Tooling for Injection Molded Micro and Nanoscale Features

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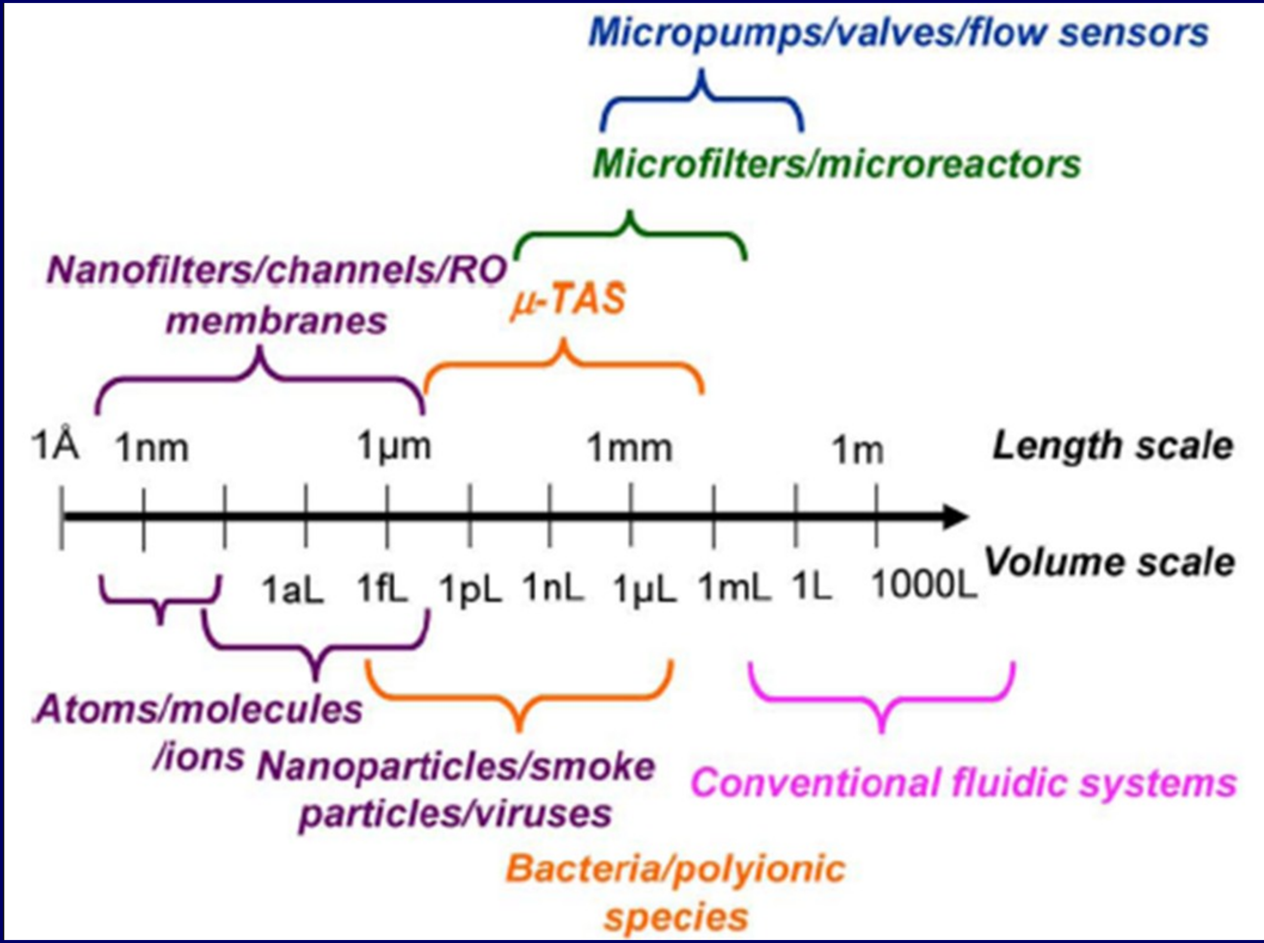
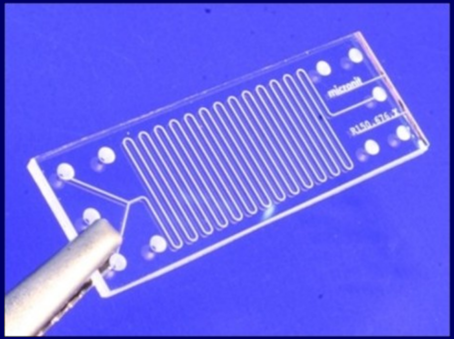
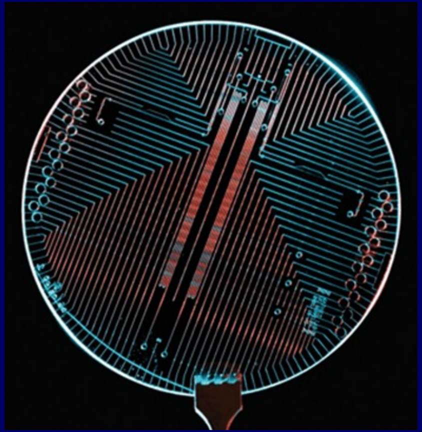
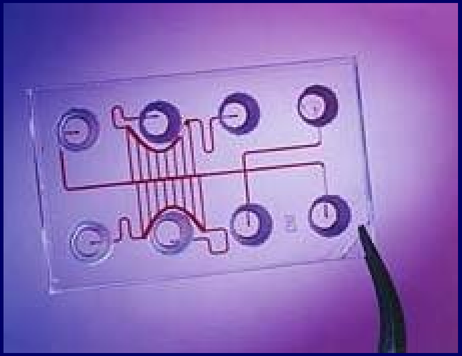
Devices Containing Small Features

Micro and nanofluidic devices









Prakash et al., *IEEE Sensors Journal*, 8.5, 441-450 (2008)

Possible Manufacturing Technologies

	Hot Embossing	Nanoimprint	Injection Molding
Materials	thermoplastics	thermoplastics or thermosets	thermoplastics or thermosets
Pressure	> 10 MPa	< 0.1 MPa	> 50 MPa
Temperature	$> T_g$	~25°C	150-400°C
Cycle time	1-10 min.	2 min.	3-14 s
Minimum Feature Size	50 nm high aspect ratio	< 157 nm low aspect ratio	Depends on tooling

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Injection molding can provide high-rate manufacturing of a wide range of materials

