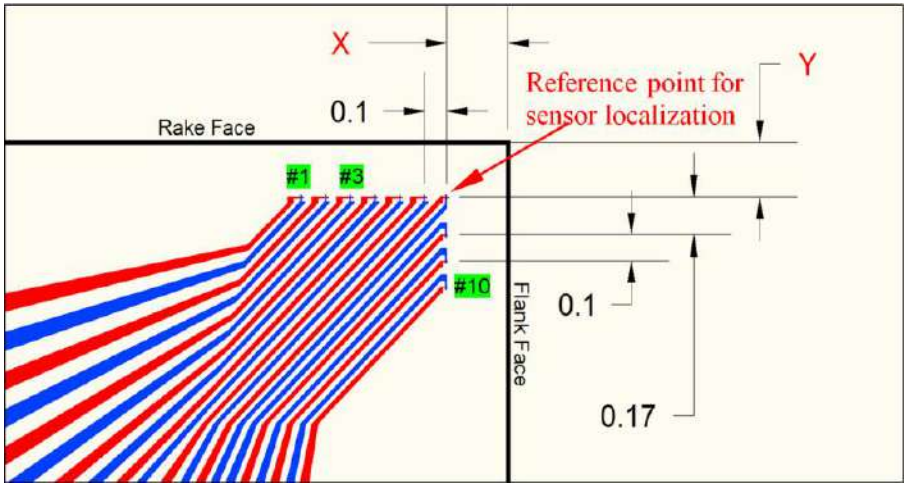
(b) Exploded view of the assembly for data acquisition from PCBN tool with embedded sensors

Fabricated Insert: Layout #2

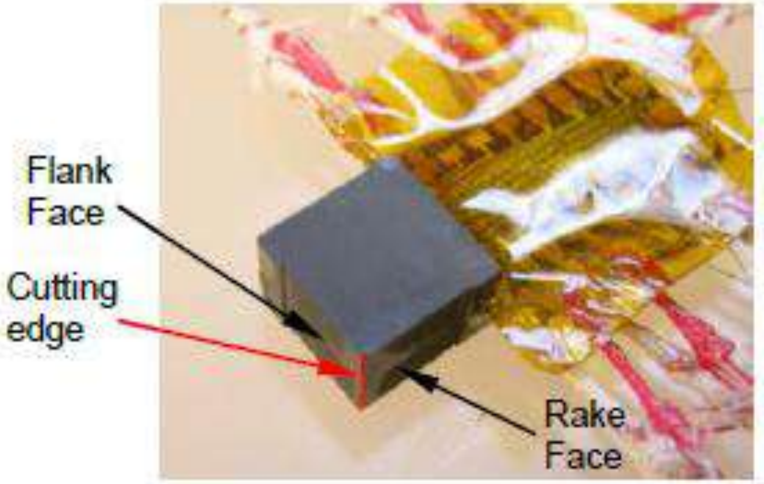




MICROFABRICATED SENSOR BEFORE DIFFUSION BONDING, SHADED AREA HIGHLIGHTS DIFFUSION BONDING AREA

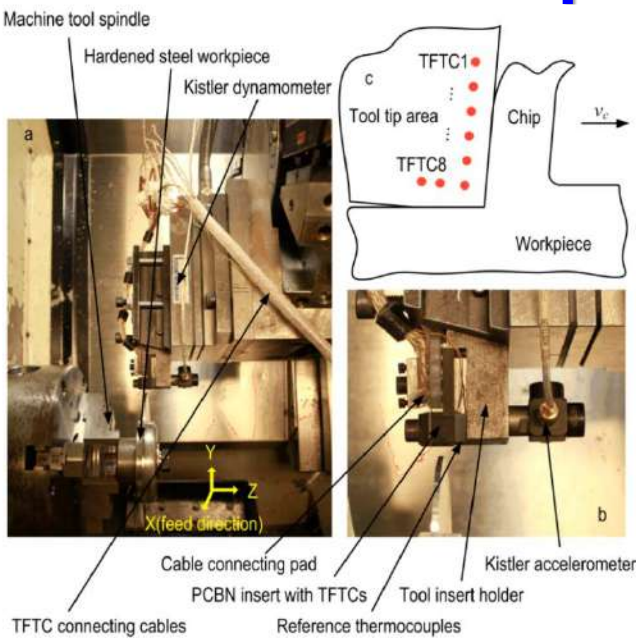


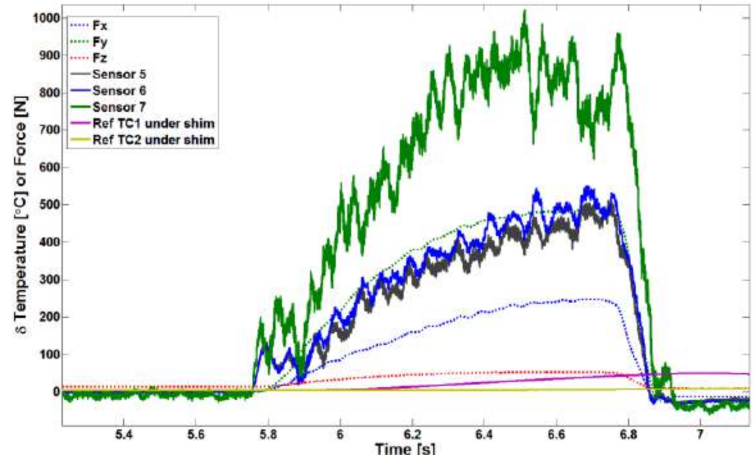
IINSERT LAYOUT



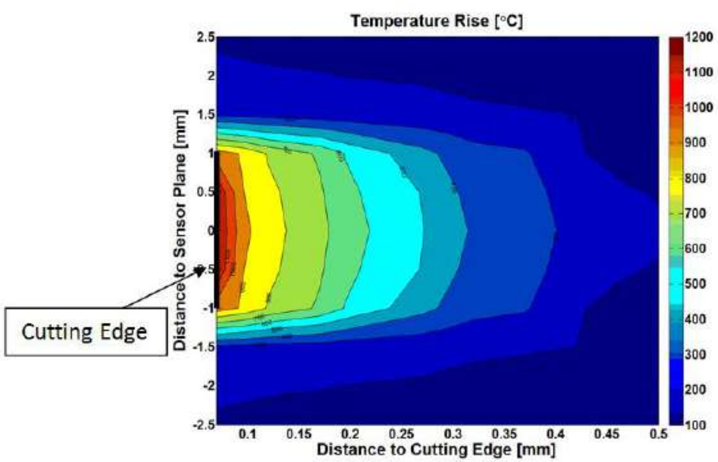
INSTRUMENTED INSERT

Experimental Results

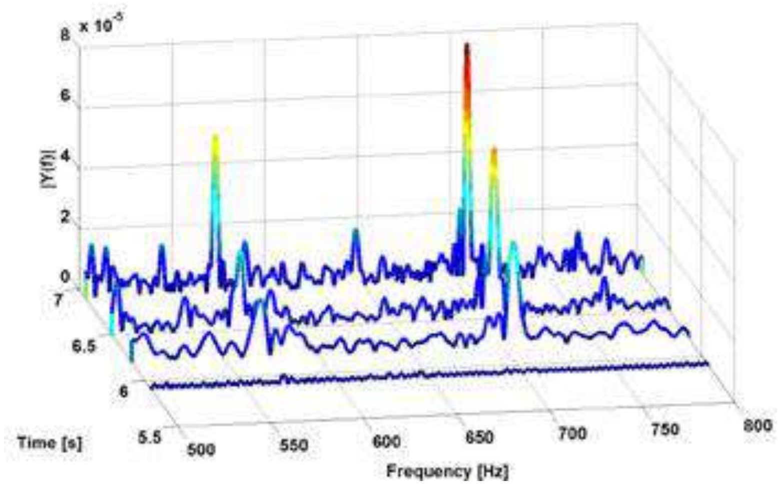




TFTCS AT 100 μm UNDER THE RAKE FACE



TOOL INTERNAL TEMPERATURE FIELD AT 190 M/MIN AND 0.075 MM FEED, 100 μm UNDER THE RAKE FACE



EVOLUTION OF CHATTER AS DETECTED BY TFTC 5

Shape of Things to Come ?????

1500 mm

10^{12}

500 mm

10^{9}

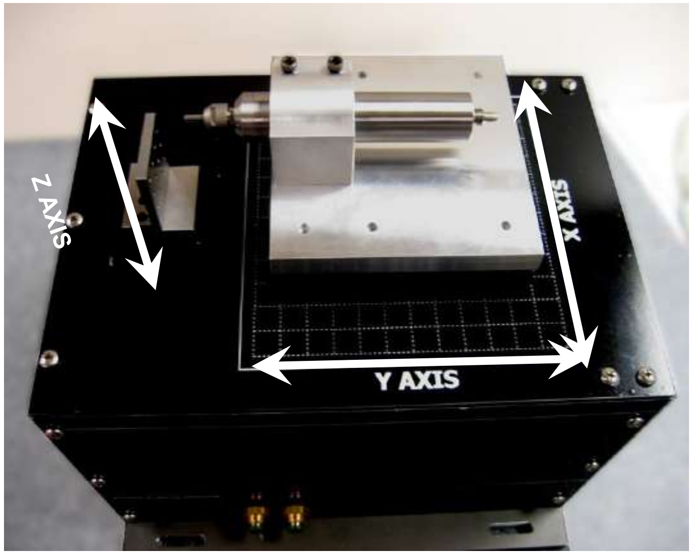
100 - 500 μm Dia
0.5 – 2.5 mm L

??????

