Microrolling-based Surface Texturing

Man-Kwan Ng, James Magargee, **Jian Cao**, Kornel F. Ehmann

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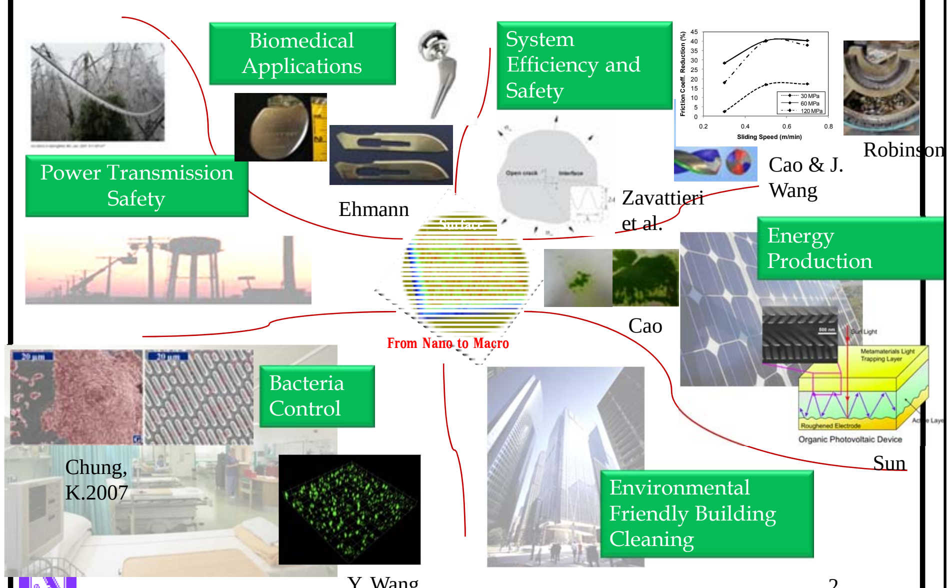
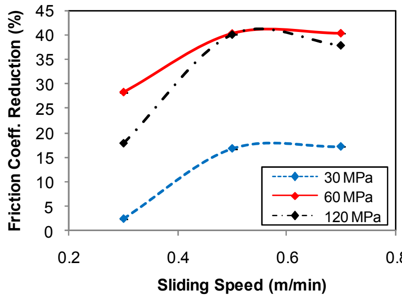
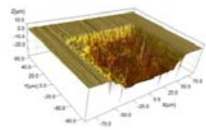
Impact of Engineered Surfaces



Laser Textured Steel Sample – Friction Evaluation





Meng, F., Zhou, R., Davis, T., Cao, J., Wang, Q., Hua, D., Liu, J., (2010) "Study on Effect of Dimples on Friction of Parallel Surfaces Under Different Sliding Conditions", *Applied Surface Science*, 256, no. 9: 2863-2875, doi:10.1016/j.apsusc.2009.11.041

Results of Textured Drill Bits

Un-textured

Baseline drills a) #1 after 30 holes drilled, b) #2 after 52 holes drilled and c) #3 after 60 holes drilled

Textured

Drills with 20% textured area a) #1 after 60 holes drilled, b) #2 after 30 holes drilled and c) #3 after 60 holes drilled

Ling, T.D., Liu, P., Xiong, S., Grzina, D., Cao, J., Wang, Q. J., Xia, Z. C. and Talwar, R. (2013) "Surface Texturing of Drill Bits for Adhesion Reduction and Tool Life Enhancement", Tribology Letter, Vol. 52, pp.113-122,

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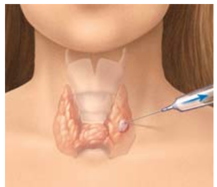
Minimally Invasive Needle Insertion Procedures

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

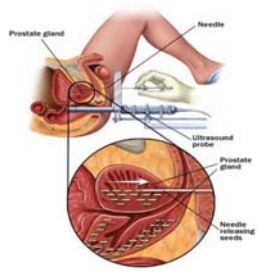


Fine-needle aspiration

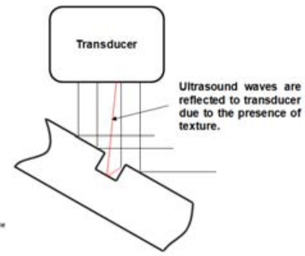
Core needle biopsy

- **Brachytherapy** - internal radiation therapy cancer

Prostate brachytherapy



Mayo Foundation for Medical Education and Research



[William C. Relative ultrasonographic echogenicity of standard, dimpled, and polymeric-coated needles. J Vasc Interv Radiol. 2000 Mar;11(3):351-8.

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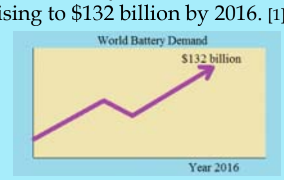
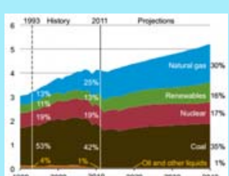
Motivations: *Electricity Generation Efficiency Improvement*

Electricity Generation Efficiency Improvement

- World battery demand is estimated rising to $132 billion by 2016. [1]



- Over 80% of electricity will be generated by coal, natural gas and nuclear energy by 2020. [2]



Micro heat exchangers [3]

- Textures on heat exchangers increases heat exchange rate.