Approach: Injection Molding

injection molding machine

mold

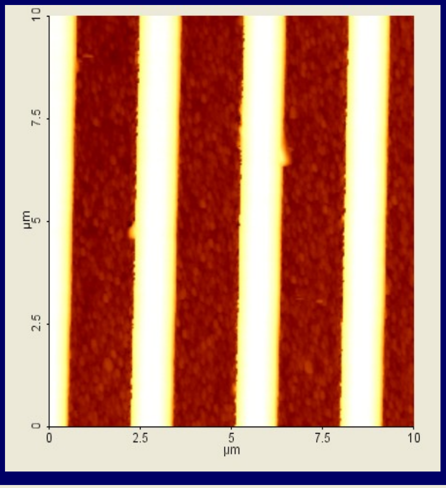
molded part

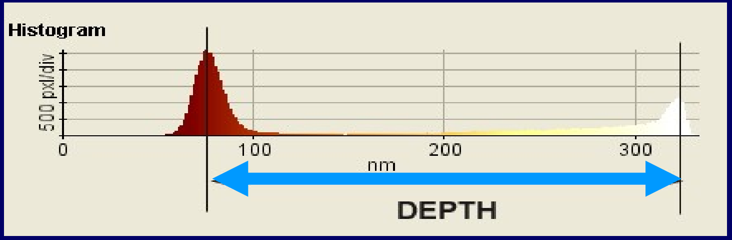
Quantifying Replication

- Feature definition

- Depth ratio

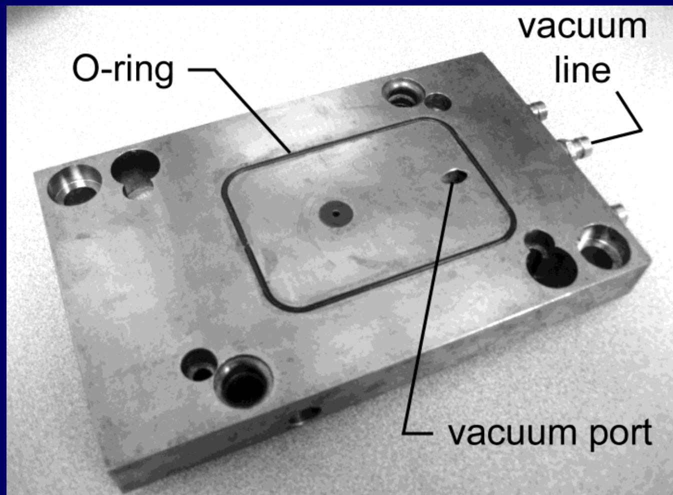
$$DR = \frac{D_{part}}{D_{tool}}$$



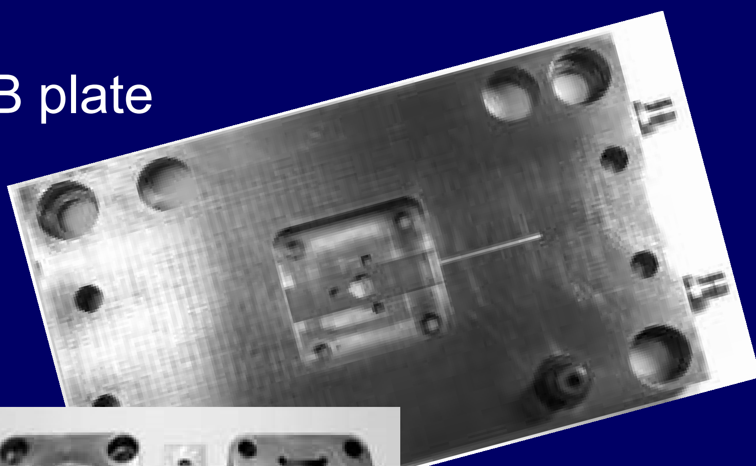


Inj. Molding: It's All About the Tooling

A plate



B plate



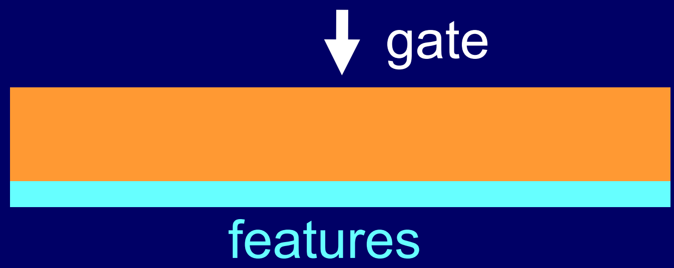
Insert & cartridge

Factors

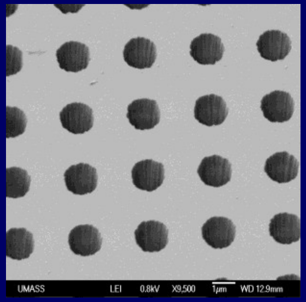
1. Gate location
2. Vacuum venting
3. Tooling features
4. Tooling materials
5. Gas assisted injection molding