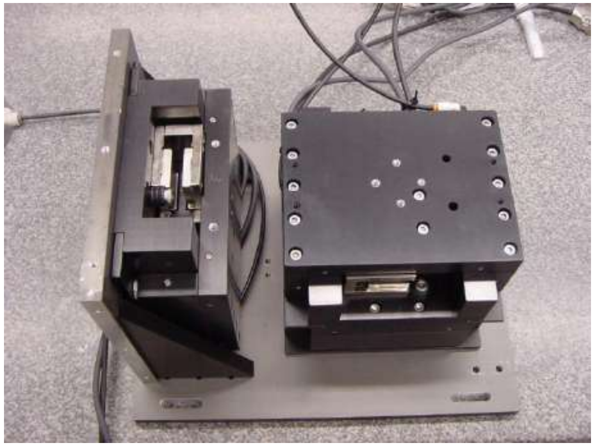
50 mm

10^{6}

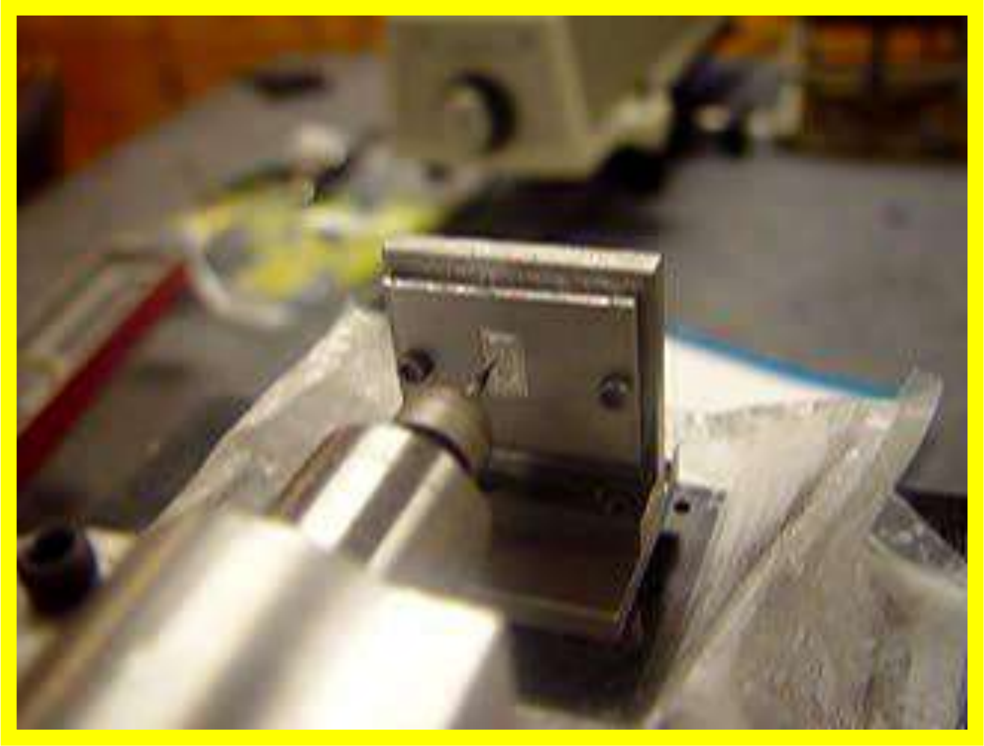
NU: mMT^3 Features



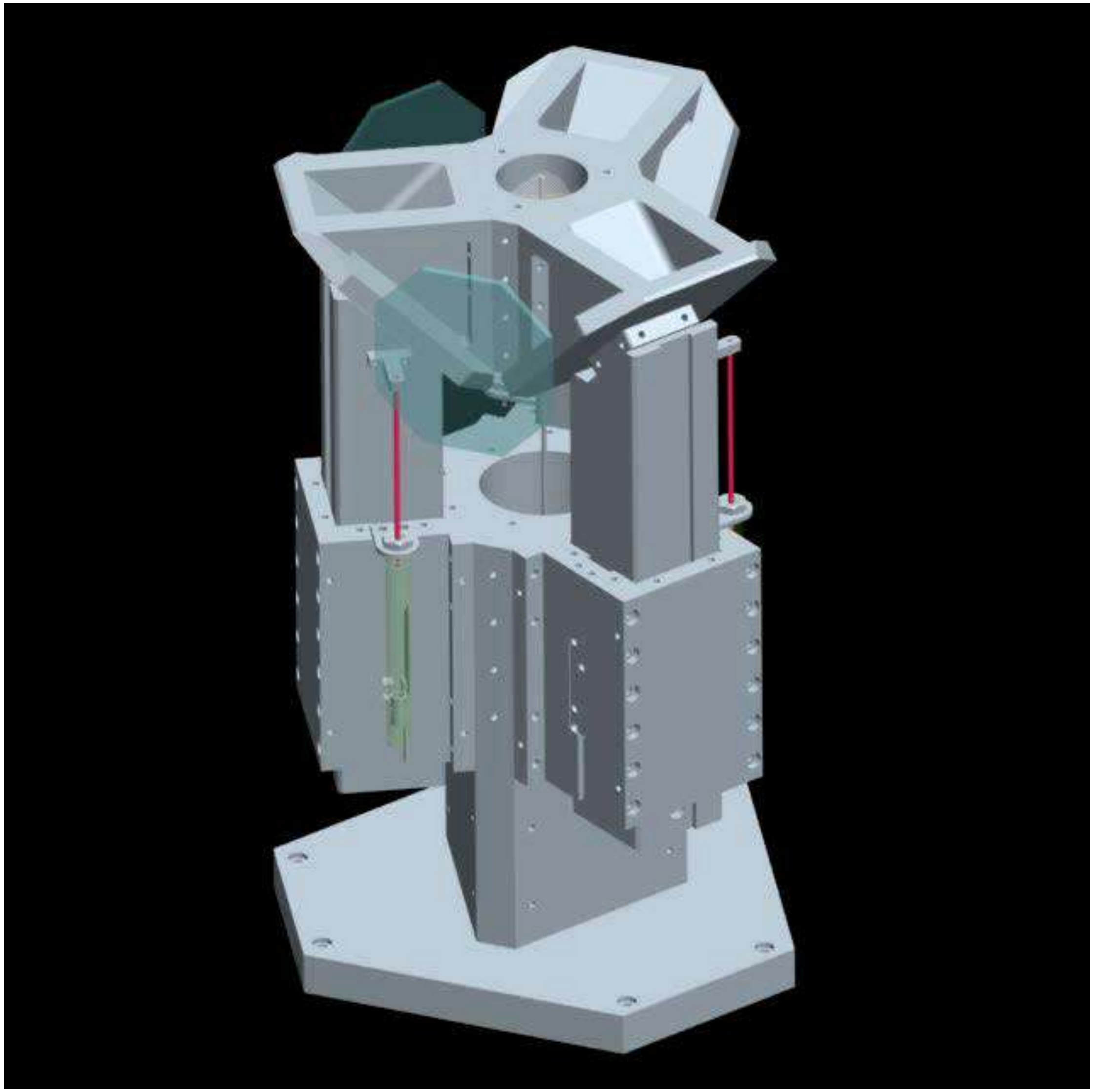
Bird's Eye View of mMT3

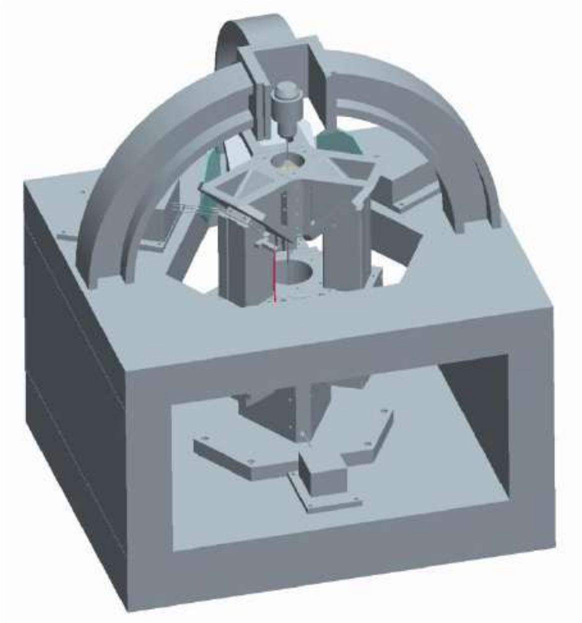


- *Type:* ***3 Axis Horizontal Milling Machine***
- *Machine Envelope:* ***300L x 200W x 250H***
- *Effective Workspace:* ***25 x 25 x 25mm***
- *Spindle:* ***Air Turbine – Roller Bearing***



NU: Micro-CMM





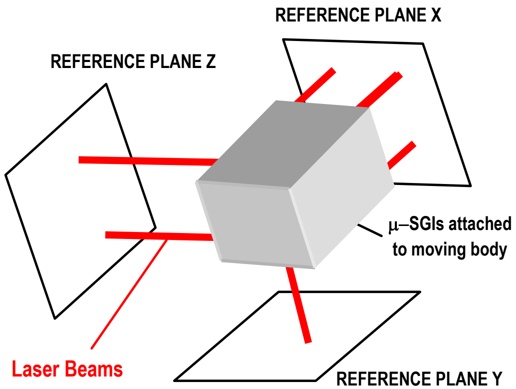


Figure 8: Principle of 6-DOF μ–SGI system for position and orientation measurements

Laser-texturing

- Ablation
- Laser-induced Plasma Micro Machining (LIP-MM)

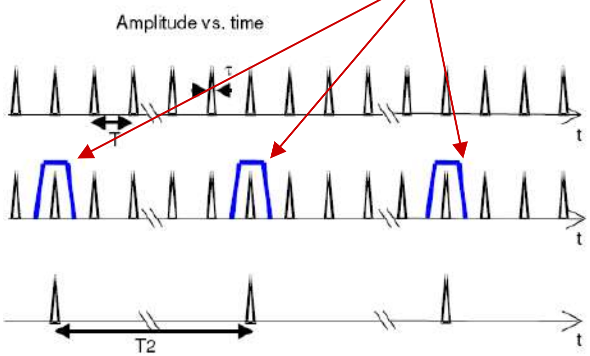
Laser Micro-manufacturing System

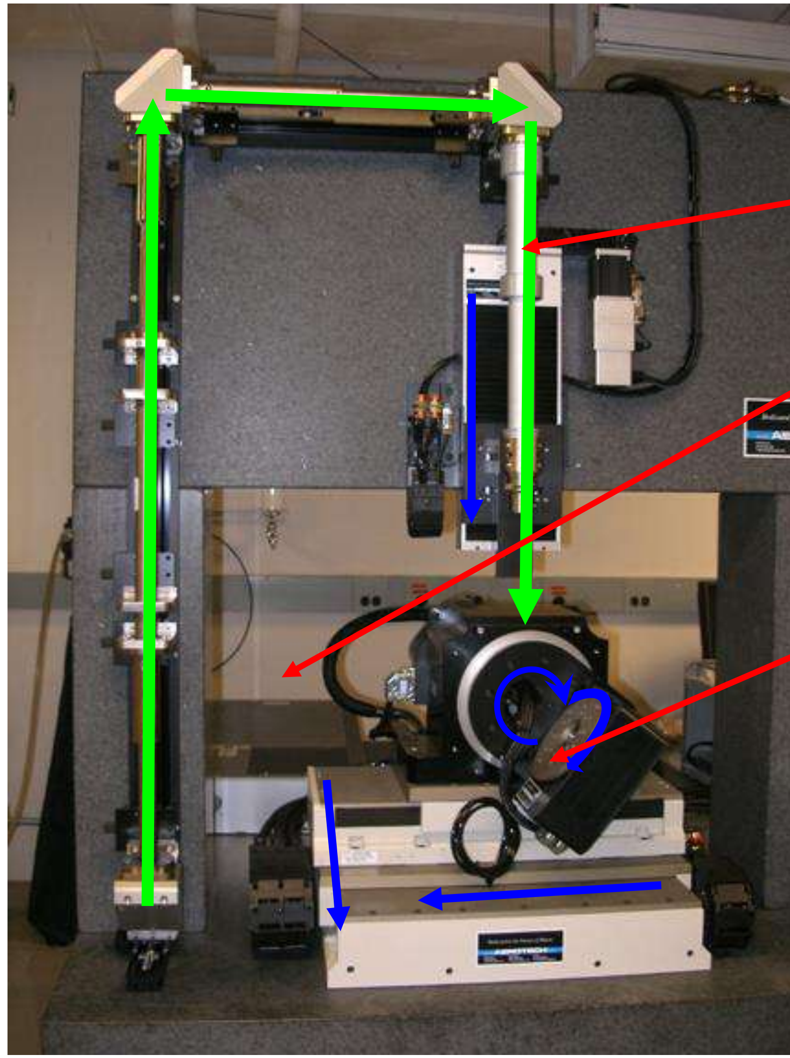
Pico-second laser pulses are generated.

⇩

'Picked' pulses are delivered from the laser to the substrate surface.

'Picked' pulses





Beam delivery system

Laser

5 DOF positioning

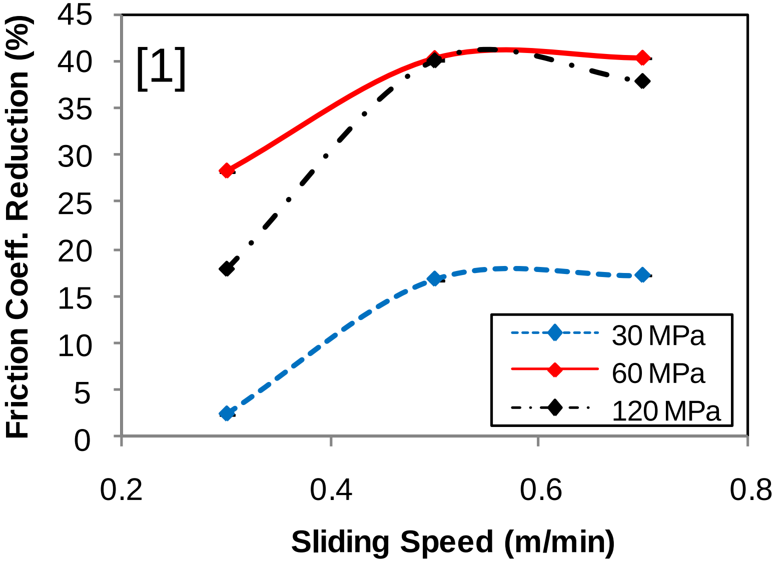
X, Y, Z, Θ, Φ

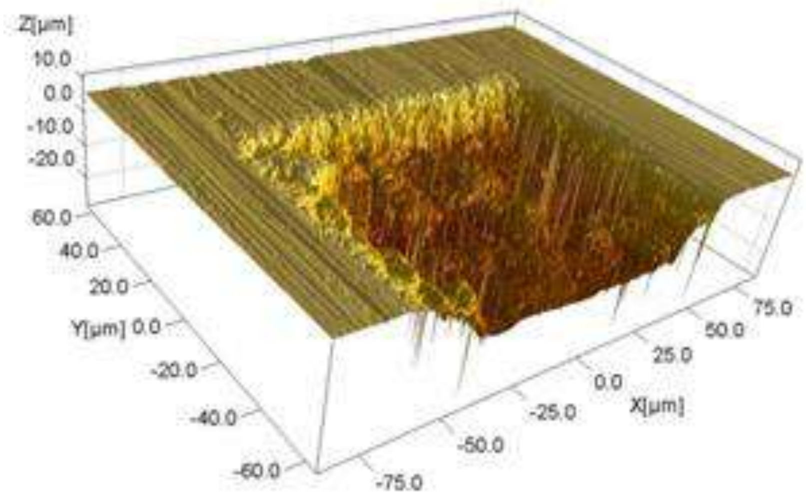
Resolution: 10nm

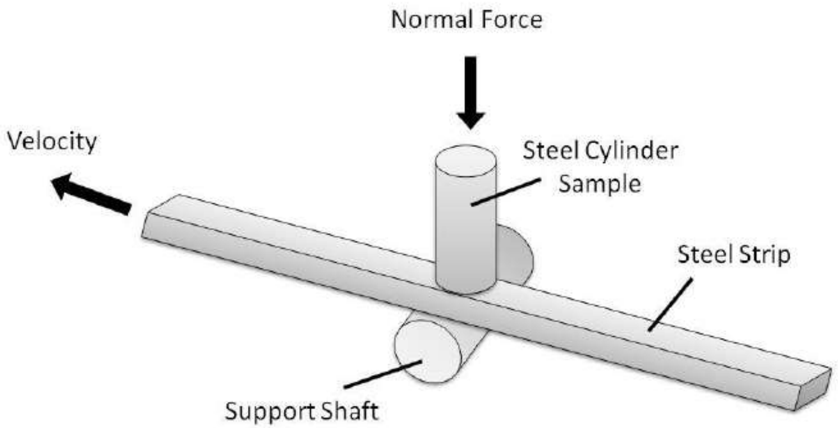
0.0001 degrees

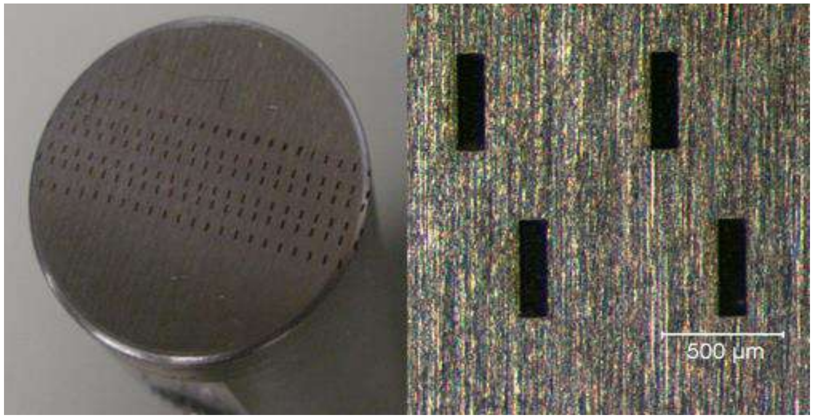
Laser Textured Steel Sample

- Reduction of friction coefficient due to surface texturing -







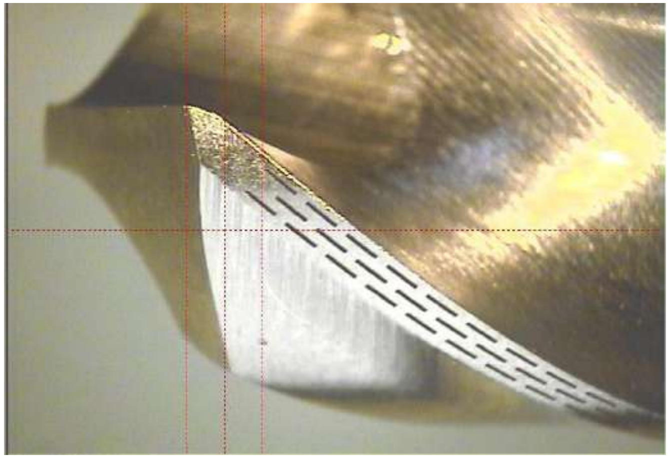


Texture direction perpendicular to the motion direction

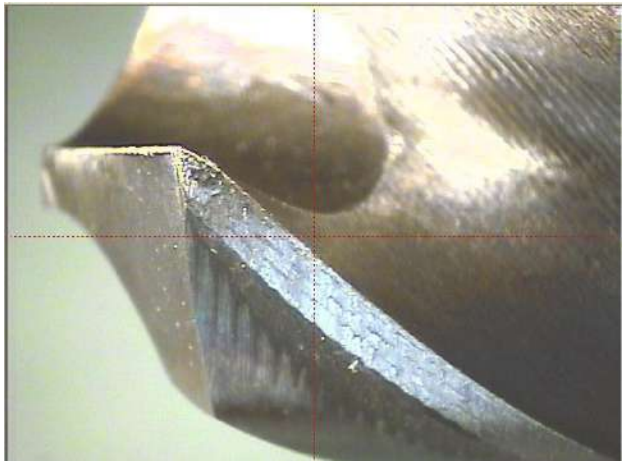
T. Davis, R. Zhou, K. Pallav, M. Beltran, J. Cao, K. Ehmann, Q. J. Wang, C. Xia, R. Talwar, and R. Lederich, "Experimental Friction Study of Micro-Scale Laser-Textured Surfaces," in *International Workshop on Microfactories, Evanston, IL, 2008.*