Material: 316 Ti

[1] Fredonia, "World Batteries", 2012. http://www.freedoniagroup.com/DocumentDetails.aspx?DocumentId=595546.
[2] AEO2013 Early Release Overview, 2013, http://www.eia.gov/forecasts/aeo/er/pdf/0383er(2013).pdf
[3] http://www.imm-mainz.de

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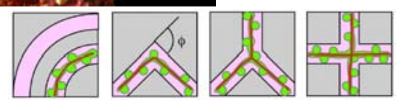
Challenges in Surface Texturing

Scalability – Speed, Resolution, Shape, Durability

Material Choices – Ceramics, Glasses, Metals



Joester and Park, Northwestern University, Study of sea urchin embryos growing crystals for magnetic and optical material research

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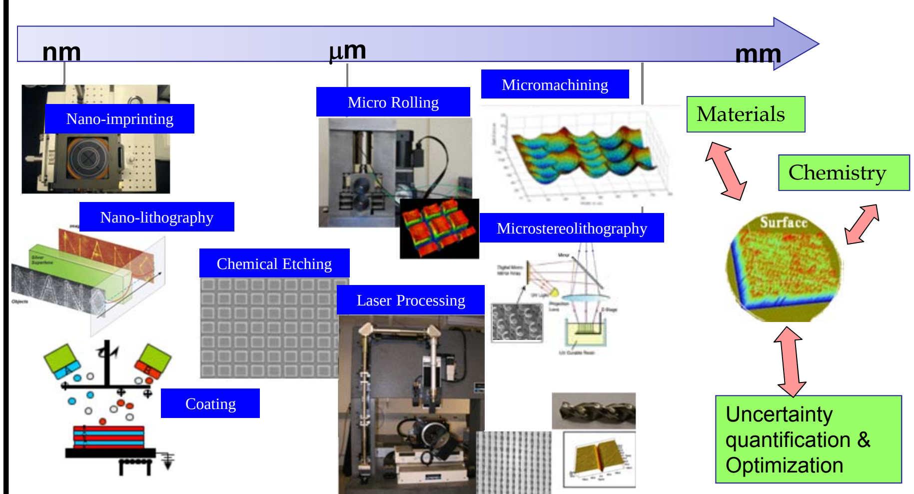
Manufacturing methods for desired surface



Outline

- Motivations
- Design of desktop microrolling mill
- Rolling-based texturing methodology
- Conventional microrolling
- Electrically-assisted microrolling (EAμR)
  - Continuous DC EAμR
  - Pulsed DC EAμR
- Future work

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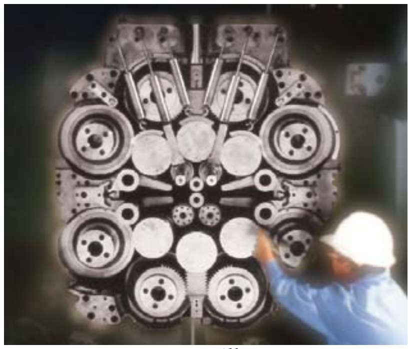
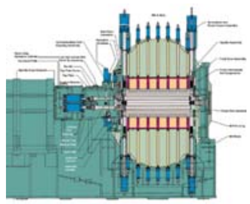
Industrial Use Microrolling Mill

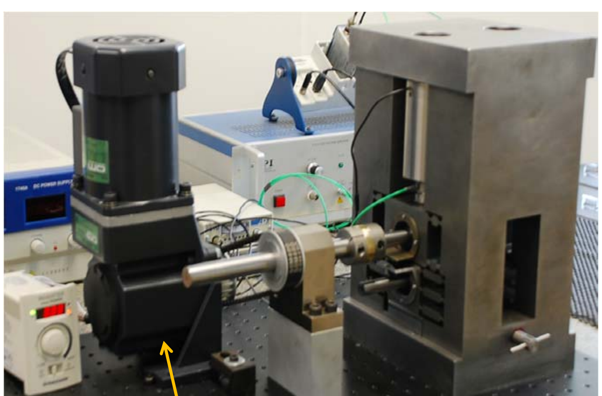


Z-mill
(http://www.waterburyfarrel.com)



\$ 1.5 – 3 million
~ 2 m^2 large

Desktop Microrolling Mill (DμRM)



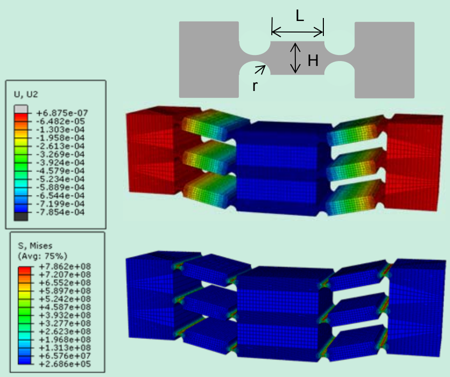
0.34 *m*

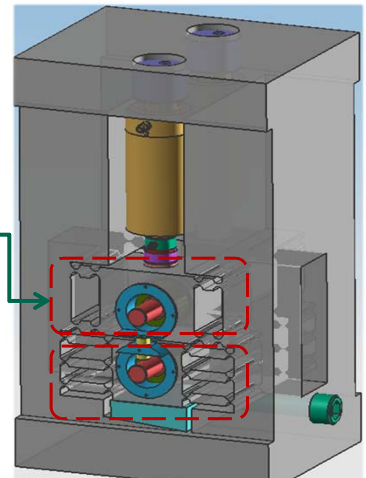
Each roll shaft is controlled by an individual speed-adjustable motor.