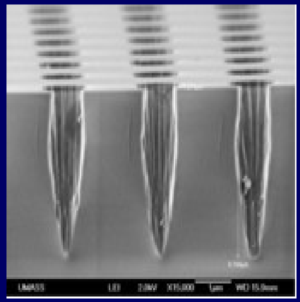
1. Impact of Gate Location

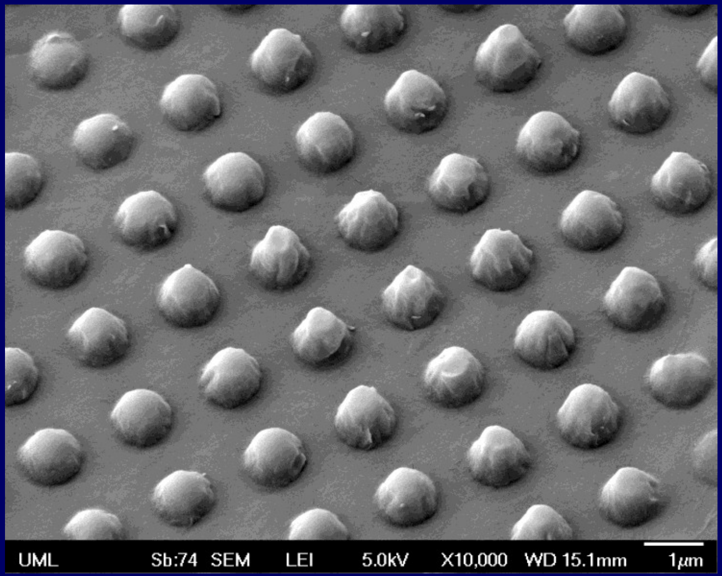
Parallel flow



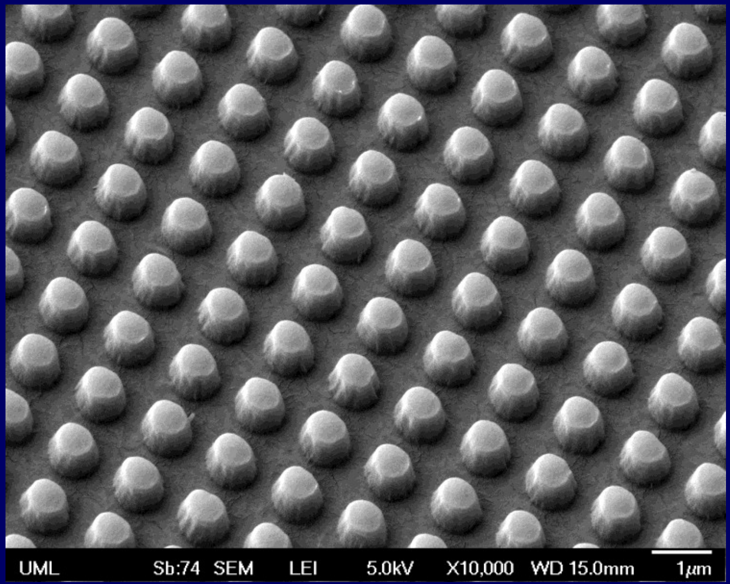
Impingement flow







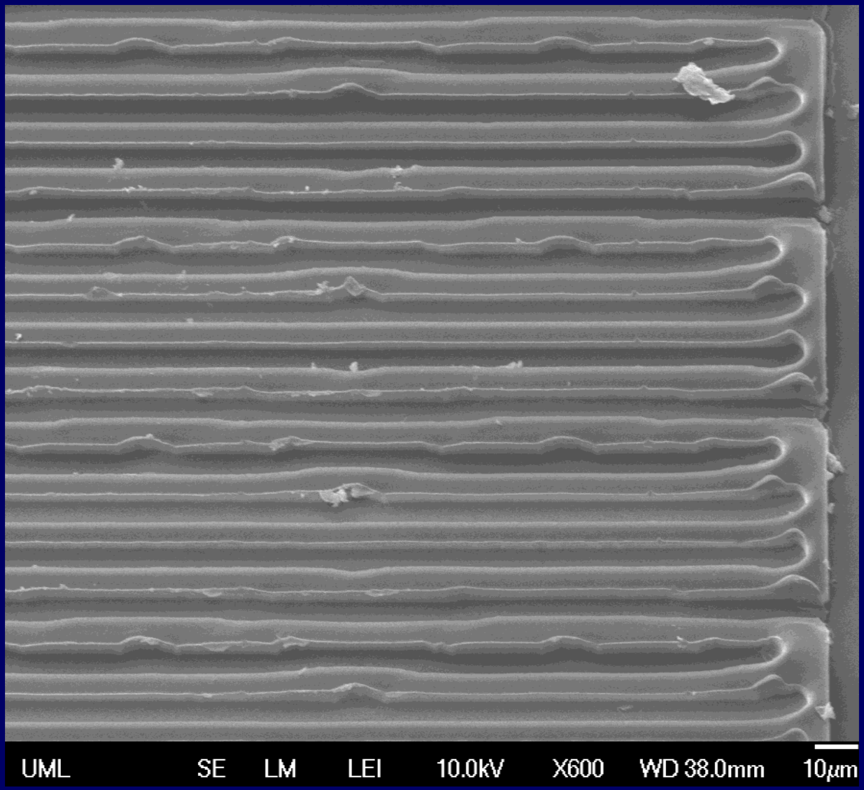
H ~ 1000 nm



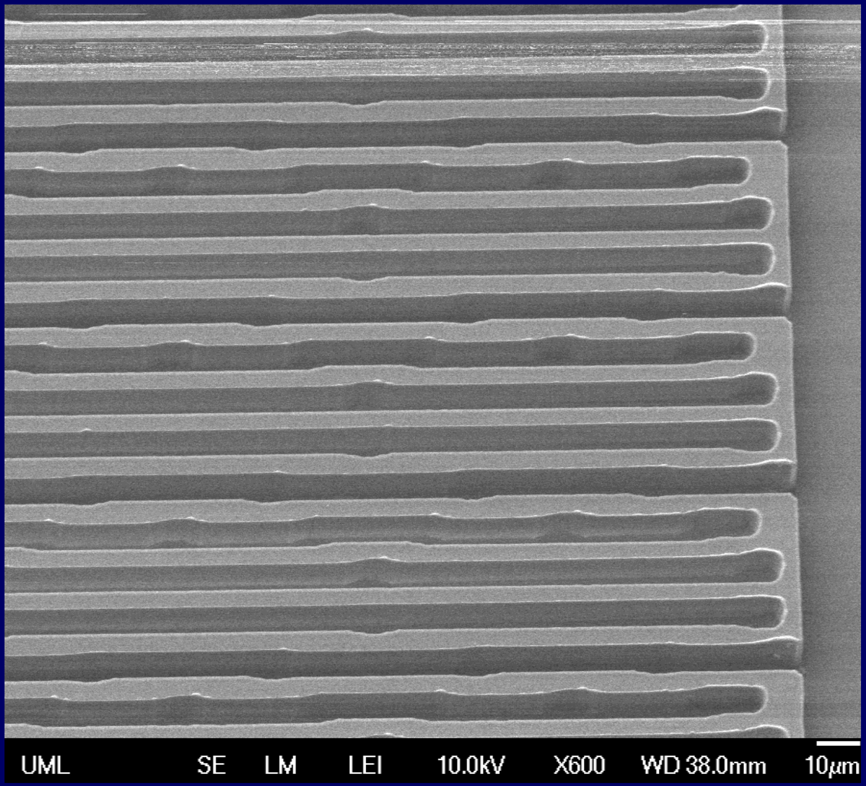
H ~ 400 nm

Yoon et al., *Polym. Eng. Sci.*, 50(2), 411 (2010)

2. Effect of Vacuum Venting



Channels without vacuum



Channels with vacuum

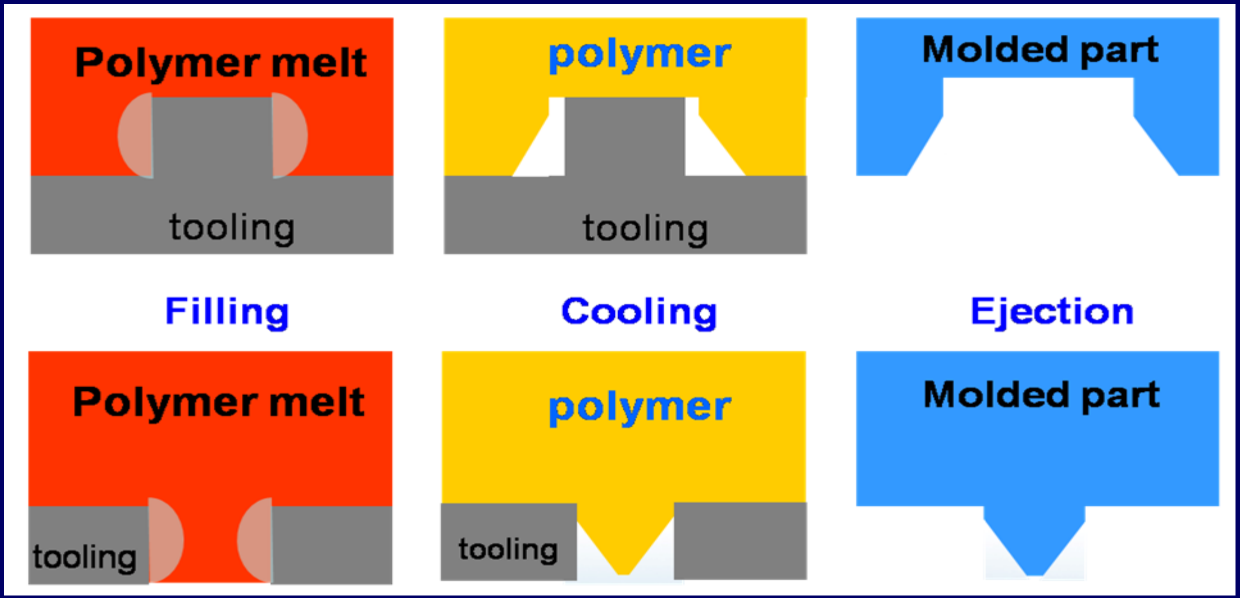
Better corner replication with vacuum venting

Yoon et al., *International Polymer Processing,* accepted (2009)
Padmanabha et al., *Proc. Ann. Tech. Conf. Soc. Plast. Eng.,* (2008)