Drilling of Titanium

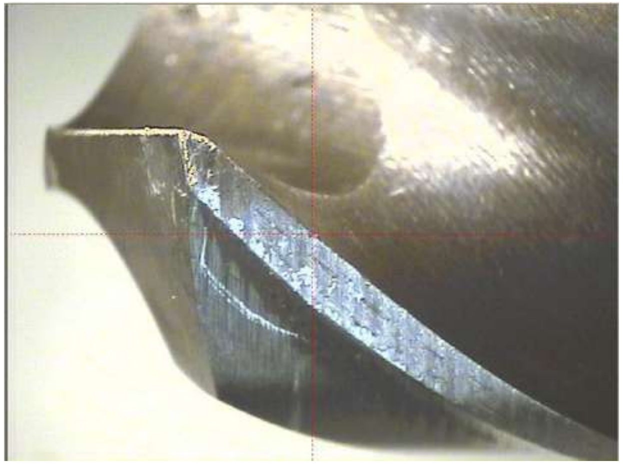
Untextured Drill: Hole 30



20% Micro-textured



20% Micro-textured: Hole 30



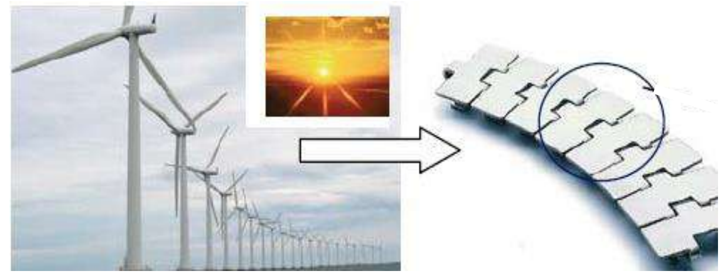
20% Micro-textured: Hole 50

Prof. Cao & Wang

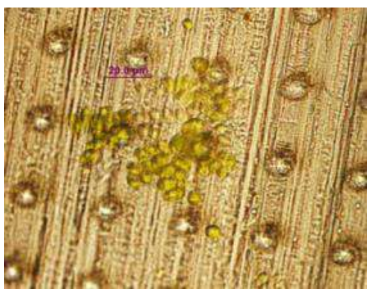
Algae Attachment

Without dimples

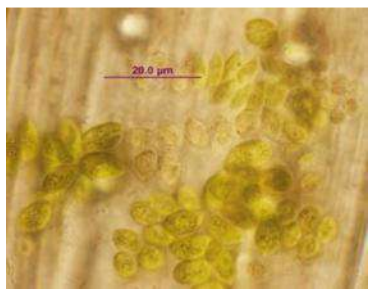
With dimples



Electrical power to drive the steel conveyor belt on water surface

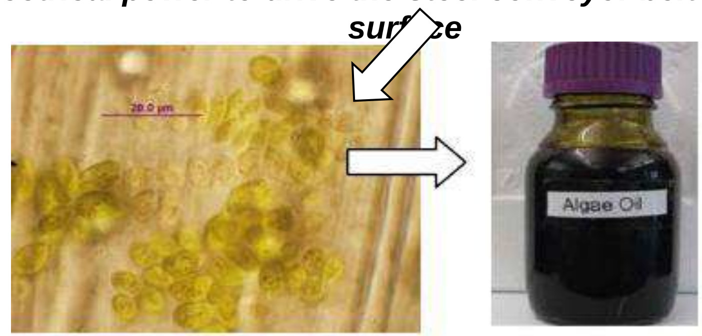


50x



100x

Green algae grown on 250 μm thick stainless steel sheets



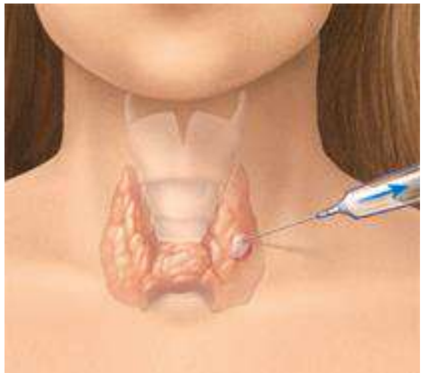
Oil extracted from algae attached to the micro-textured steel surface [1]

- Stainless steel sheets are textured to a particular pattern via laser texturing to facilitate strong attachment and growth of algae on the sheet media
- Textured surfaces enable more than a 100 times increase in algae attachment

[1] Cao, J., Yuan, W., Pei, Z.J., Davis, T., Cui, Y. and Beltran, M. (2009) "A preliminary study of the effect of surface texture on algae cell attachment for a mechanical-biological energy manufacturing system", accepted to ASME Journal of Manufacturing Science and Engineering.

Minimally Invasive Needle Insertion Procedures

- **Biopsy**: *a medical procedure to remove cells or tissues for examination.*

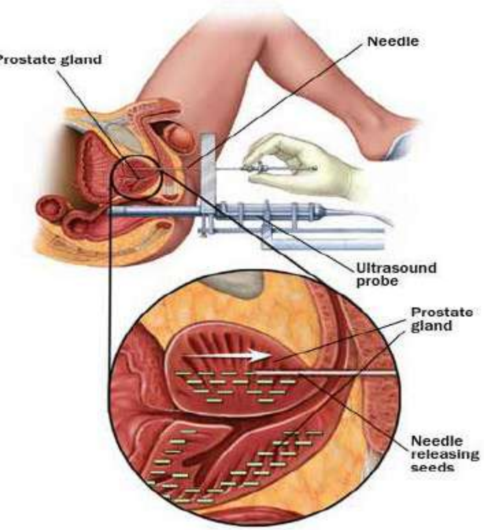


Fine-needle aspiration

Core needle biopsy

- **Brachytherapy** *- internal radiation therapy cancer treatment.*

  During brachytherapy, the needle containing radioactive seeds is inserted into body tissue.

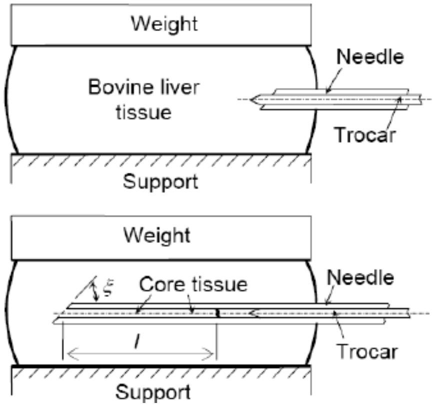


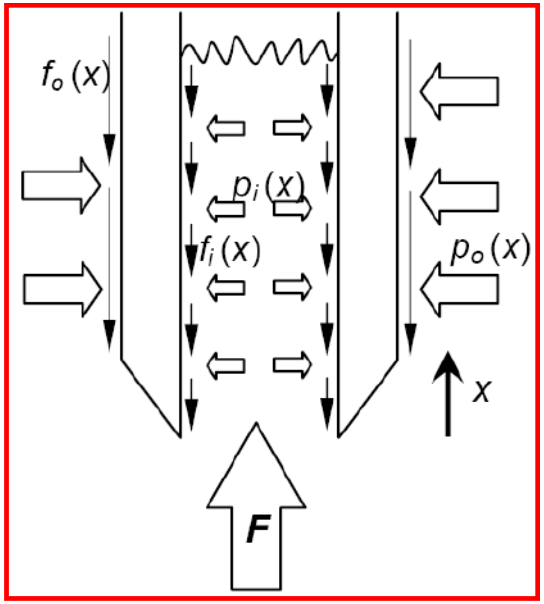
Prostate brachytherapy

Mayo Foundation for Medical Education and Research

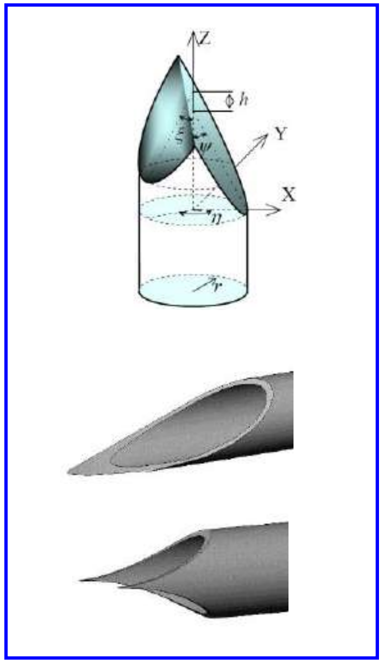
Development of High-efficiency Biopsy Needles

Some conventional needle tip designs





Friction of tissue inside and outside of a biopsy needle



Nontraditional needle tip designs with non-symmetric two-plane surfaces and non-flat curved needle tips

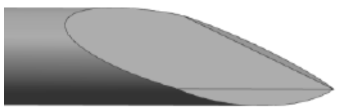
Needle tissue cutting tests to determine the sample length

Prof. Ehmann & Shih

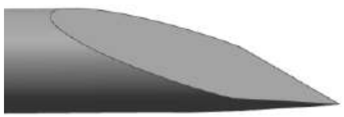
Needle Tip Designs

Bevel tip needle stylet

Bevel tip needle cannula

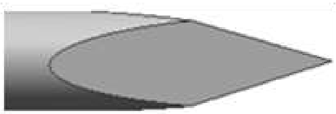


Lancet point needle stylet

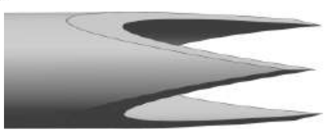


Back bevel needle stylet

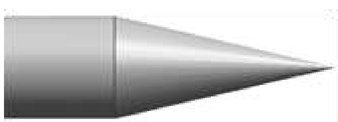
Back bevel needle cannula



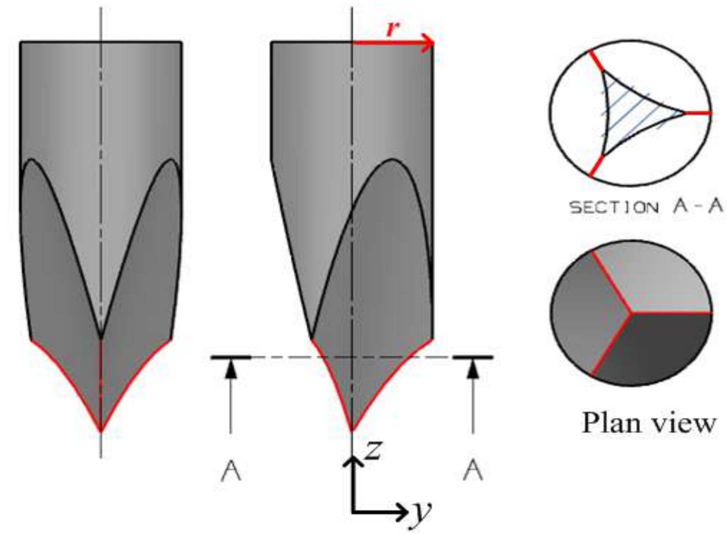
Trocar tip needle stylet

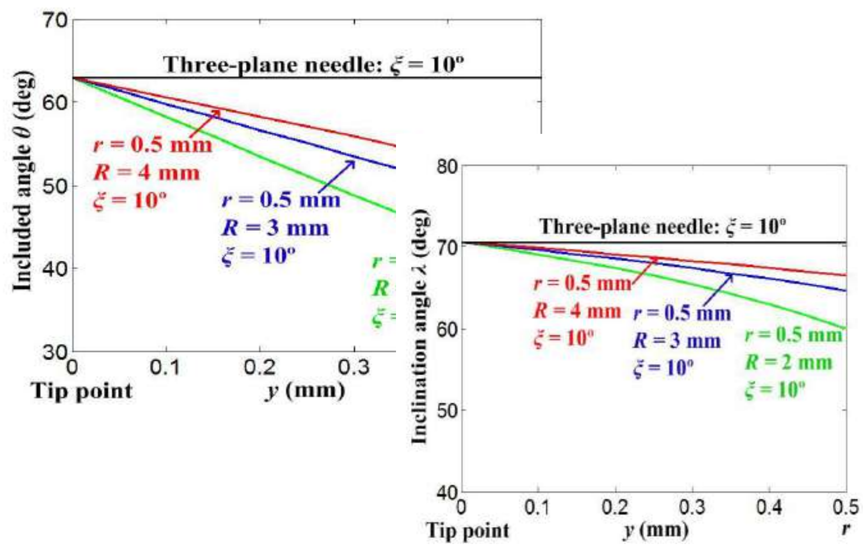


Franseen tip needle cannula



Conical tip needle stylet





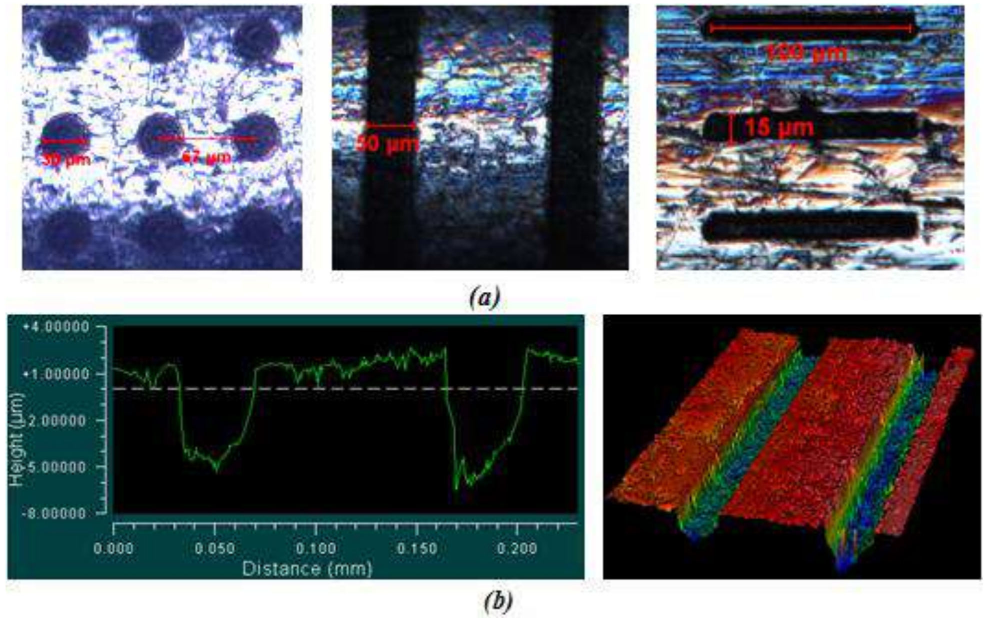
Micro-features for Friction and Adhesion Control

Needle insertion into soft tissue:

- *Low load.*
- *Low speed (2-10 mm/s).*
- *Lubricant: tissue fluid, low viscosity.*

Surface texture trade-offs:

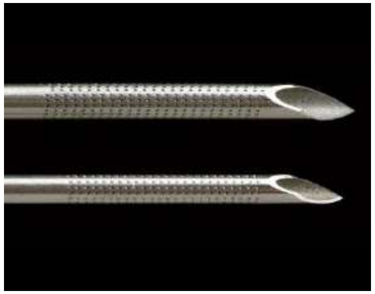
- *Decreased contact area – good or bad?*
- *High stress intensity at sharp edges – bad.*
- *Possible hydrodynamic lift - good.*



(a) optical images of the needle shaft; (b) Zygo interferometer images of the needle shaft after surface texturing.