- Max. speed: 2,400 rev/min
- Permissible Torque: 1.29 $N{\cdot}m$

Desktop Microrolling Mill (DμRM)

Flexural Bearing Housing





FPM	H (mm)	r (mm)	L (mm)	Width (mm)	Stiffness (N/micron)	Natural Frequency(*Hz*)	Critical Stress (*MPa*)	Movement Range (*μm*)
#1	10	3.7	8	50	80	1600	400	100
#2	8	3.3	28	50	12	1000	800	800

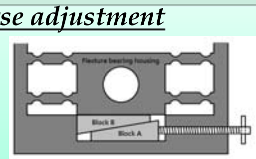
Desktop Micro-rolling Mill (DμRM)

Roll gap adjustment

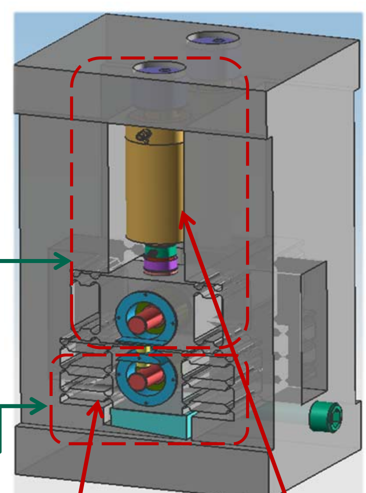
Fine adjustment

Piezo-actuators push the upper Flexural bearing housing (FBH) downward .

Coarse adjustment



Wedge adjusting unit pushes the lower flexural bearing housing upward.



Desktop Microrolling Mill (DμRM) - Sensors

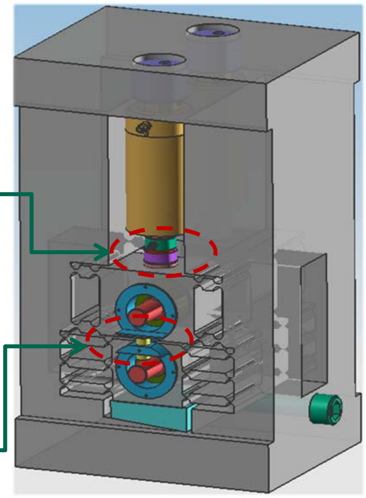
Monitoring and Measurements

Piezoelectric load cells

For roll separating force measurement.

Capacitive position sensors

For roll gap size measurement.



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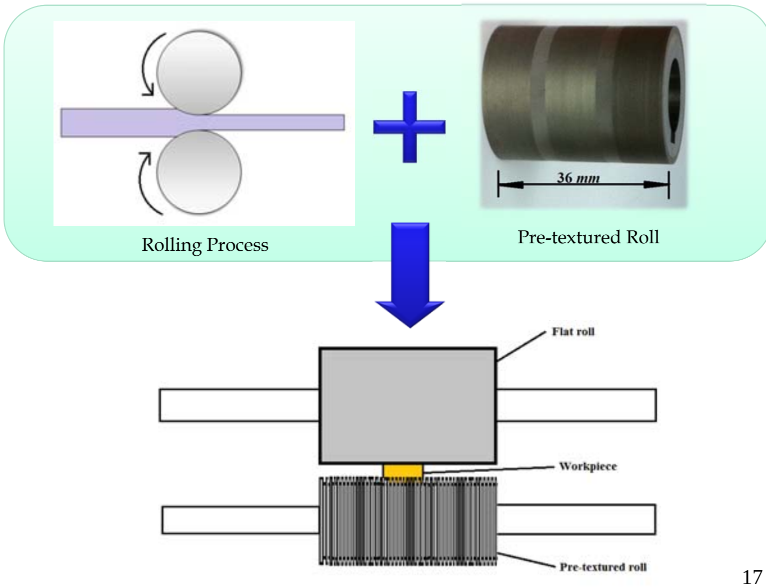
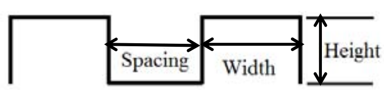
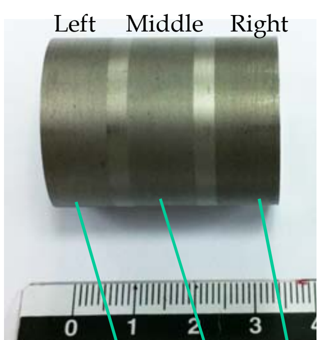
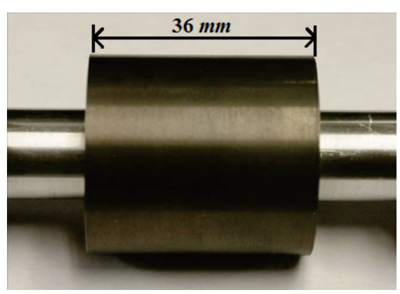
Microrolling-based Texturing