3. Tooling Features

Positive features

Negative features

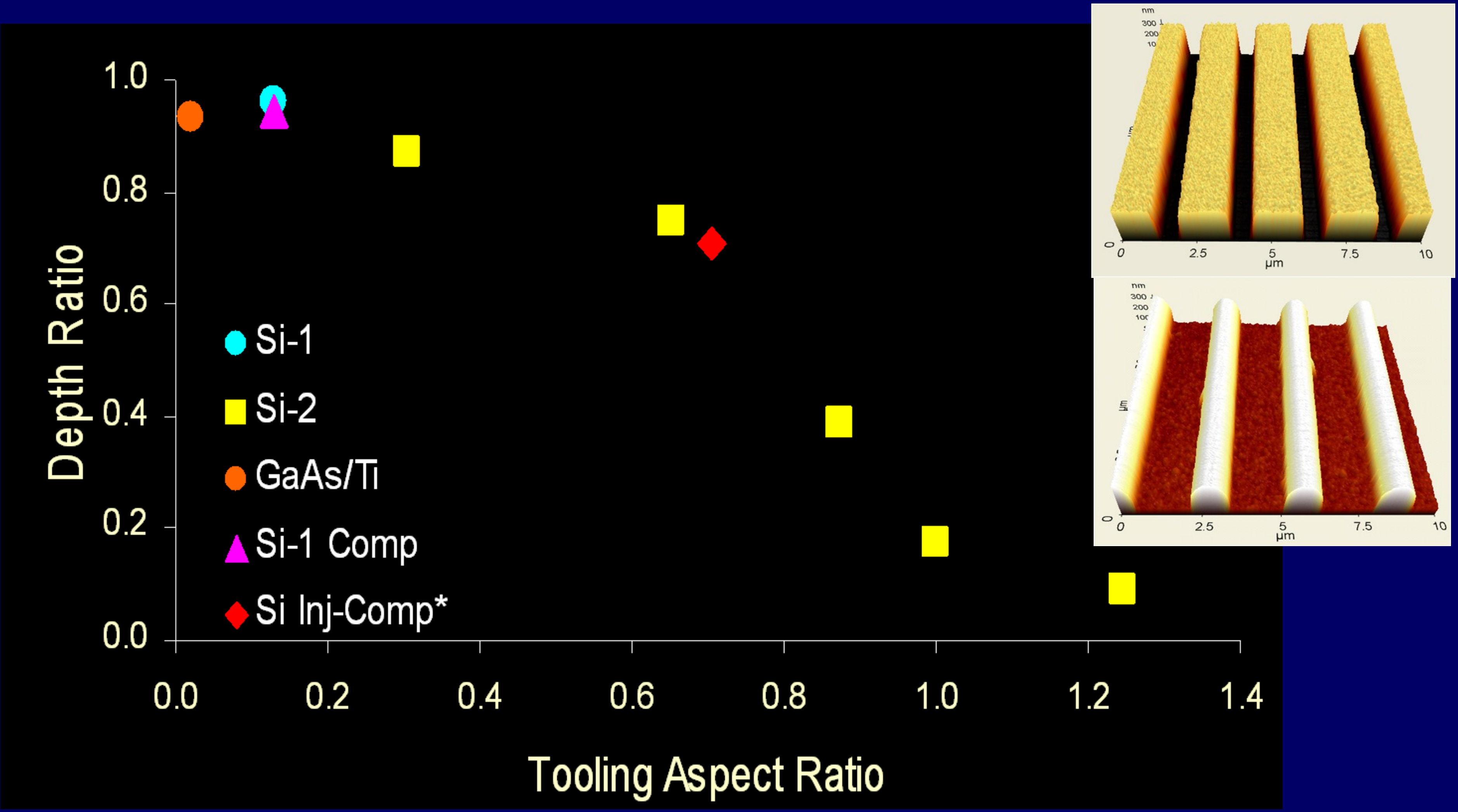


Thermoplastic Elastomer	DR Positive	DR Negative
COPE	1.03	0.60
TPU-45	0.87	0.67
TPU-39	0.75	0.68

Poorer replication with negative features

Yoon et al., Rubber Expo & 176th Technical Meeting, ACS Rubber Division, October 13-15 (2009).

Effect of Feature Size



Smaller features are more difficult to replicate

Yoon et al., *Proc. SPIE*, 5763, 107-116 (2005)

4. Materials for Tooling Inserts

Method	Resolution	Aspect Ratio	Material
CNC machining	100 μm	N/A	steel
Micro milling	50 -100 μm		
Micro wire EDM	1 - 50 μm		
Electroforming	~ 20 nm	~2.5	nickel alloys
Lithography - UV	157 nm	typically low, but up to 30[1]	silicon, glass
Lithography - EUV	13 nm		
Lithography - E-beam	< 10 nm		

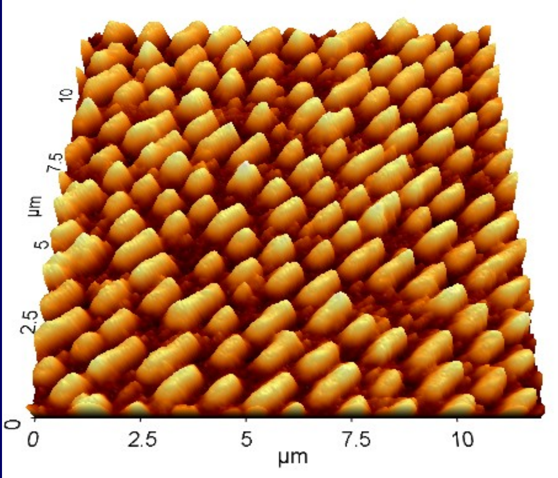
Created hybrid tooling for better feature replication

[1] RIE inductive coupled plasma source (http://www.oxfordplasma.de/process/sibo_ha.htm)

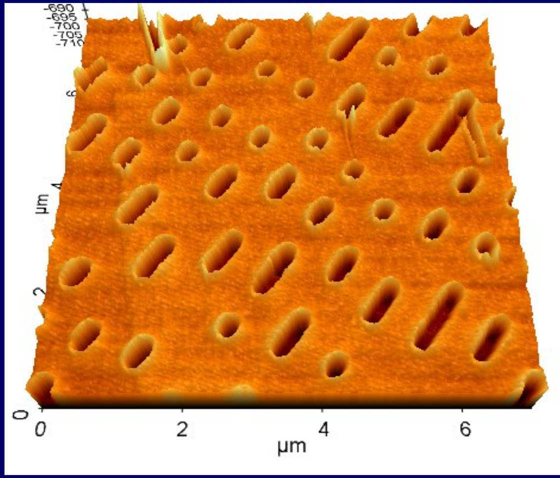
Molding with Nickel Tooling

- CD/DVD molding
  - Incomplete replication
    - Max. DR ~ 0.80 (PC)
- Molding with DVD tooling
  - Material-dependent replication

Polymer	R_g, nm	*DR*
PMMA	3.9	0.91
PC	6.5	0.80
PS	14	0.60



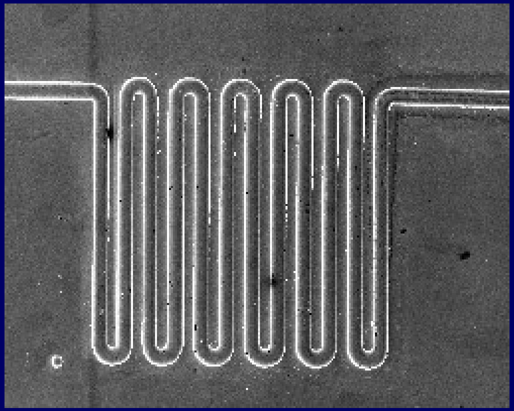
DVD tooling

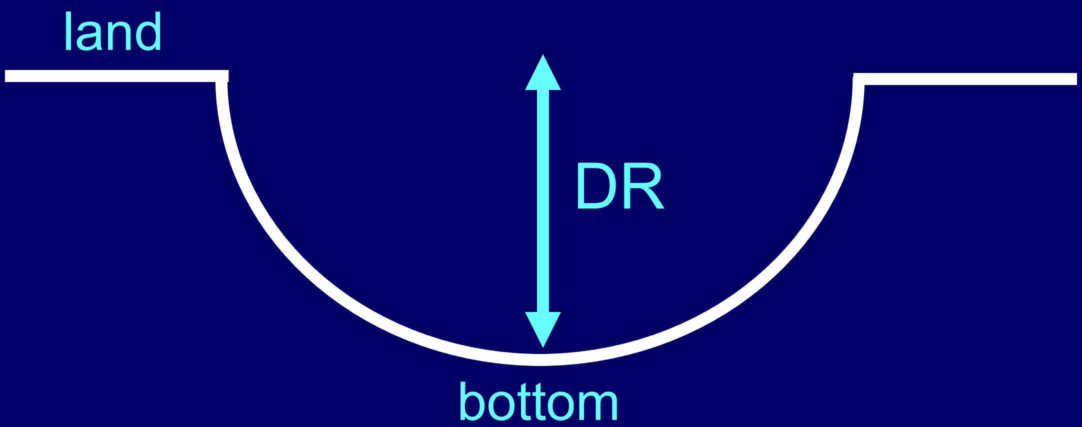


molded part

Srirojpinyo, Dissertation, 2005; Srirojpinyo et al. Proc. Ann. Tech. Conf. Soc. Plast. Eng. (2004)