Micro-features Increase Ultrasound Visibility

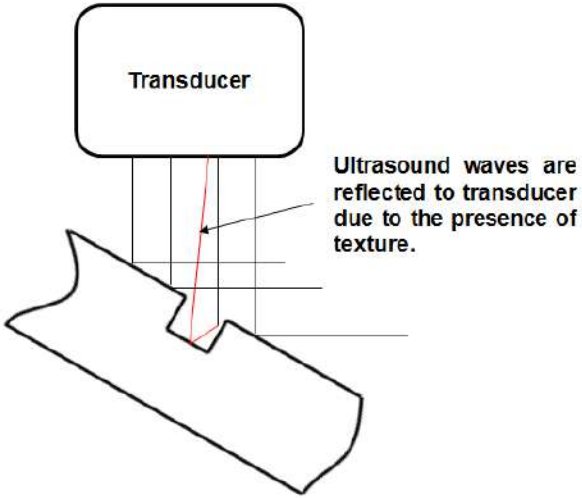
- *Micro-features serve as ultrasound wave reflectors allowing ultrasound waves to be reflected to the transducer.*



Dimpled needles [1]

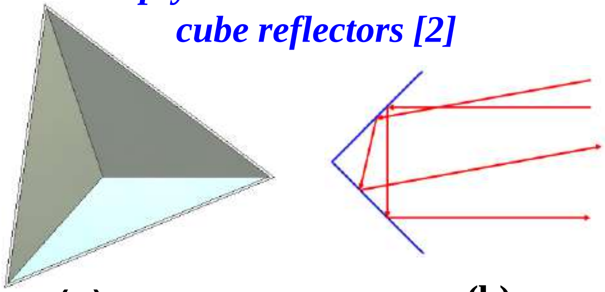
Micro laser etching on needle [2]

Surface texture makes the tip visible under ultrasound [3].



- *Optimal geometry:* ***corner cube reflector***.
- *Reflects the waves back to the source with a minimum scattering.*
- *Consists of three intersecting flat surfaces perpendicular to each other.*

Biopsy needles with 16 corner cube reflectors [2]



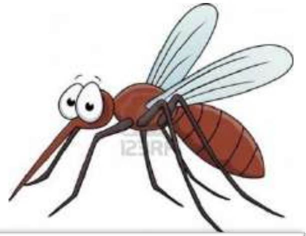
(a) **(b)**

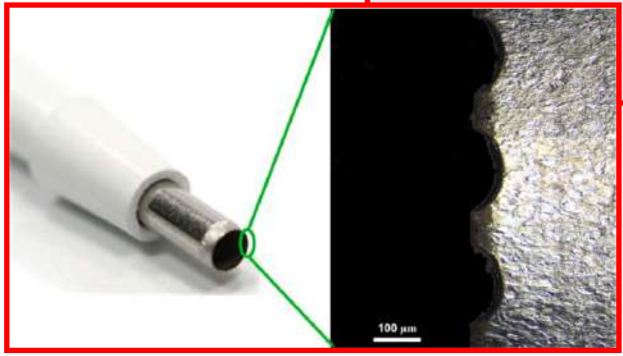
(a) geometry of a corner cube reflector; (b) working principle of a corner cube reflector.

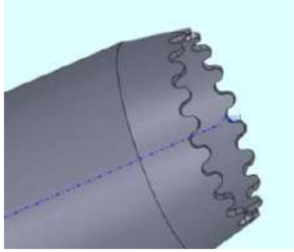
[1] Cook medical.
[2] Havel's Inc.
[3] William C. Relative ultrasonographic echogenicity of standard, dimpled, and polymeric-coated needles. J Vasc Interv Radiol. 2000 Mar;11(3):351-8.

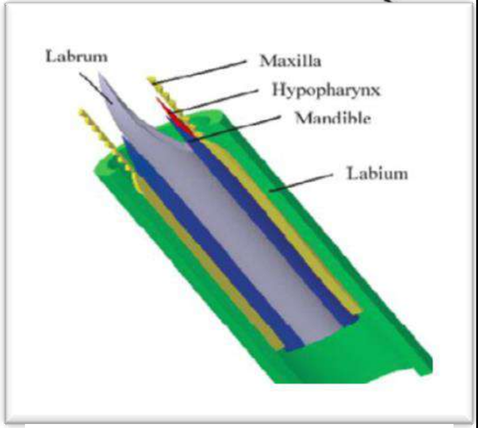
Bio-inspired Biopsy Punches

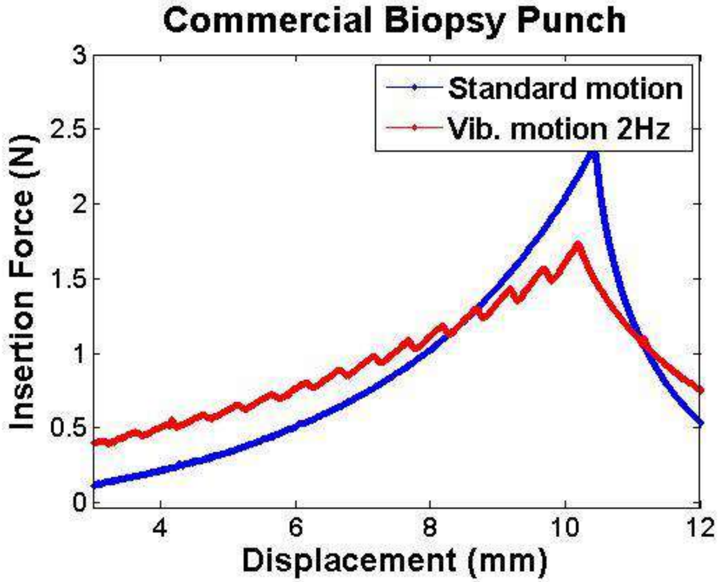
Biopsy Punches

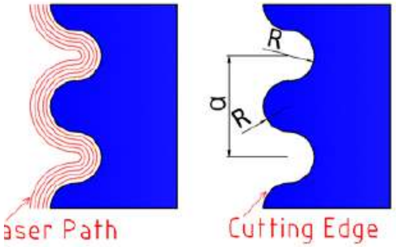




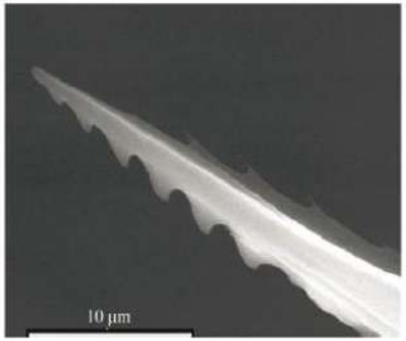








Maxilla



SEM image

Laser Induced Plasma Micro-Machining (LIP-MM)

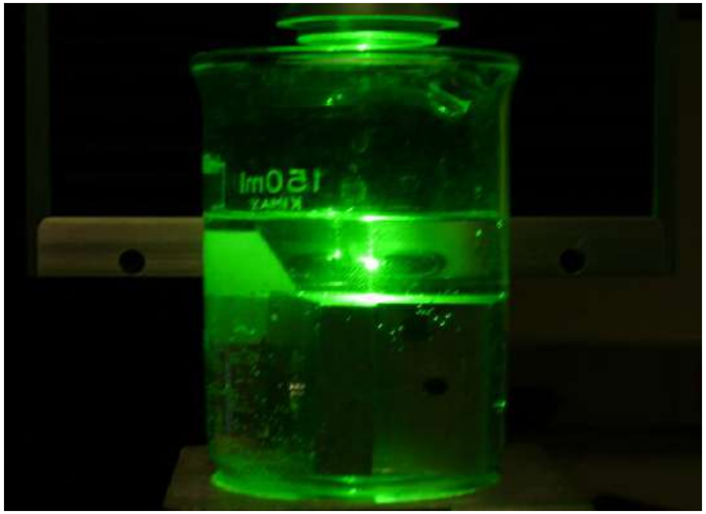
- Working Principle -

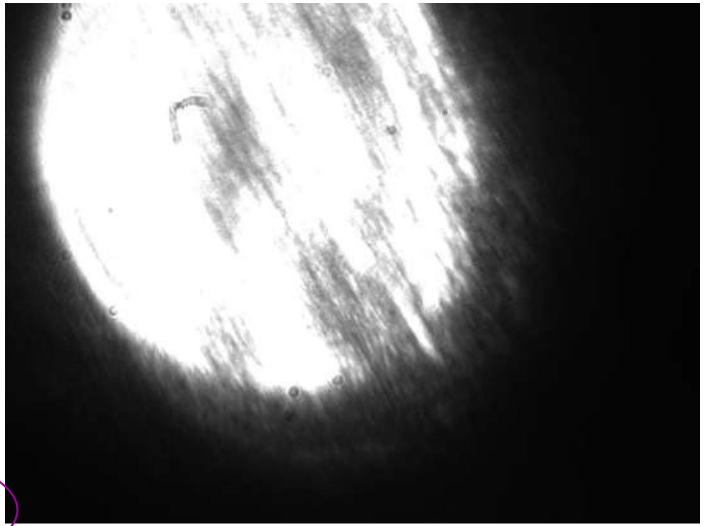
High peak power laser focused in dielectric near the workpiece

Dielectric breakdown creates plasma near the workpiece

Plasma expands explosively causing cavity formation on the workpiece

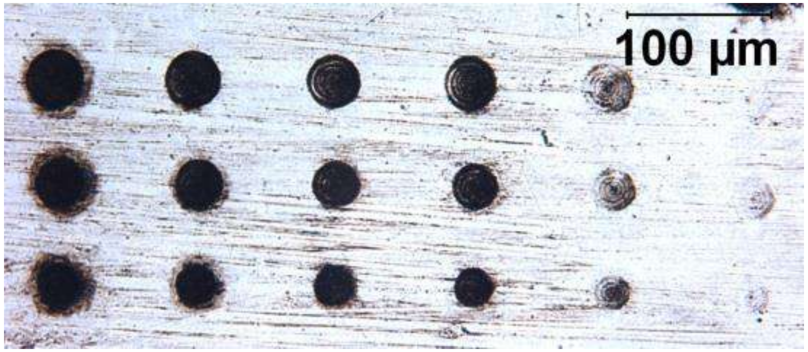
Similar to μ-EDM



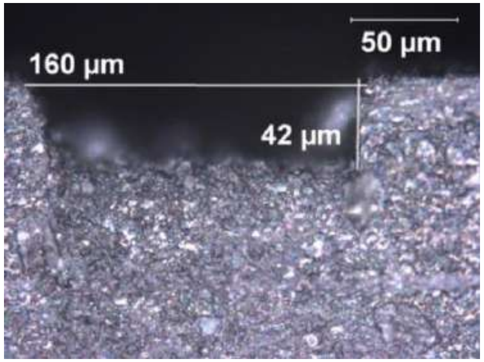


LIPMM: Multi-material Capability

Machining Steel, PCBN, Polycarbonate and Transparent Materials

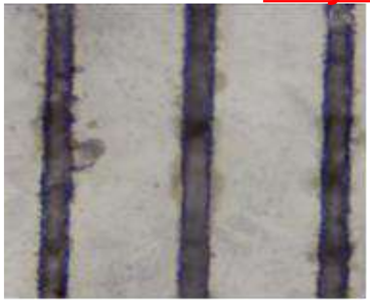


*Craters machined in **stainless steel** by 1,000, 500, 100, 50, 10 and 1 plasma discharges, while the plasma is at a depth of 10 µm (top), 5µm (middle) and 0 µm (bottom) [1]*

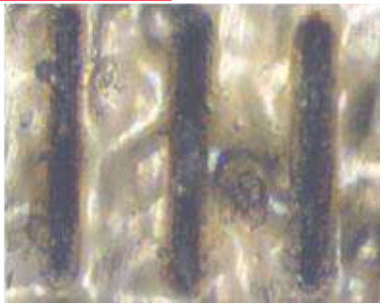


*Micro-groove on **PCBN** using LIPMM (high ablation coefficient material) [1]*

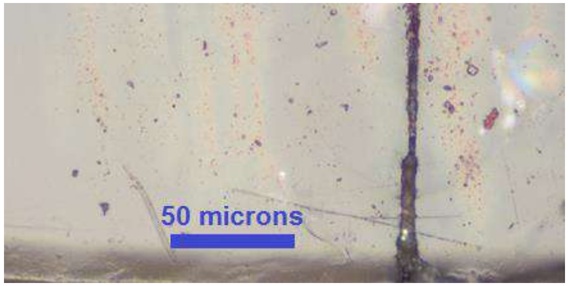
Polycarbonate



LIP-MM (Less Heat Affected Distortion)



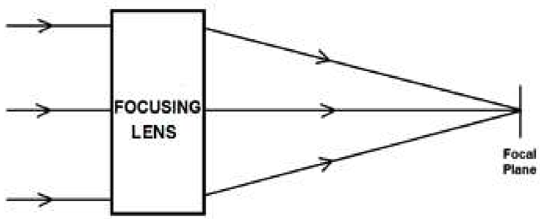
Laser Micro-machining



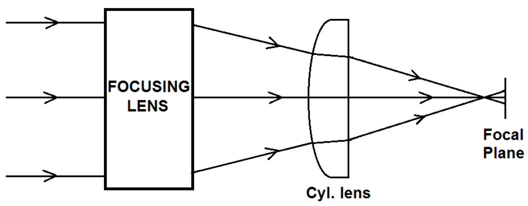
*5 µm wide x 5 µm deep micro-channel on **Alumina ceramic** (transparent and brittle material)*

[1] K. Pallav and K. F. Ehmann, "Laser Induced Plasma Micro-Machining," ASME Conference Proceedings, vol. 2010, pp. 363-369, 01/01/ 2010.