Pre-textured Roll







	Left	Middle	Right
Teeth width	60	15	50
Teeth height	50	30	110
Spacing	100	80	200

Teeth width	100
Teeth height	100
Spacing	100

Unit: [μm]

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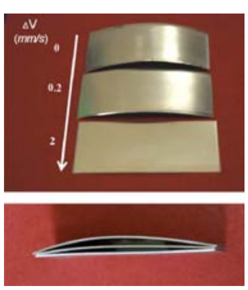
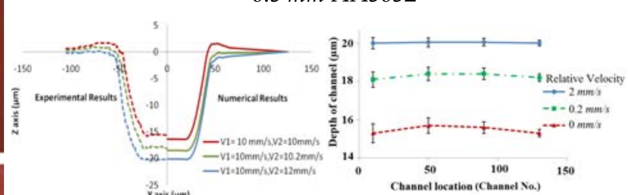
Relative Velocity Effect

- The relative velocity between upper and lower roll affects the curvature and channel depth of a rolled part. [1]



0.5 *mm* AA5052



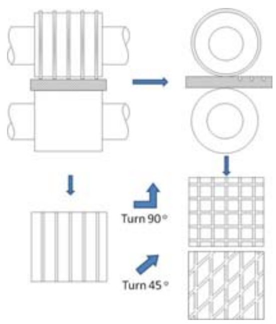
Higher velocities ***reduce the curvatures*** of rolled parts. [1]

Higher velocities ***increase the channel depths*** of rolled parts. [1]

Zhou, R., Cao, J, Ehmann, K., Xu, C., (2011), "An investigation on deformation-based micro surface texturing", ASME Journal of Manufacturing Science and Engineering, Vol. 133(6)

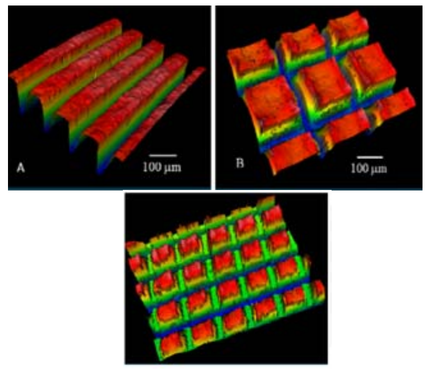
Multi-pass micro-rolling

- Enabling the production of different texture patterns. [1]



Schematics of texturing grid and rhombus patterns by multi-pass texturing.

0.5 *mm* AA5052



3D scanned images of rolled parts by a white light interferometer (WLI).

Zhou, R., Cao, J., Xu, C. and Ehmann, K. (2011) "An Investigation on Multi-pass Deformation-based Surface Texturing", Steel Research International, pp. 171.

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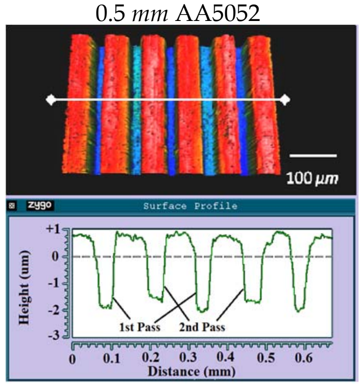
Multi-pass micro-rolling

- Hardening of rolled material in the 1st pass leads to a shallower channel production in the 2nd pass. [1]

0.5 *mm* AA5052

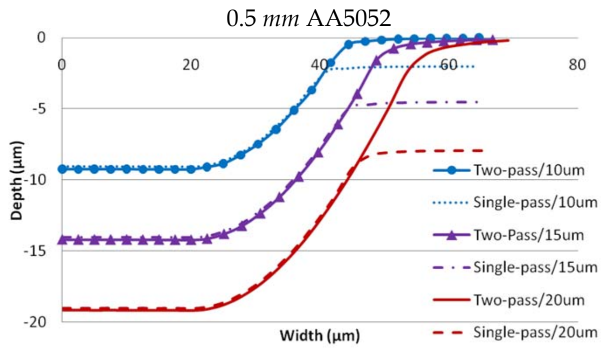


WLI scanned image (top) and its surface profile (bottom).

Zhou, R., Cao, J., Xu, C. and Ehmann, K. (2011) "An Investigation on Multi-pass Deformation-based Surface Texturing", Steel Research International, pp. 171.

Multi-pass micro-rolling

- Increasing the thickness reduction and channel depth of a rolled part. [1]



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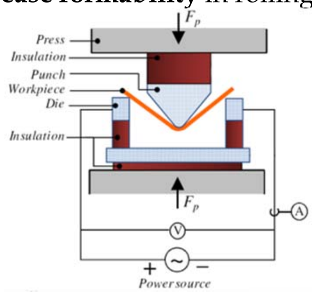
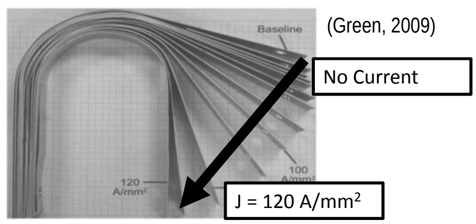
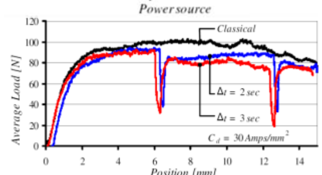
Enhanced Process Capabilities in EA-forming