Factors Affecting Replication

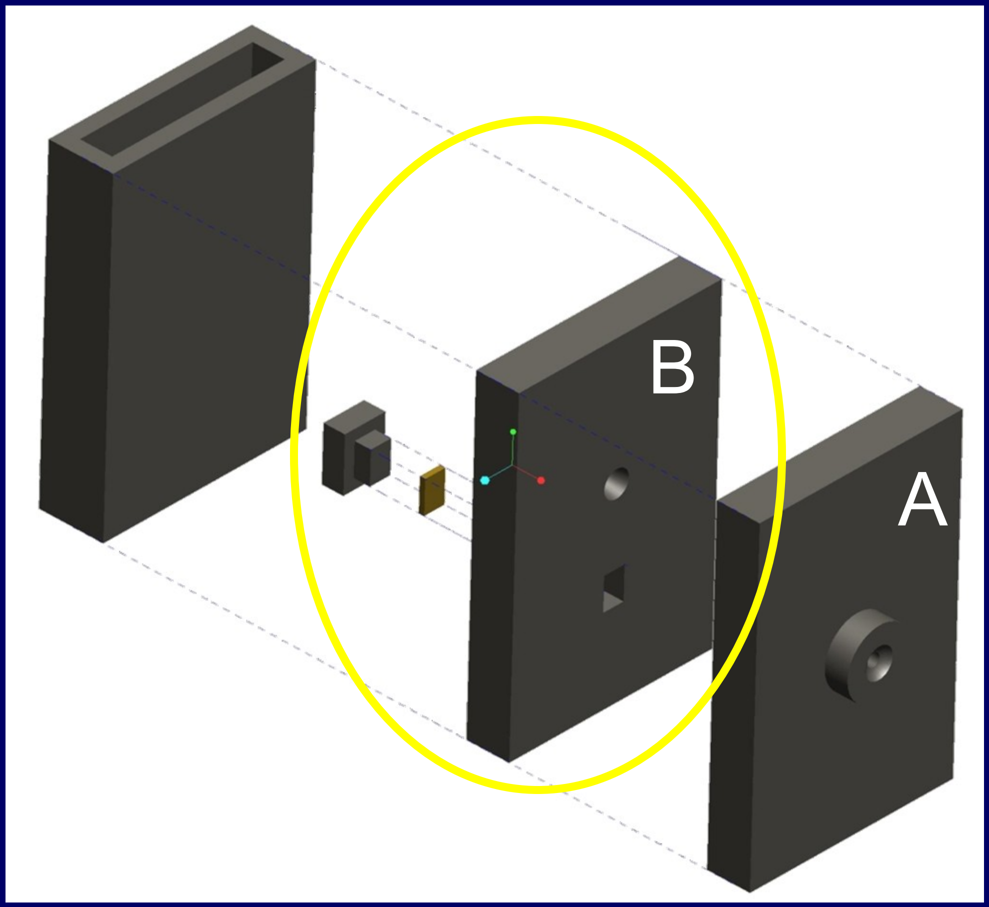


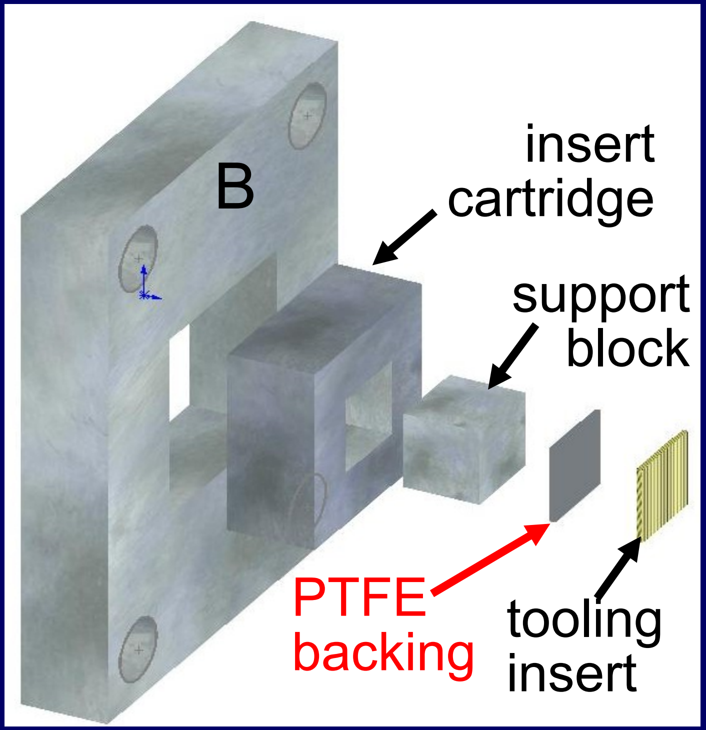


- Replication of feature depth (i.e., DR) depends on material viscosity
- Replication of channel bottom depends on solidification time
- Replication of lands depends on achieving DR = 100%

Thiruvenkataswamy et al., *Proc. Ann. Tech. Conf. Soc. Plast. Eng.*, 2463 (2008)

Molding with Silicon Wafers



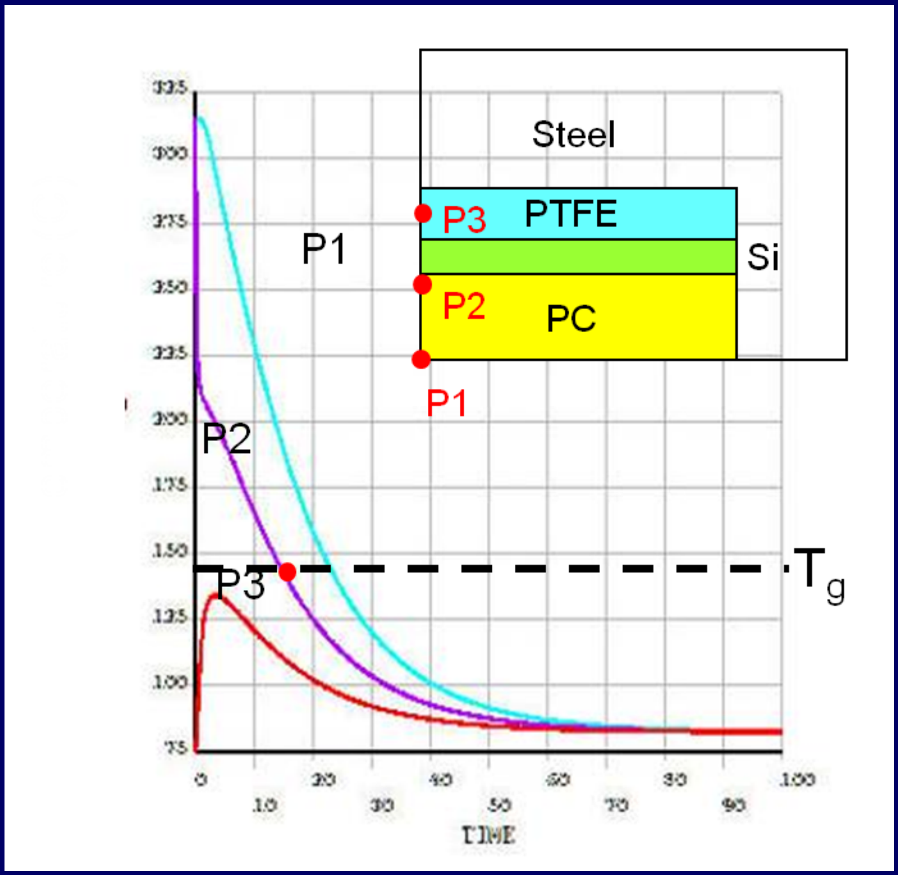


PTFE prevented fracture of fragile tooling inserts → 3000 molding cycles

Yoon et al., *Proc. Ann. Tech. Conf. Soc. Plast. Eng.*, 738-742 (2004)