Line-based LIPMM



Spot focus



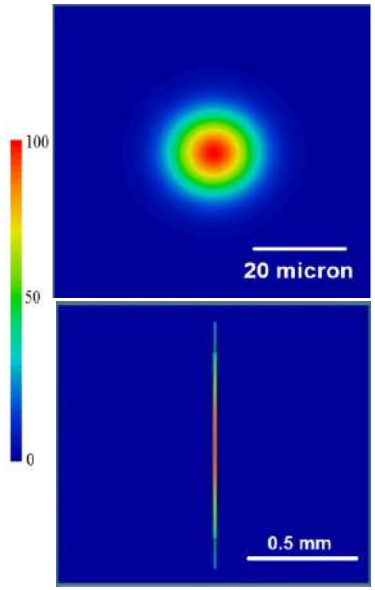
Line focus

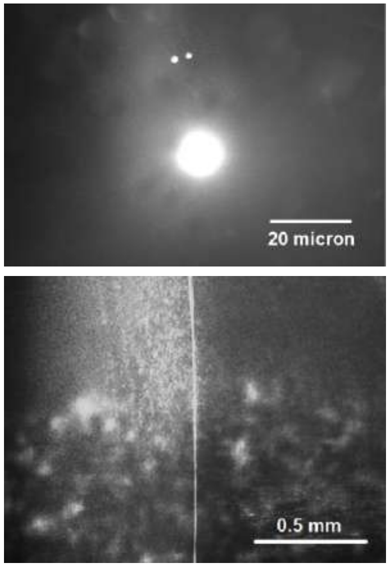
Diameter of focal spot: $D_s = \left(\frac{4\lambda}{\pi}\right)\left(\frac{F}{D}\right)$

(F = Focal length, D = Beam diameter, λ = Wavelength)

Simulated Laser Spots

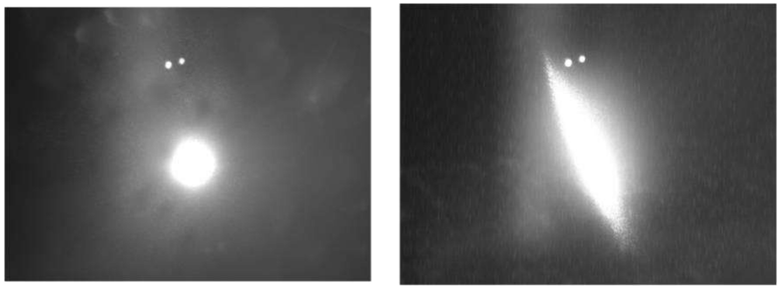
(Plot generated by Code V Beam Propagation Analysis)





Corresponding plasma plume shapes, captured on CCD camera

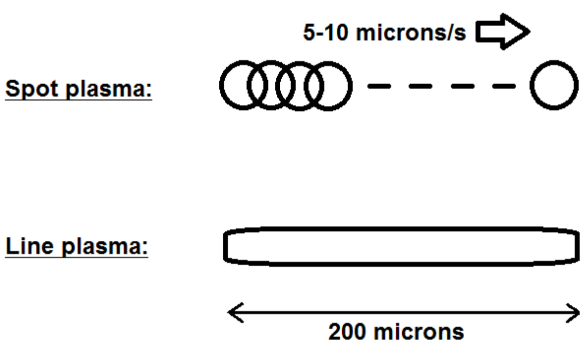
Micro-channels Created by Line-plasma



Spot plasma

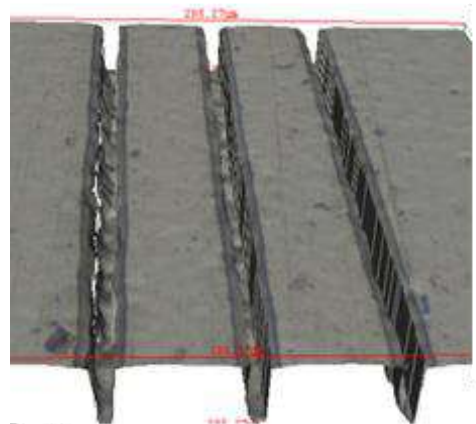
Line plasma

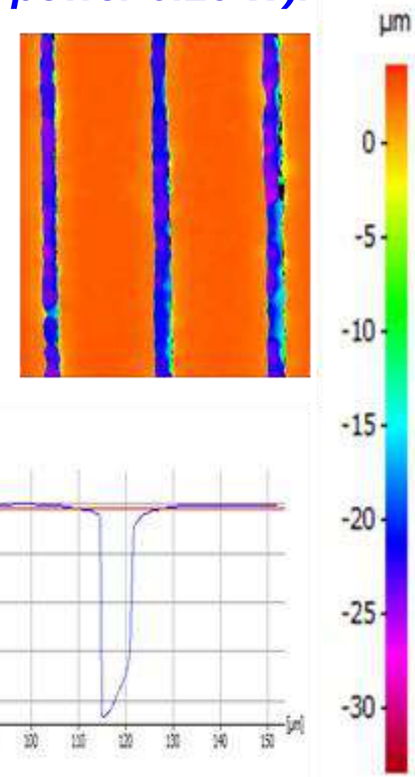
Images of spot and line plasma taken with an in-line CCD camera.

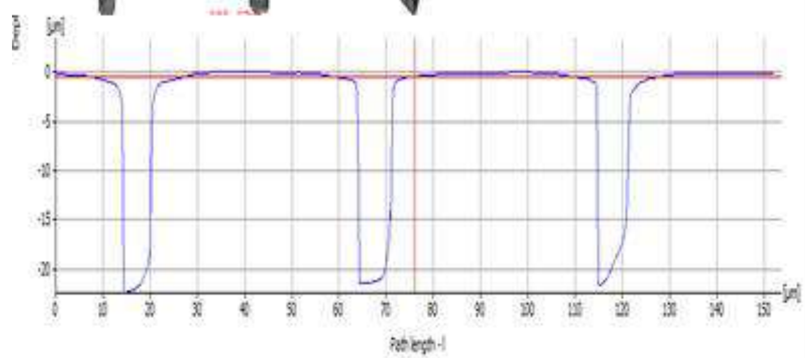


Machining of micro-channels with spot and line plasma methods

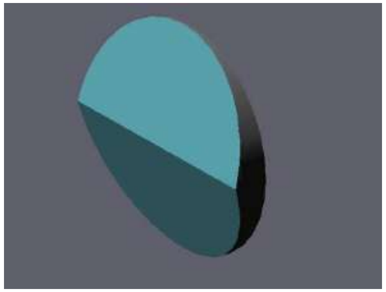
Micro-channels fabricated with a depth of 22 ±2 µm and width 7 ±2 µm (Laser parameters: 10 kHz, power 0.16 W).



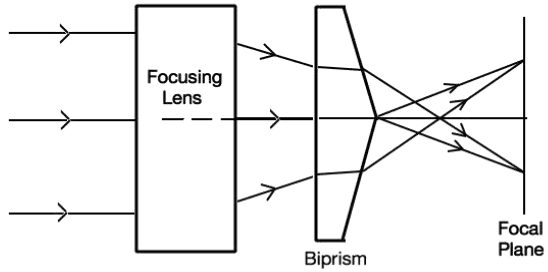


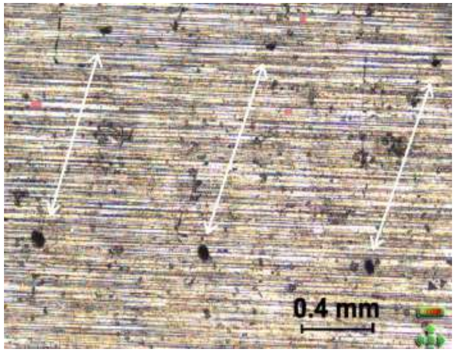


Optical Manipulation of Plasma in LIPMM

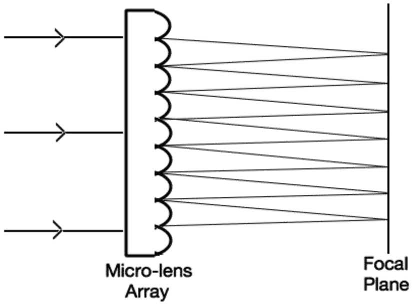


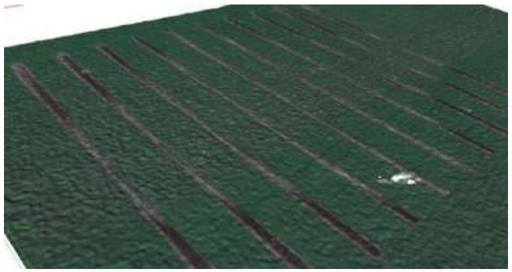
Biprism

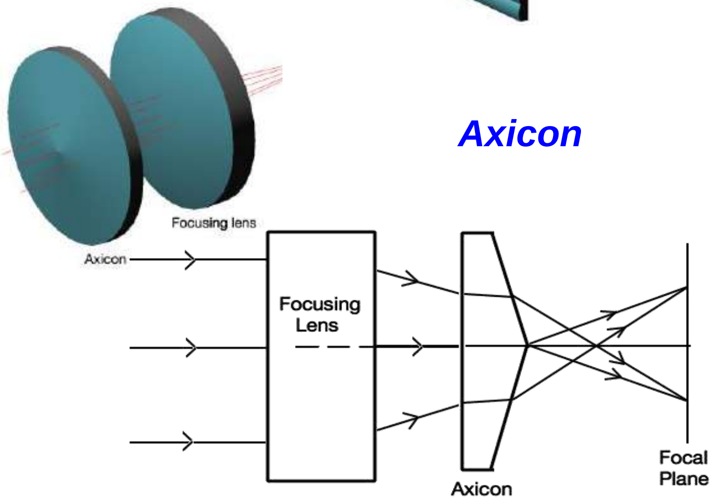




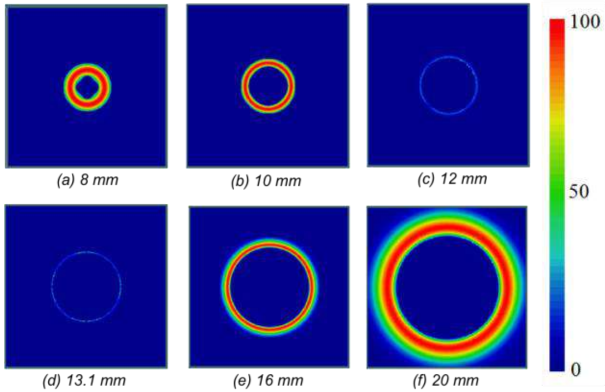
Micro-lens array

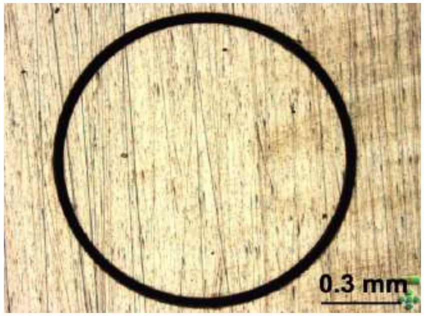




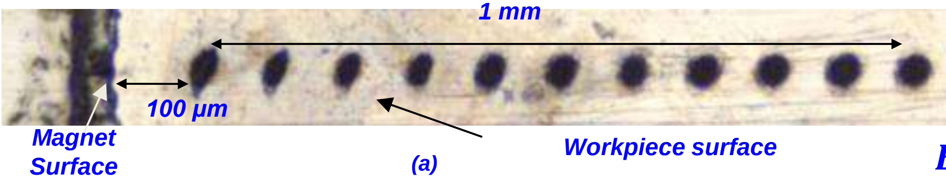


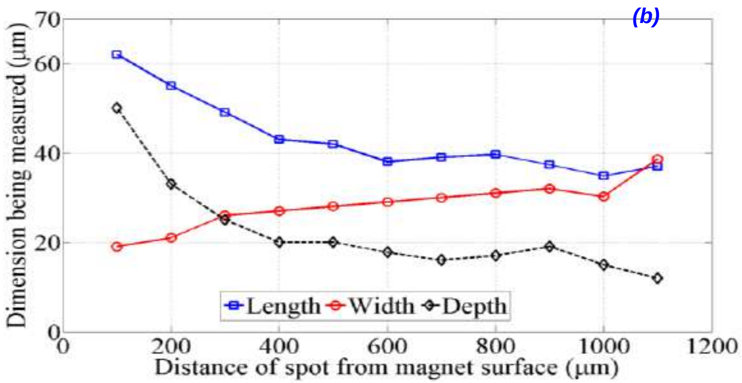
Axicon



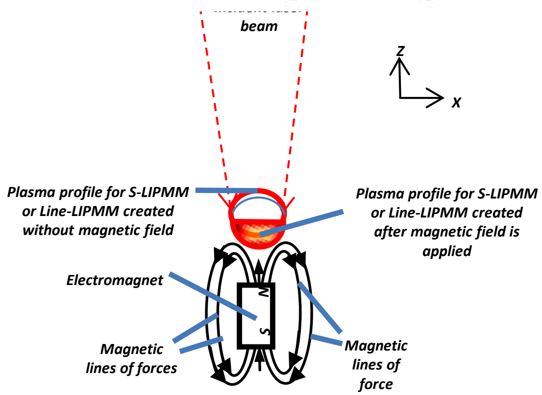


Magnetically-assisted Plasma Micromachining



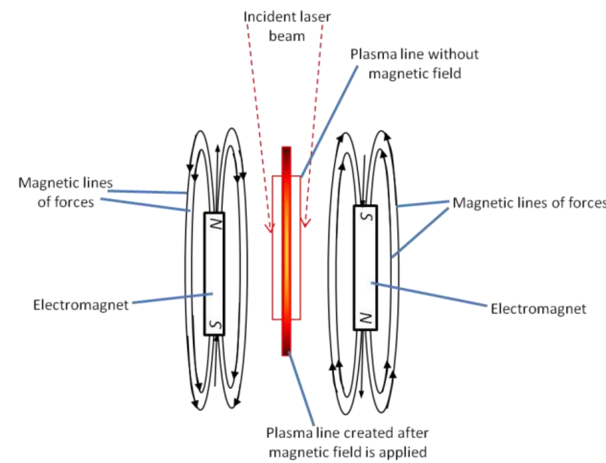


Effect of magnetic field in S-LIPMM (Power: 0.12 W, Frequency: 10 kHz, Dielectric: Distilled water, Z translation up to a 20 µm depth, AA5052 workpiece).