- **Reduced forces** in sheet bending (Salandro, 2011; Jordan, 2012)
- **Eliminate springback** after bending (Green, 2009; Salandro, 2011)
- **Increase formability** in rolling (Klimov, 1997; Xu, 2007; Yanagimoto, 2009)

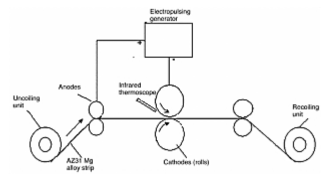




(Green, 2009)



(Salandro, 2011)



(Xu, 2007)

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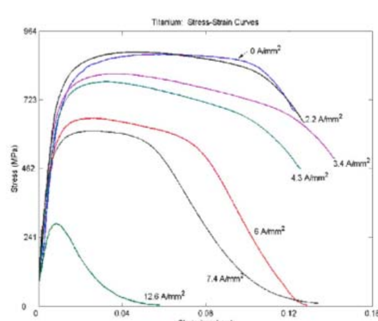
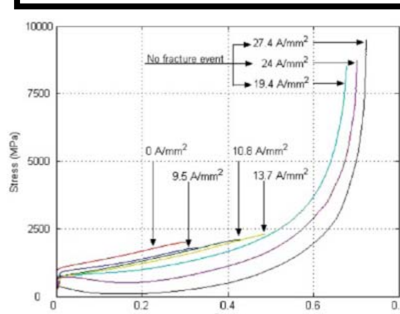
Observations of EA-Deformation

- Applied electric current (either DC or pulsed) cause **stress reductions** (%) and **increased ductility** (%) during deformation
- Attributed to **nonthermal effect**



EA-tension Ti 6Al-4V

(Ross, 2009; Perkins, 2007)



EA-compression Ti 6Al-4V

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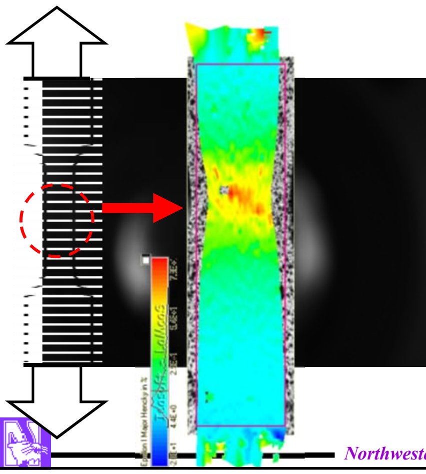
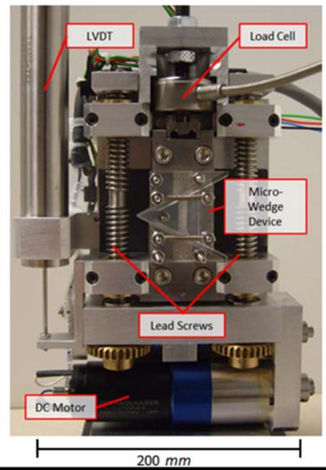
Miniature Mechanical Testing System

<u>Mechanical testing system</u> for <u>small-sized materials</u> (Magargee, JMSE, 2011)

- **Digital Image Correlation** method (DIC) to measure strain (~ 2μ strain resolution)





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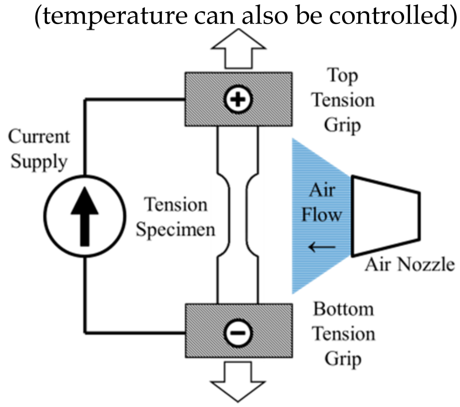
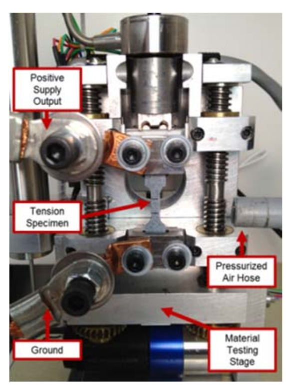
Electrically Assisted Tension Testing

- **DC power supply** (300A, DC and pulsed output)
- Insulating layers between tension grips & machine
- **Air-cooling** system to reduce Joule heating temperatures (ΔT~ 400 °C) (temperature can also be controlled)





Magargee, J., Morestin, F., and Cao, J. (2013) "Characterization of Flow Stress for Commercially Pure Titanium Subjected to Electrically-Assisted Deformation", ASME Journal of Engineering Materials and Technologies, Vol.135(4),