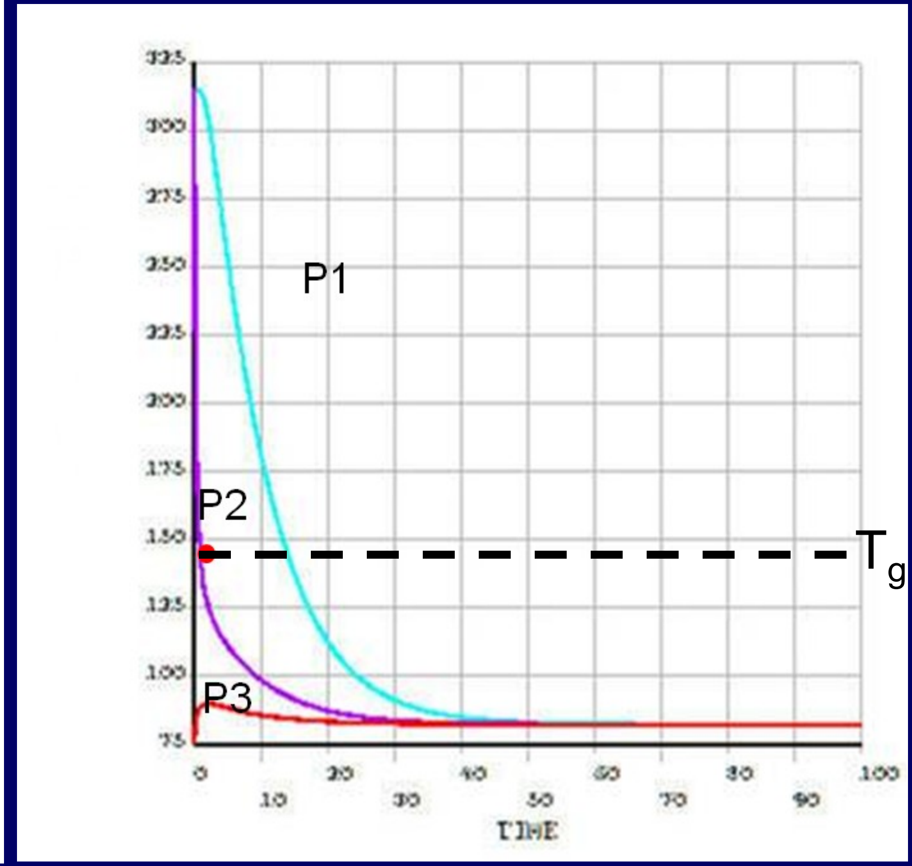
Effect of Backing Material

PTFE backing



Solidification time: 14 s

Cu backing

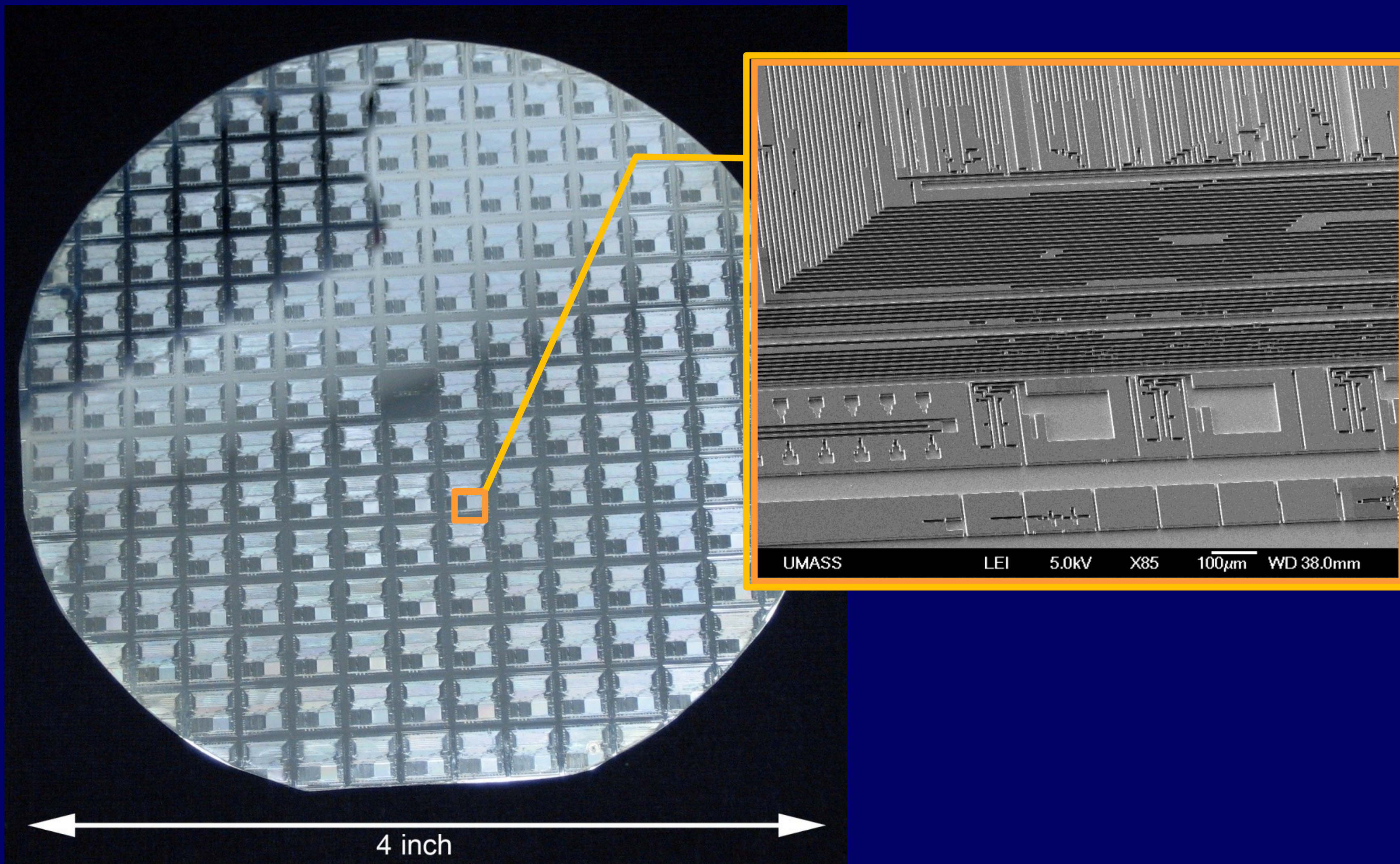


Solidification time: < 1 s

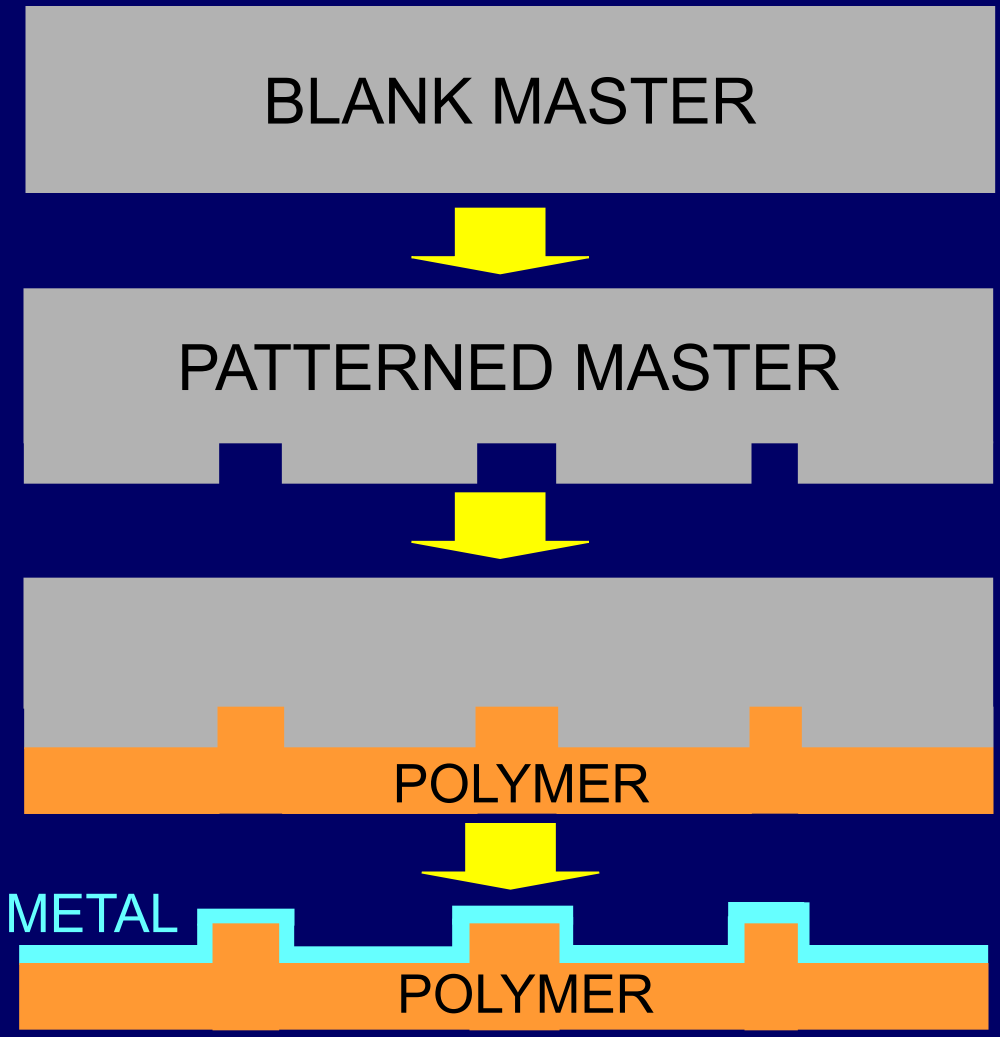
PTFE retarded heat transfer from silicon insert to steel mold