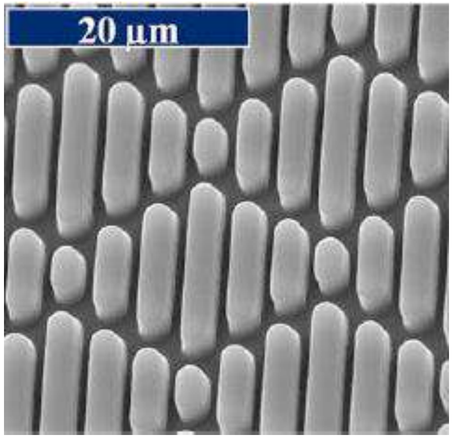


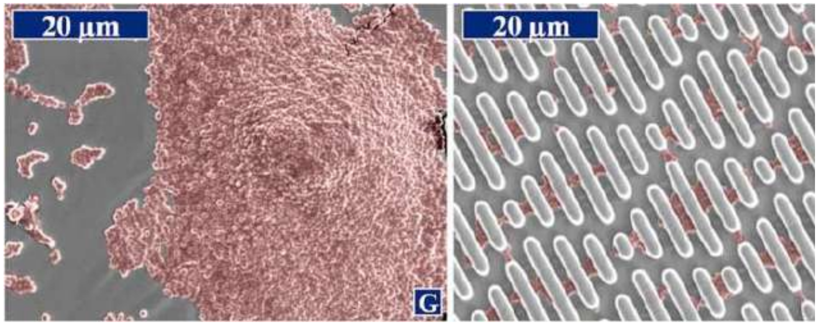
Downward displacement of line plasma (cross-section view) by a longitudinal magnetic field

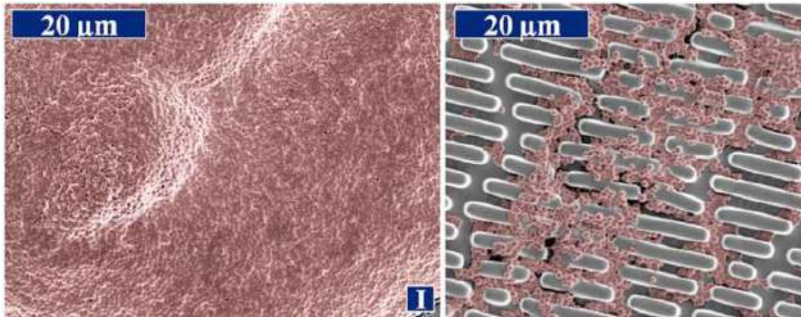
Elongation of line plasma under the effect of a lateral magnetic field



"Sharklet" Pattern

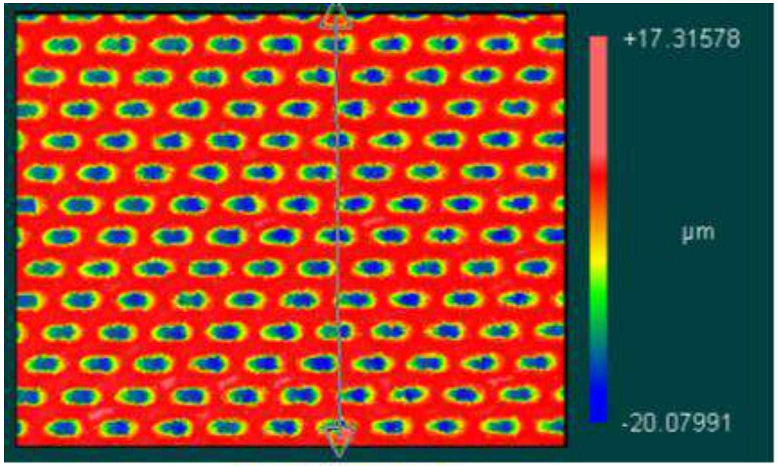




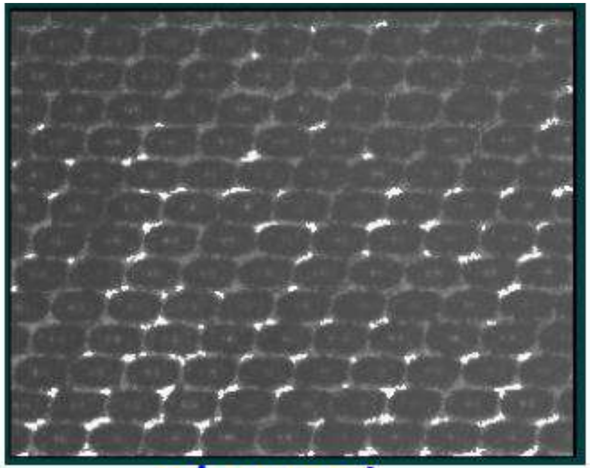


FRepresentative SEM images of S. aureus on PDMS surfaces at day 14 (G) and day 21 (I). Areas of bacteria highlighted with color to enhance contrast. On the left of each group shows the smooth PDMS surface and the right shows textured PDMS surface [3].

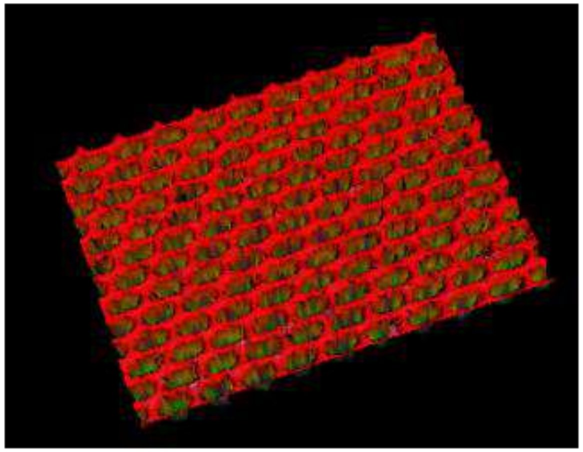
LIP-MM Sample Bacteria Growth



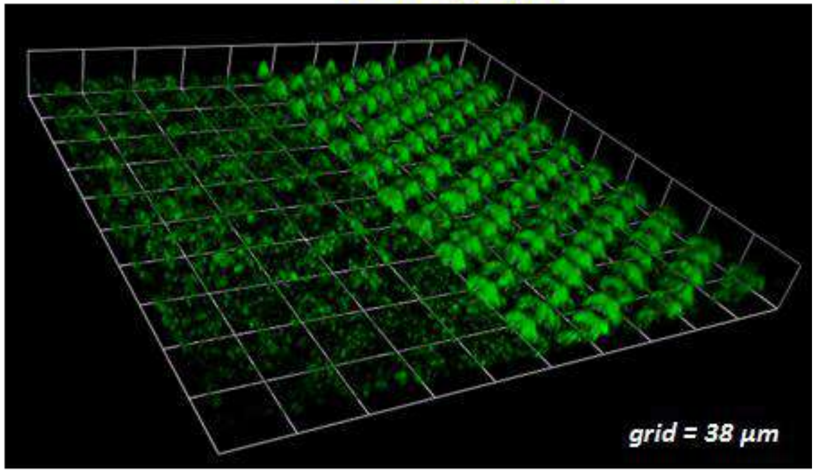
Depth scan



micrograph

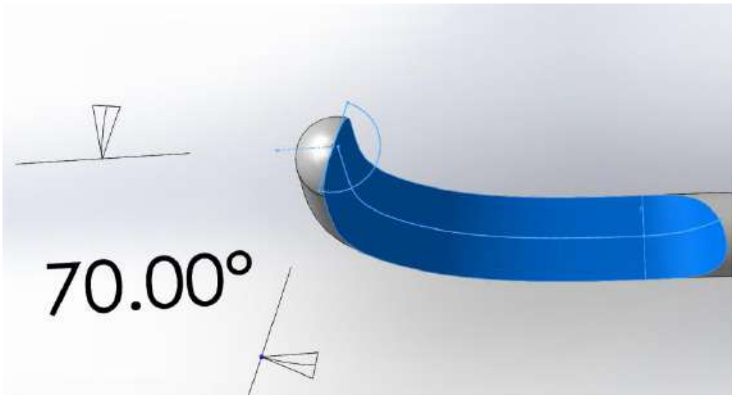


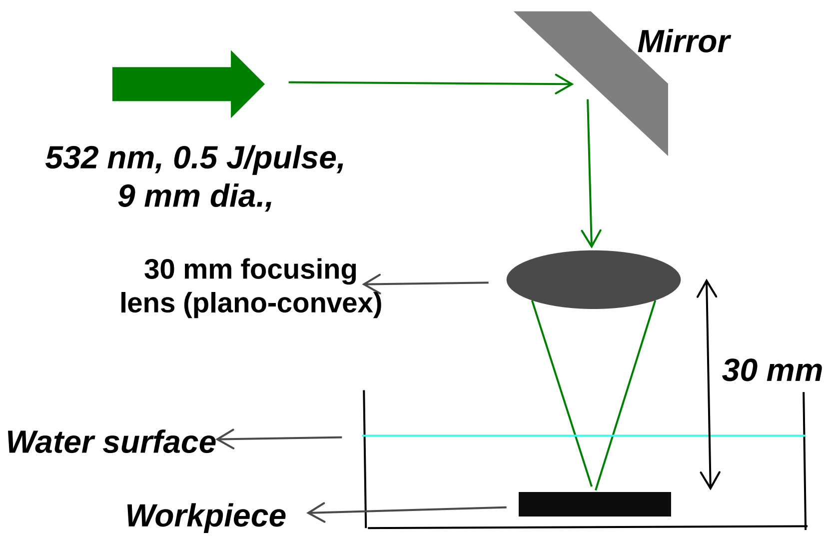
3D view



Biofilm study

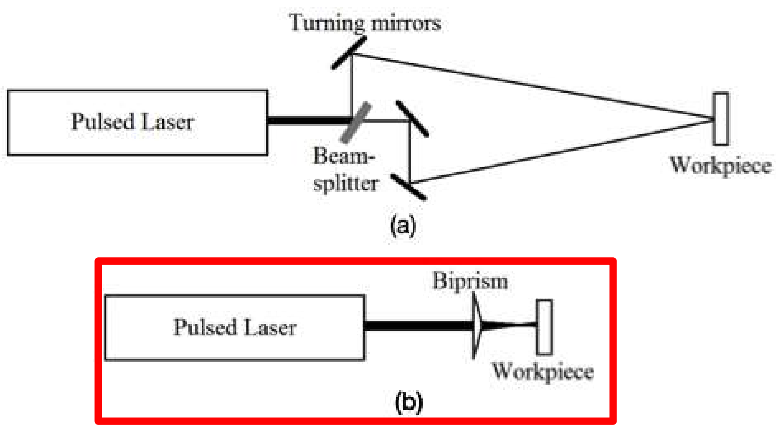
Laser Shock Peening of Dental Instruments



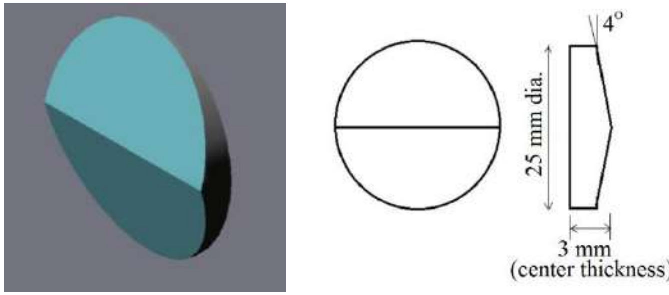


- Distance from lens principal plane to workpiece = 30 mm
- Distance of top of lens holder from workpiece = 33.4 mm

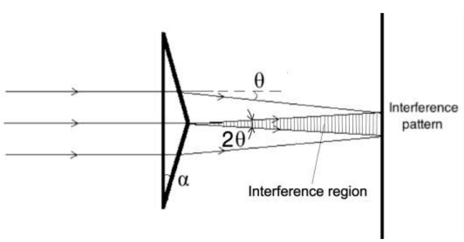
Large-scale Periodic Surface Micro-feature Generation by Biprism Interference Micro-machining



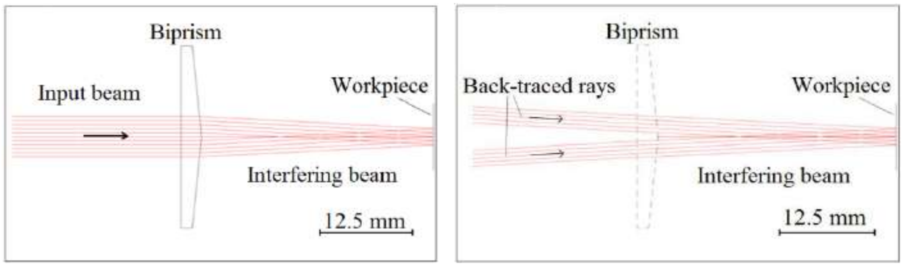
Schematics of: (a) current laser interference micro-machining; (b) proposed biprism interference micro-machining



(a) 3D perspective view (b) Orthogonal views
Biprism design with a circular cross-section.



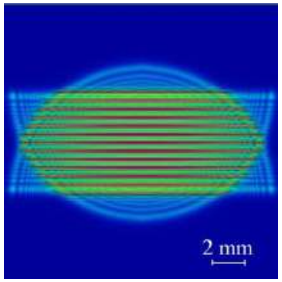
Biprism interference for a collimated incident beam.

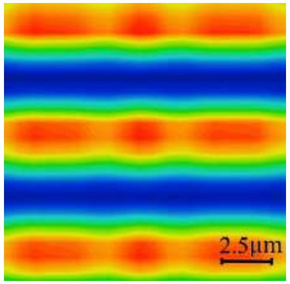


(a) (b)

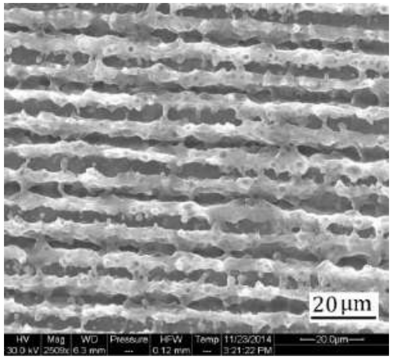
Figure 6. Ray tracing analysis of a collimated beam incident on a biprism in configuration A, for: (a) sequential rays; (b) back traced rays.

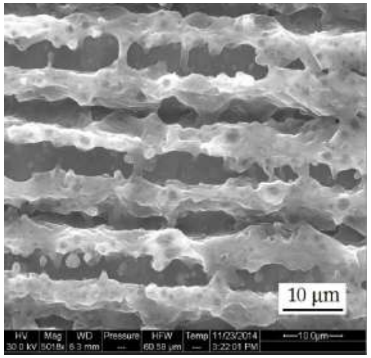
Large-scale Periodic Surface Micro-feature Generation by Biprism Interference Micro-machining



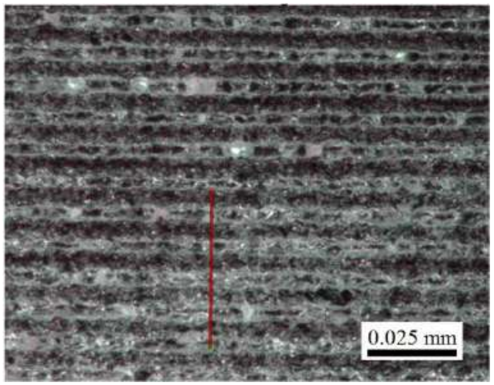


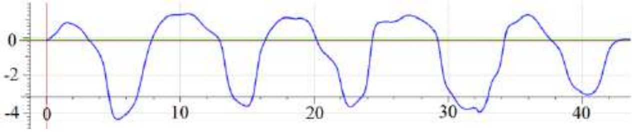
Simulated intensity distribution across the beam cross-section, showing the entire cross-section and a 0.02 mm section.

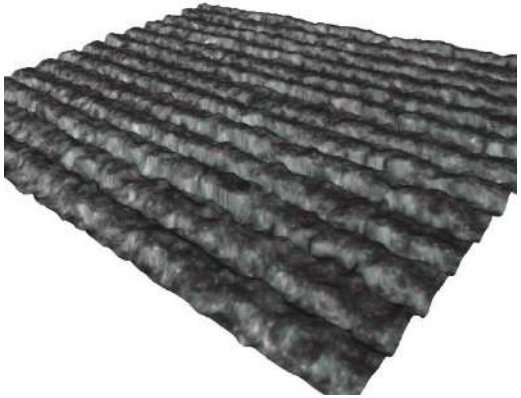




SEM images of ablated micro-pattern, at 2500x and 5000x magnifications.