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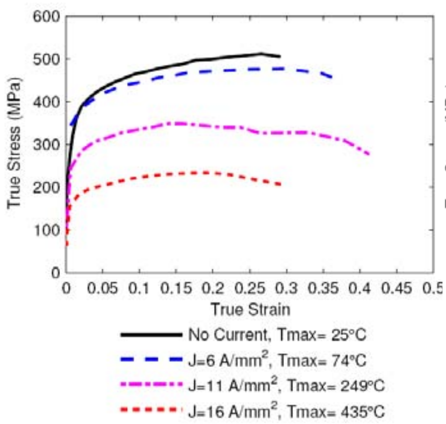
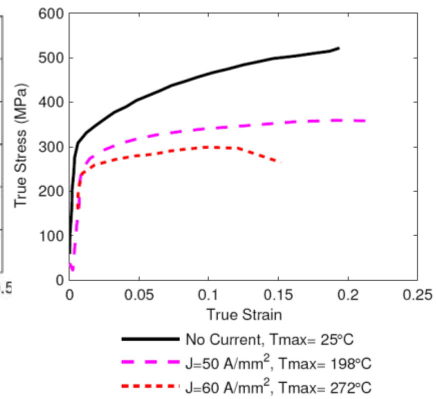
Electrically Assisted Tension Testing Results

EA-tension tests of cp Ti (left) and AA 2024-T3 (right)

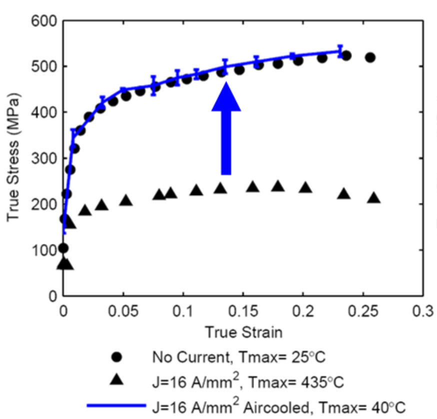


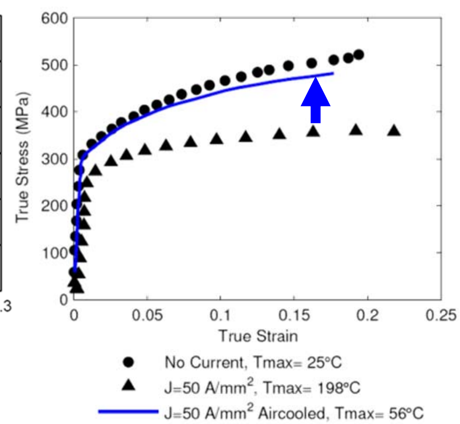


Increased stress reduction with increasing current

Electrically Assisted Tension Testing Results

Air-Cooled EA-tension tests of cp Ti (left) and AA 2024-T3 (right)





No stress reduction with air-cooling!

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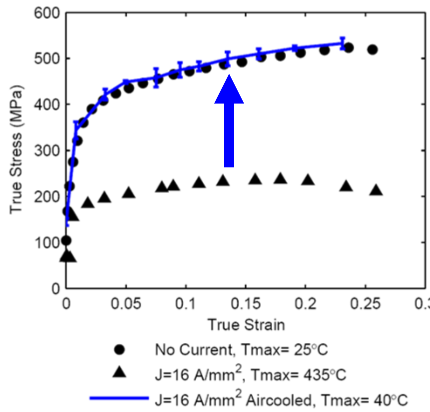
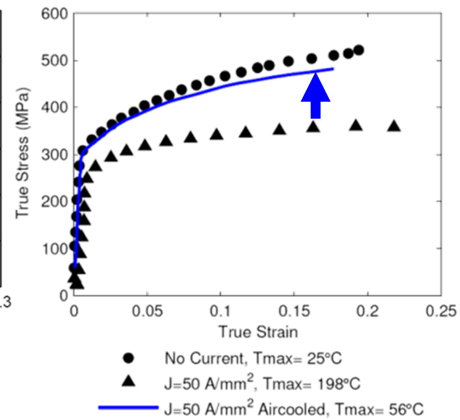
Electrically Assisted Tension Testing Results

Air-Cooled EA-tension tests of cp Ti (left) and AA 2024-T3 (right)





Temperature IS significant

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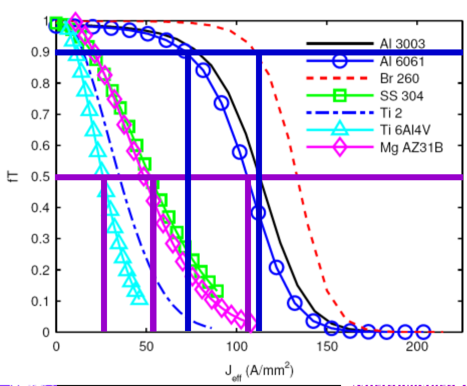
Joule Heating induced Thermal Softening

- Comparison with experiments:

  Ex: ~50% reduction in tensile strength (Perkins, 2007):

		model
AA 6061 vs Ti 6Al-4V:	J = 60.8/19.7 A/mm² = **3.1**	**4.1**
AA 6061 vs SS 304:	J = 60.8/34.9 A/mm² = **1.7**	**2.1**
SS304 vs Ti 6Al-4V	J = 34.9/19.7 A/mm² = **1.8**	**2.0**



Helps explains
current density threshold
(Cu and Al alloys)

Experiment:
AA 6061: $J_{threshold}$ = 75 A/mm²
Brass 360: $J_{threshold}$ = 54 A/mm²
SS 304: No threshold
Ti 6Al-4V: No threshold
(Perkins, 2007)