Yoon et al., *Proc. SPIE*, 6380, (2006)

Molding with Hybrid Tooling



Fabrication of Hybrid Tooling

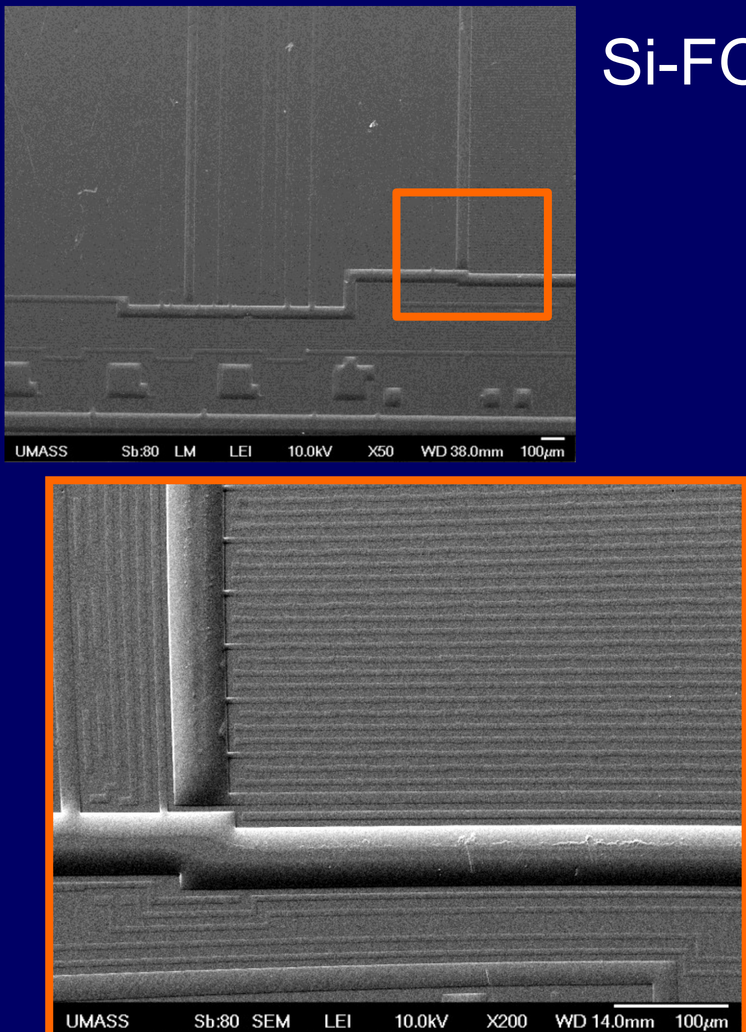


1. Lithography and etching
2. Imprint
3. Metal coating

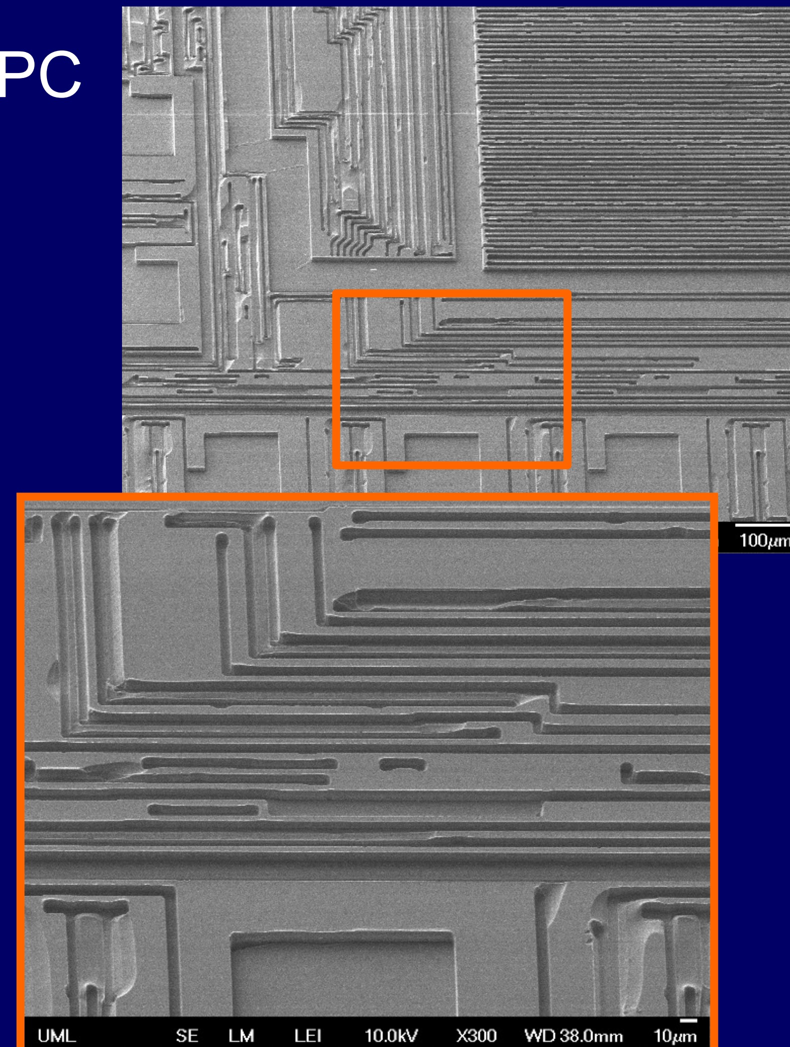
International Patent Application Serial No. PCT/US09/40890