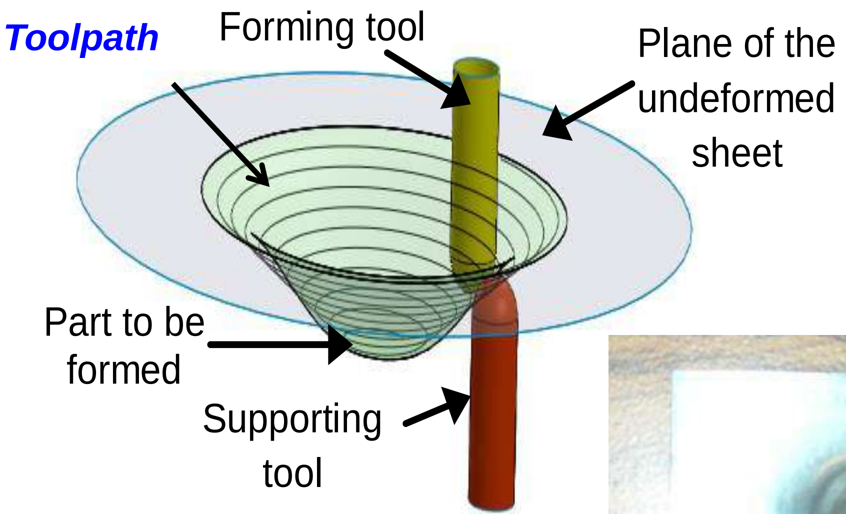


Generated micro-pattern: optical surface image; profile cross-section along the indicated path and three-dimensional view;

Deformation-based texturing

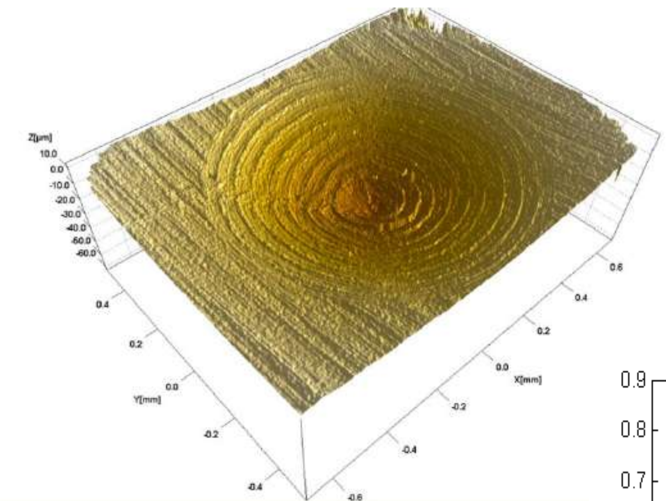
- Micro Incremental Forming
- Micro Rolling -

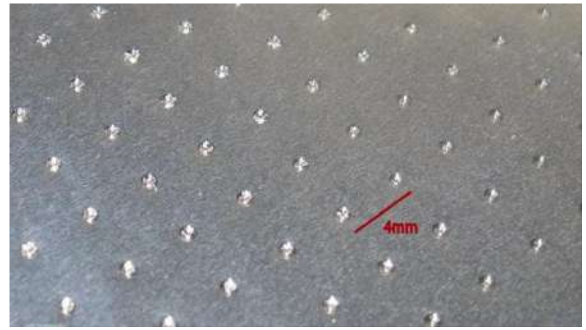
Double Sided Incremental Forming: DSIF



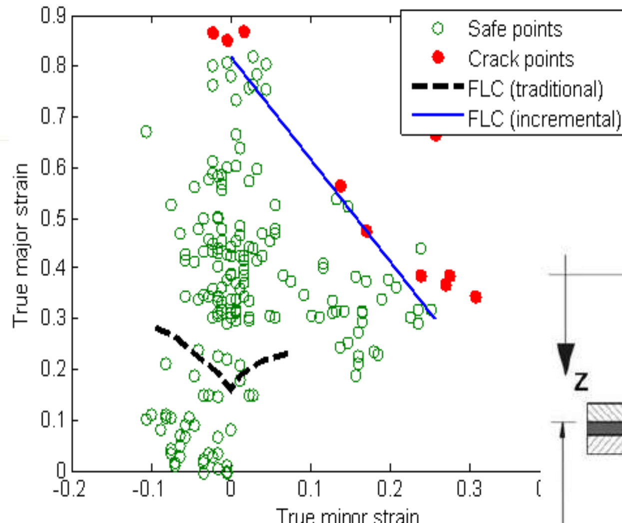
- ***DSIF uses two tools, one on each side, of a peripherally clamped sheet metal to locally deform the sheet along a predefined toolpath***
- ***The sum total of the local deformations adds up to result in a final formed part***

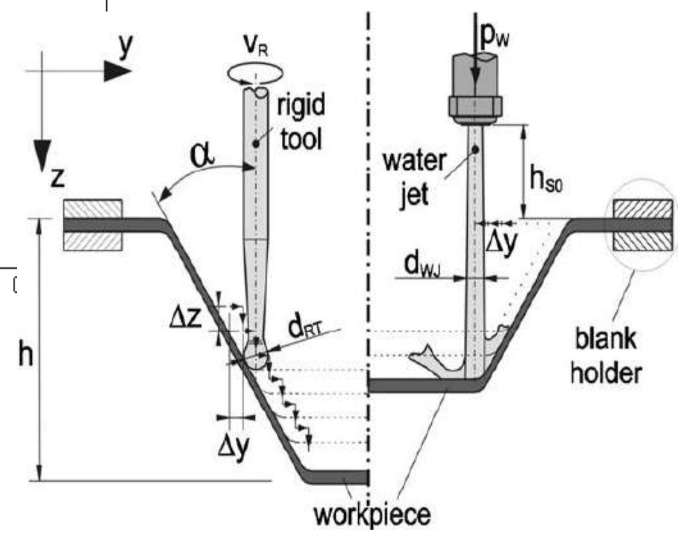
Incrementally Formed Textured Sheet





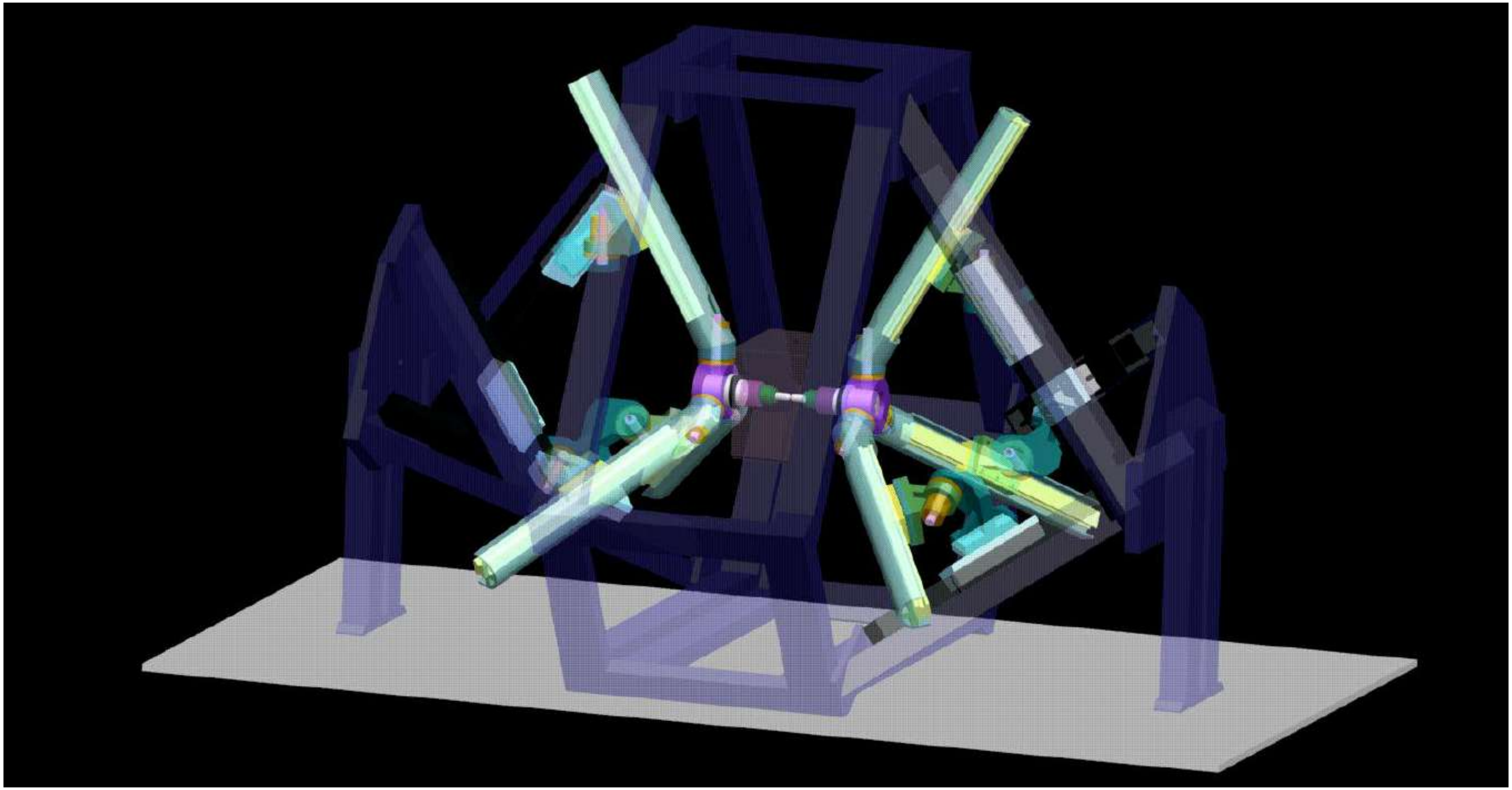
Stainless steel sheets: 250 µm – 1 mm in diameter





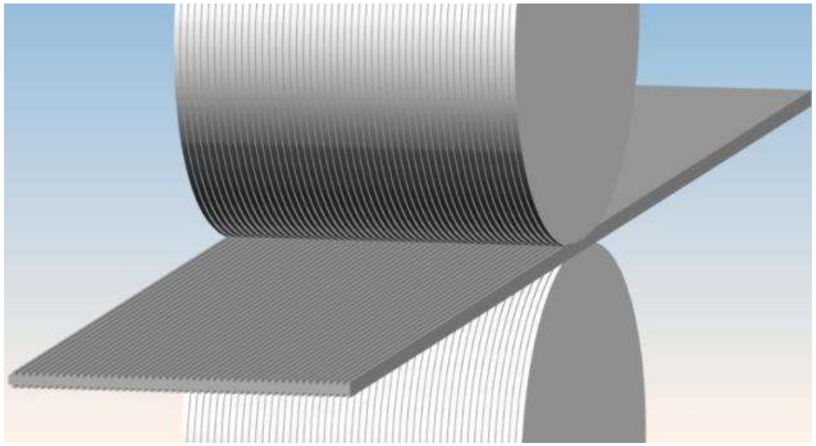
Cao, J., Yuan, W., Pei, Z.J., Davis, T., Cui, Y. and Beltran, M. (2009), ASME *Journal of Manufacturing Science and Engineering*, Vol. 131(6), doi:10.1115/1.4000562.