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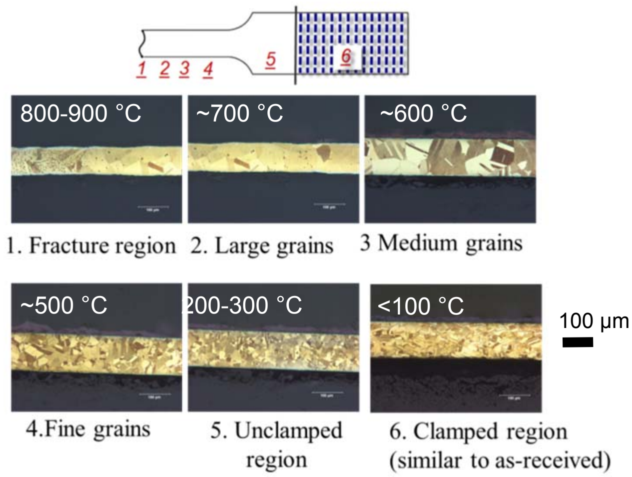
New Observations of Material Microstructure

Non-Uniform Grain Growth along specimen

- Electrically-assisted tension test of 260 brass (cold-rolled, as-received)



Magargee, J., Fan, R., and Cao, J., 2013, "Analysis and Observations of Current Density Sensitivity and Thermally-Activated Mechanical Behavior in Electrically-Assisted Deformation," ASME Journal of Manufacturing Science and Engineering, submitted. 33

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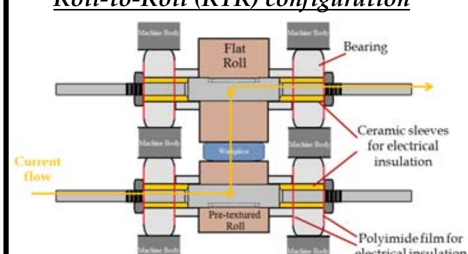
Electrically-assisted micro-rolling

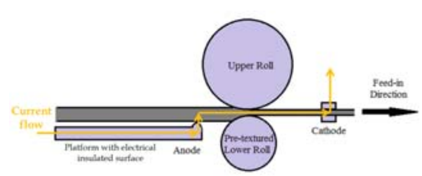
Micro-rolling + *Joule Heating* → *Texturing*

Electrically-assisted Micro-rolling

Roll-to-Roll (RTR) configuration



End-to-End (ETE) configuration



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Joule Heating Effect

- The Joule heating effect heats up the workpiece when current passing through. The heat softens the material for easier forming.

$$\Delta T = \rho J^2 t_p / (C_p \rho_D)$$

Adiabatic Temperature Rise

Material Density

Material Resistivity

Material Specific Heat Capacity

Current Density

Current Pulse Duration

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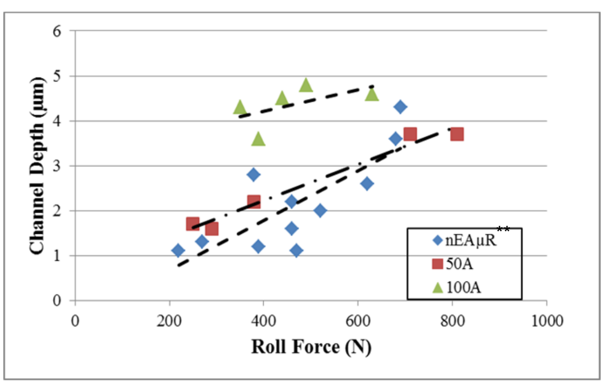
EAμR with Continuous DC

- The Joule heating effect reduces material flow stress for a deeper channel production. [1]

0.4 *mm* Titanium 6Al-4V alloy EA-rolled in RTR configuration



* EAμR: Electrically-assisted micro-rolling
** nEAμR: non-electrically-assisted micro-rolling (no current microrolling)

Ng, M.K., Magargee, J., Fan, R., Gao R.X. and Cao, J. (2013) "Surface texturing in titanium alloy by electrically-assisted micro-rolling", Proceedings of the 8th International Conference on Micromanufacturing.

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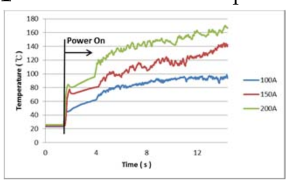
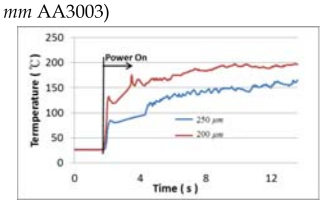
EAμR with Continuous DC

- In ETE configuration, workpiece surface temperatures are effected by current sizes and roll gap sizes. [1]

Temperature Profiles (0.4 *mm* AA3003)





Statistical data on channel depth rolled on AA3003 strips with a 250 *μm* roll gap at different DC current sizes. (ETE config.)

Current (A)	Average depth (μm)	Standard deviation (μm)	Ratio of standard deviation to the mean value
nEAμR	7.74	4.10	0.53
100	5.04	4.75	0.94
150	10.81	6.51	0.60
200	10.73	3.53	0.33

Statistical data on channel depth rolled on AA3003 strips with 200 *μm* and 250 *μm* roll gaps at 200 *A* DC. (ETE config.)