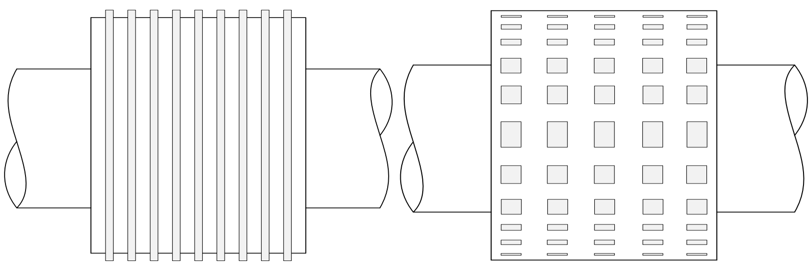
Desktop DSIF Tri-Pyramid Robot

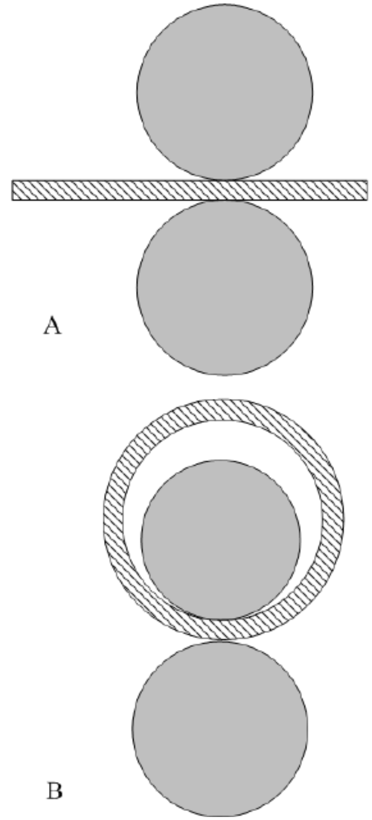


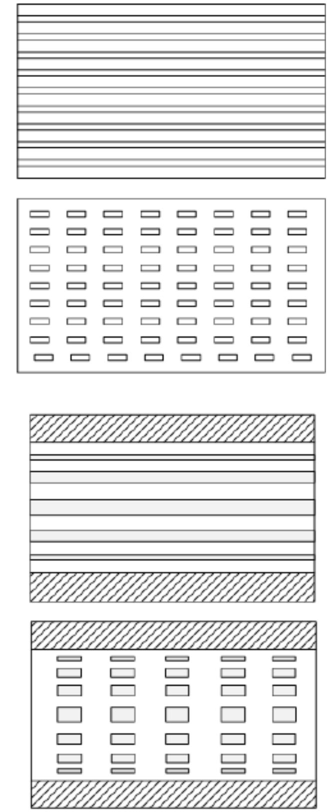
~ 500 mm

Roll-to-Roll Texturing





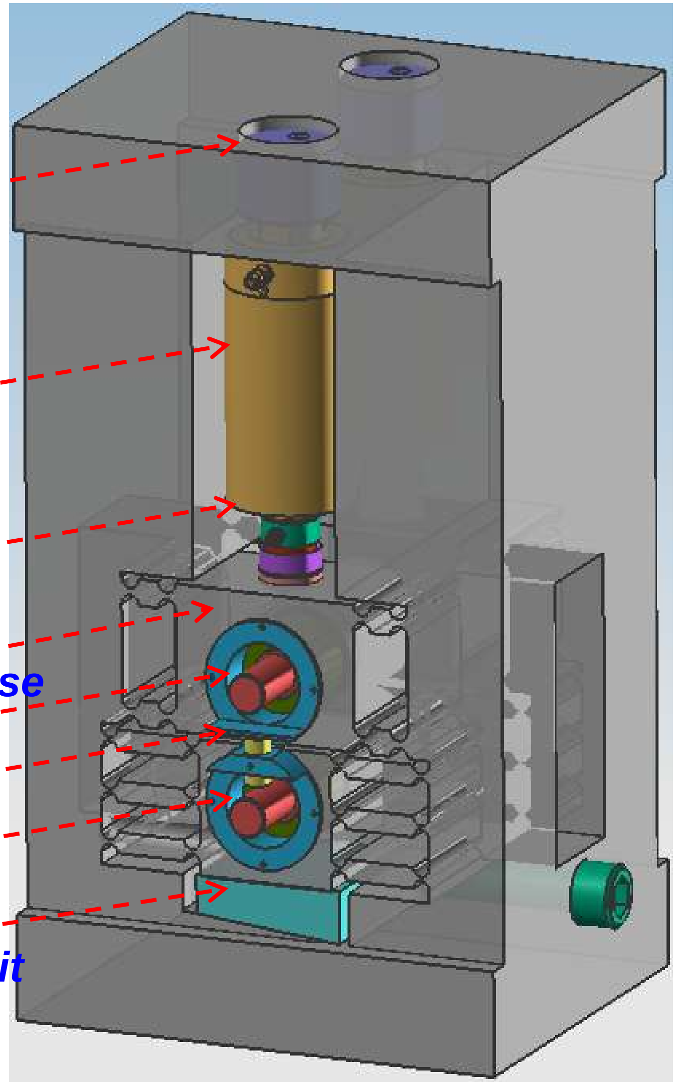


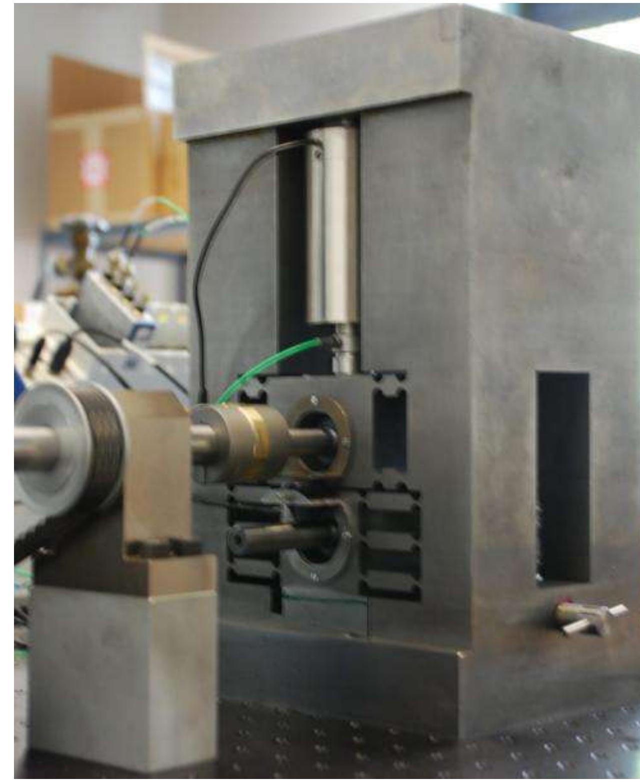


ADVANTAGES:

- Quick fabrication
- Works for different materials
- Low cost at high manufacturing volumes
- High energy efficiency

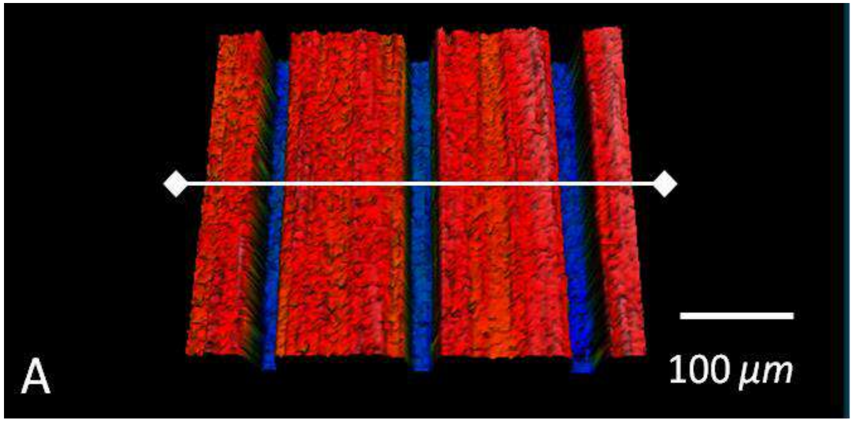
Desktop Micro-Rolling-Based Surface Texturing

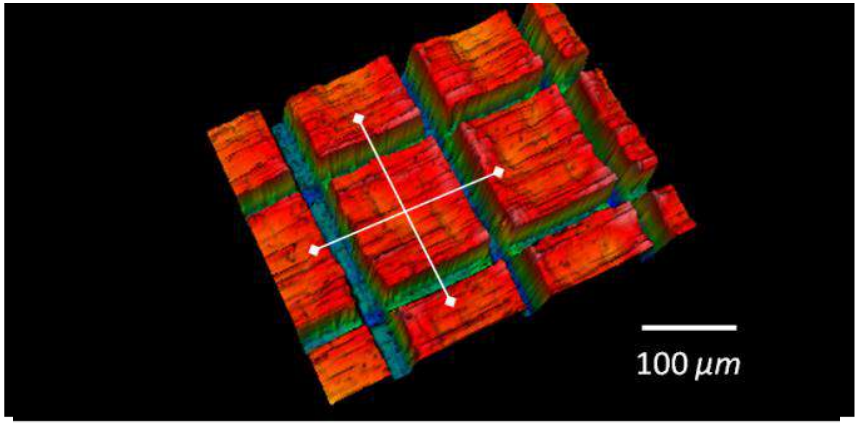


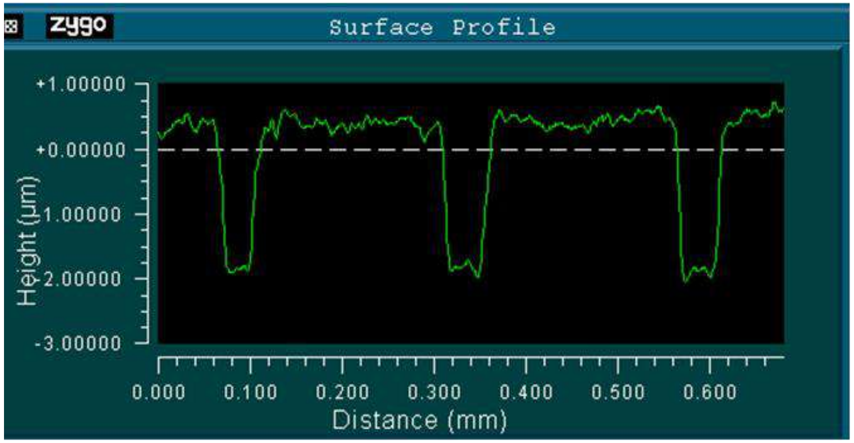


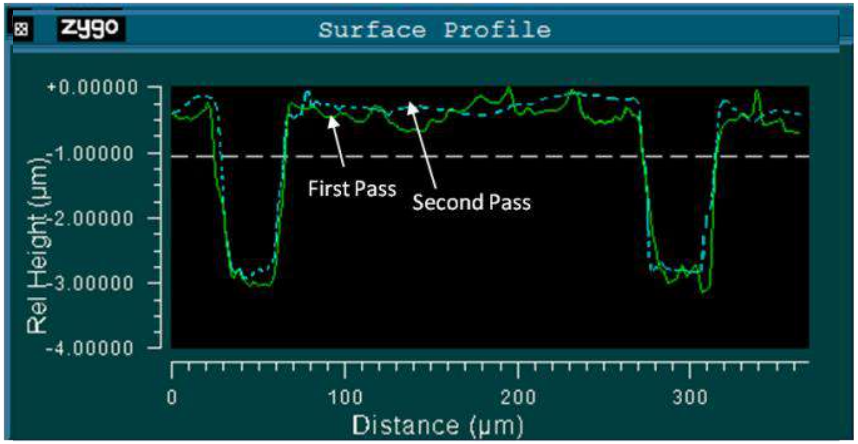
Size:
340 mm x 200 mm x 166 mm

Multi-pass Surface Texturing by Micro-rolling

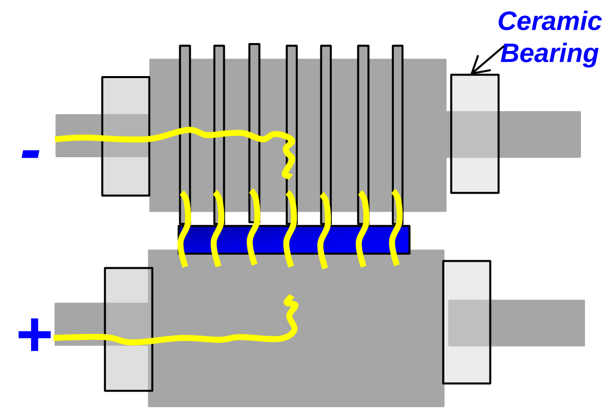


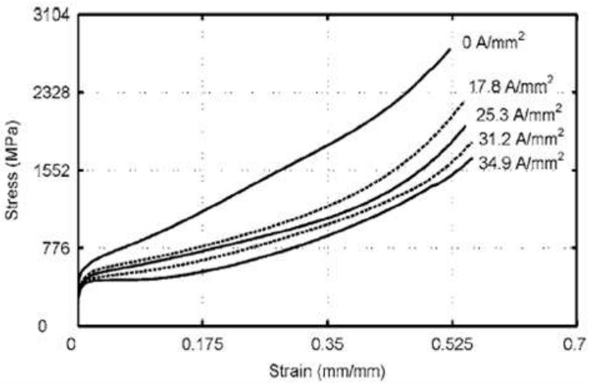




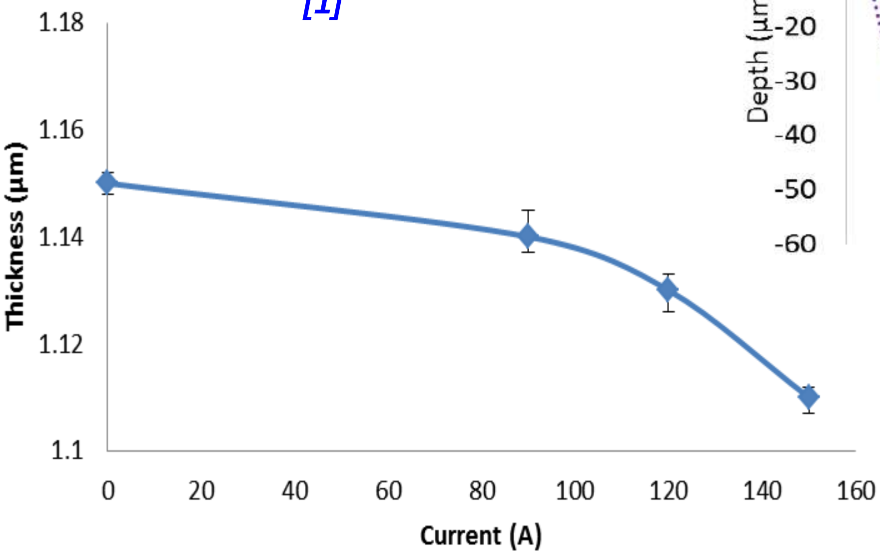


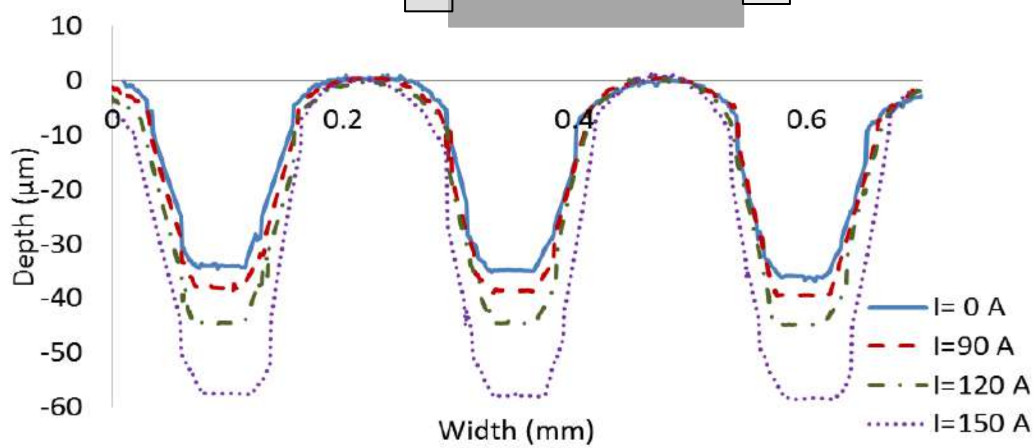
Electrical Effect





Stainless steel stress strain curves [1]





With 150 A current (density of 25 A/mm^2) pass through:

- *The depth of micro channel increased more than 68%*
- *The thickness of the sheet reduced around 3%*

[1] T.A. Perkins, T.J. Kronenberger, and J.T. Roth. 2007. Metallic forging using electrical flow as an alternative to warm/hot working. Transactions of the ASME 129.

CONCLUSION

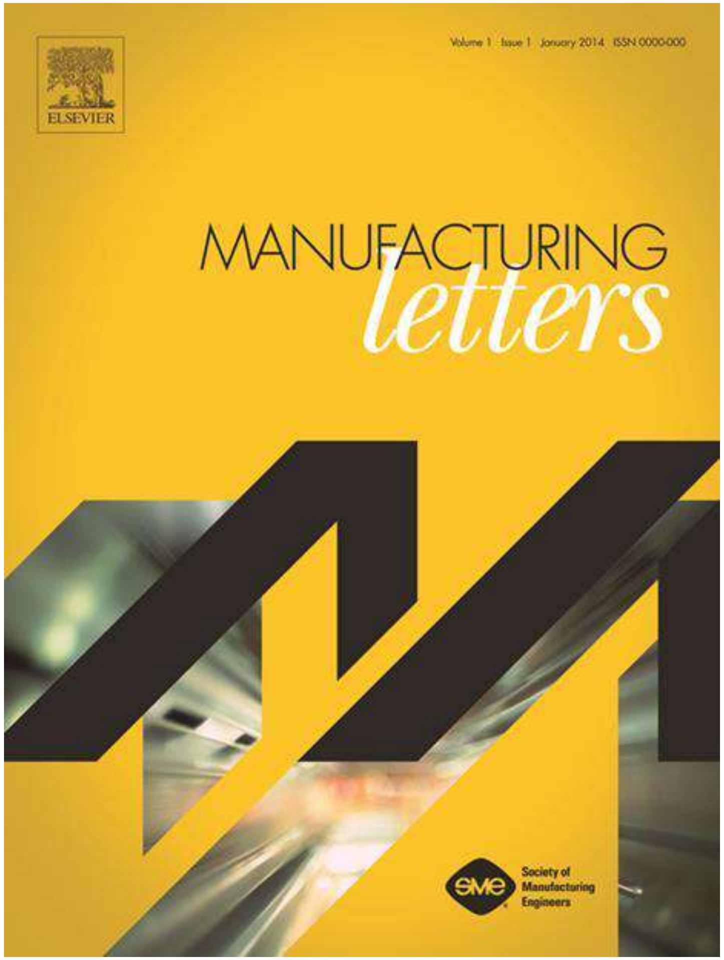
I have just tried to scratch the surface!

ACKNOWLEDGEMENTS

I gratefully acknowledge the work of all the members of the

Advanced Manufacturing Processes Laboratory

at Northwestern without whose dedication, imagination and hard work none of the presented results would have been possible.



K. Ehmann
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EDITOR

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EDITOR

THANK YOU!

QUESTIONS?