Roll gap (μm)	Average depth (μm)	Standard deviation (μm)	Ratio of standard deviation to the mean value
200	11.96	2.24	0.19
250	10.73	3.53	0.33

Higher current strengthens the Joule heating effect increasing produced channel depths.

Smaller roll gap gives a more significant Joule hearting producing deeper channels.

[1] Ng, M.K., Fan, R., Zhou, R., Smith, E.F. III , Gao, R.X. and Cao, J. (2012) "Micro surface-texturing by electrically-assisted micro-rolling (EAμR)", Proceedings of the 7th International Conference On Micromanufacturing, pp. 259-266.

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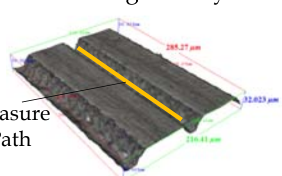
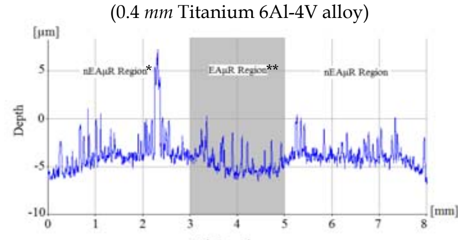
EAμR with pulsed DC

- Pulsed DC EAμR process improves the geometric versatility of channels. [1]

0.5 *s* ON-time/ 1 *s* OFF-time pulsed DC produces wave-like channel geometry.



Channel Profiles
(0.4 *mm* Titanium 6Al-4V alloy)



Example of 0.4 mm AA 3003 sheet textured with pulsed DC.

* EAμR: Electrically-assisted micro-rolling
** nEAμR: non-electrically-assisted micro-rolling (No current rolling)

Ng, M.K., Magargee, J., Fan, R., Gao R.X. and Cao, J. (2013) "Surface texturing in titanium alloy by electrically-assisted micro-rolling", Proceedings of the 8th International Conference on Micromanufacturing.

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Outline

- Motivations
- Design of desktop microrolling mill
- Rolling-based texturing methodology
- Conventional microrolling
- Electrically-assisted microrolling (EAμR)
  - Continuous DC EAμR
  - Pulsed DC EAμR
- Future work

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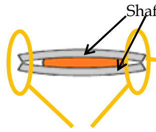
Future Work

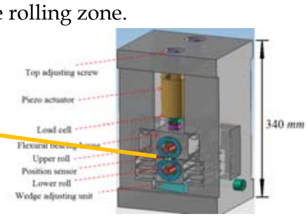
- Advance the data acquisition method to improve the process control.
  - Obtain the localized information, including temperature, roll gap variation in roll axial direction and pressure distribution, at the rolling zone.

For example,

The roll pressure cannot be measured precisely right at the rolling zone.



Locations of roll force measured with load cell



A schematic diagram of the micro-rolling mill

- Improve the channel geometric uniformity in EAμR by means of, for example, temperature, roll force and current controls.

Current (A)	Average depth (μm)	Standard deviation (μm)	Ratio of standard deviation to the mean value
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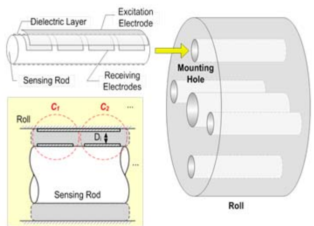
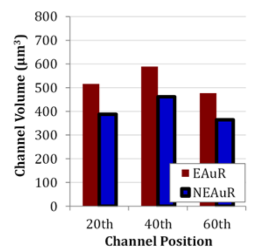
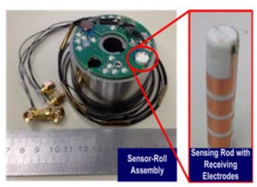
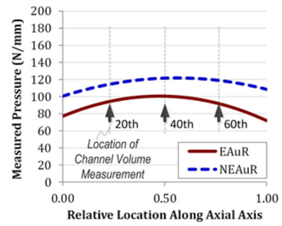
Embedded Capacitive Sensing

- Sensing principle
  - correlate measured capacitance change with forming pressure;
  - reconstruct pressure distribution.









Fan, R.,Ng, M.K.,, Cao, J. and Gao R.X. (2012) CIRP 2012

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Future Work

- Advance the data acquisition method to improve the process control.
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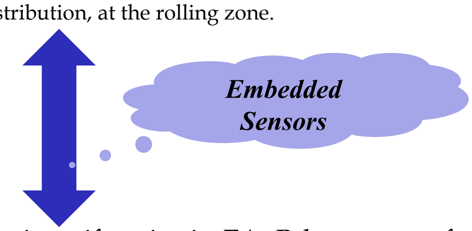

- Improve the channel geometric uniformity in EAμR by means of, for example, temperature, roll force and current controls.

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- National Science Foundation, Ford and Boeing for their support
- NU Materials Research Science and Engineering Center (MRSEC) shared facilities:
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  - Central Laboratory for Material Mechanical Properties (CLAMMP, DMR-0520513)
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- Rose Fan for micrography
- MIRDC for rolls
- Prof. Gao of UConn and his team for embedded sensors

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