Feature Definition with Hybrid Tooling

Si-FOTS

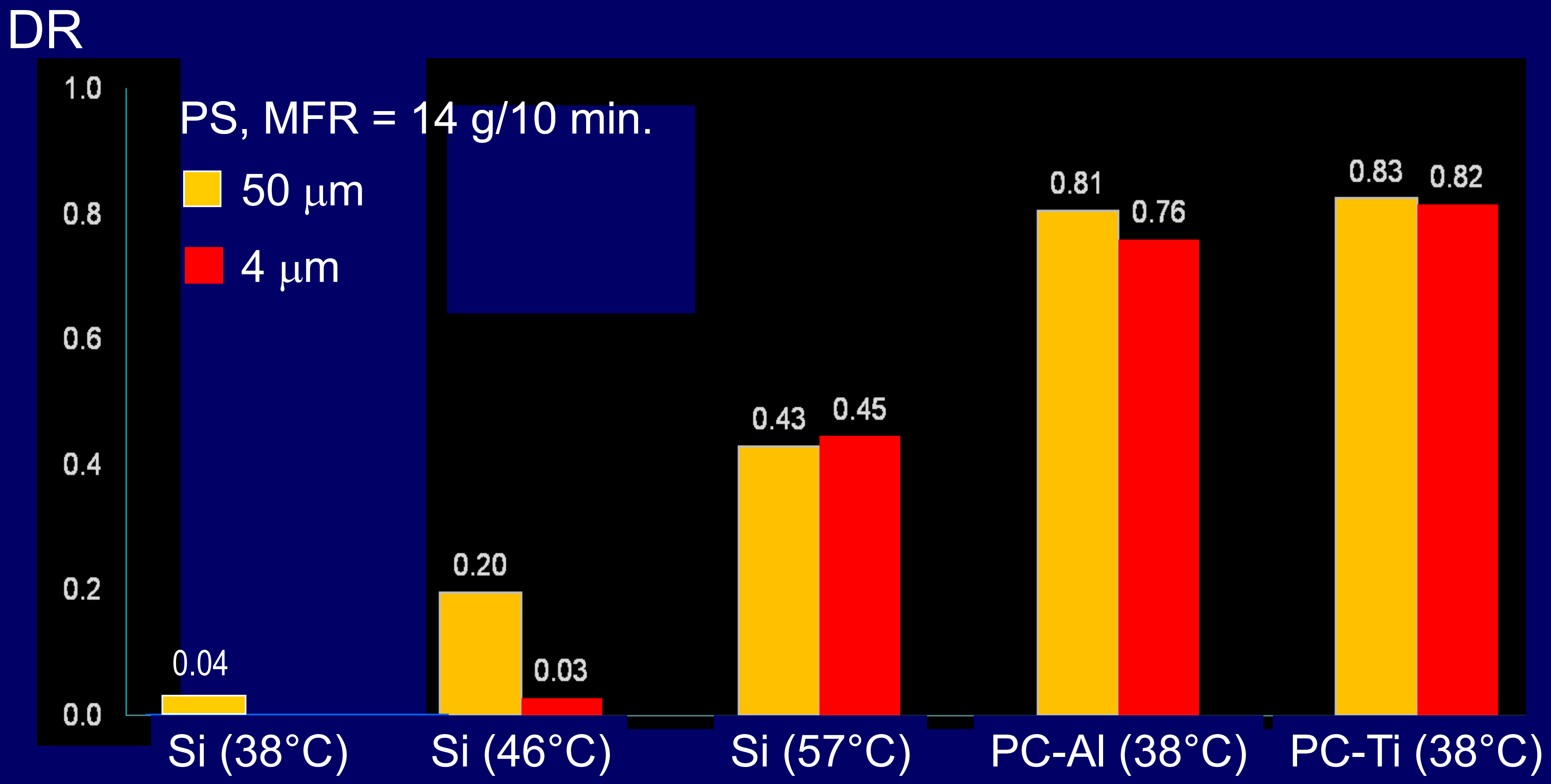


Al-PC



Yoon et al., *Proc. IMECE09*, November 13-19, Lake Buena Vista, Florida (2009)

Depth Ratio with Hybrid Tooling

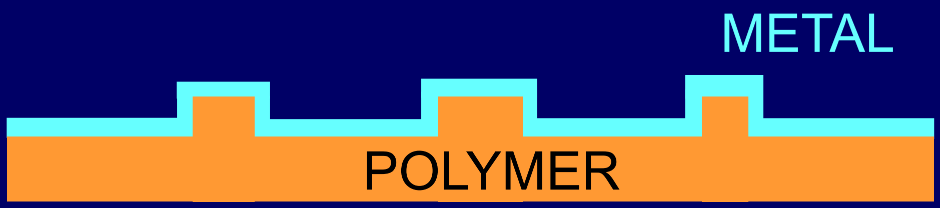


Hybrid tooling enhanced replication, but deformed during molding

Yoon et al., *Proc. Ann. Tech. Conf. Soc. Plast. Eng.*, 2473 (2008)

New Polymer Layers

- Candidate polymers
  - Polyetherimide (T_g: 216˚C)
  - Polyimide (T_g: 350˚C)
  - Thermosets (Epoxy)



- Performance of polymer layers

Property	Units	PC	PI-1	PI-2
Thickness	µm	500	400	100
T_g	˚C	151	369	>400
Performance	---	Good	Good	Poor

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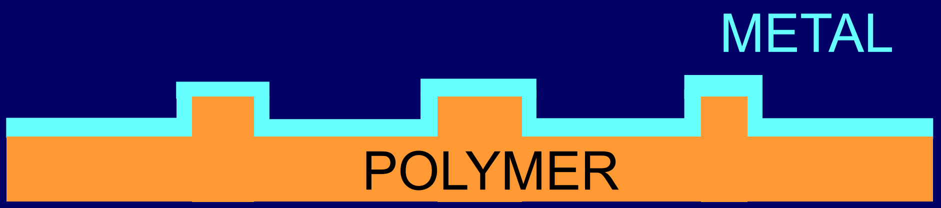

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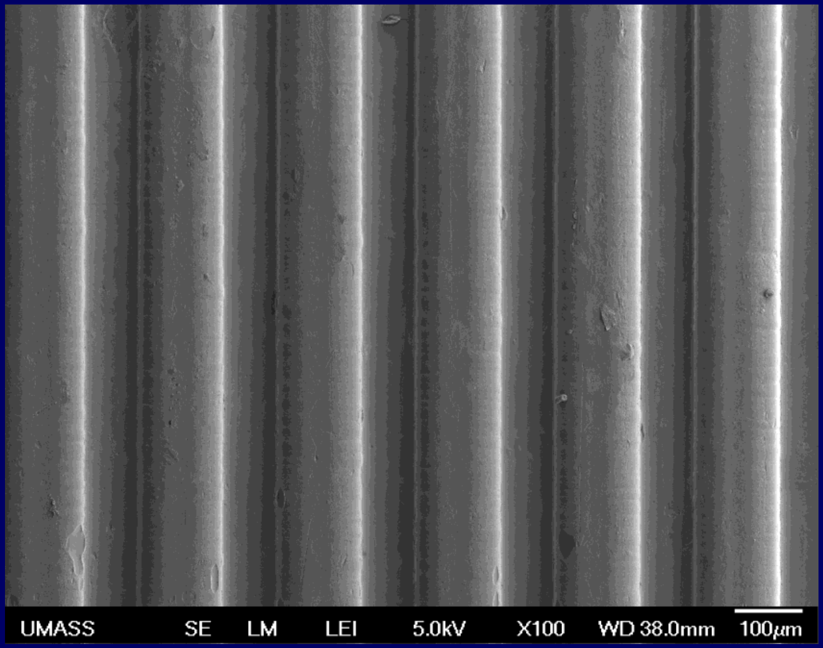
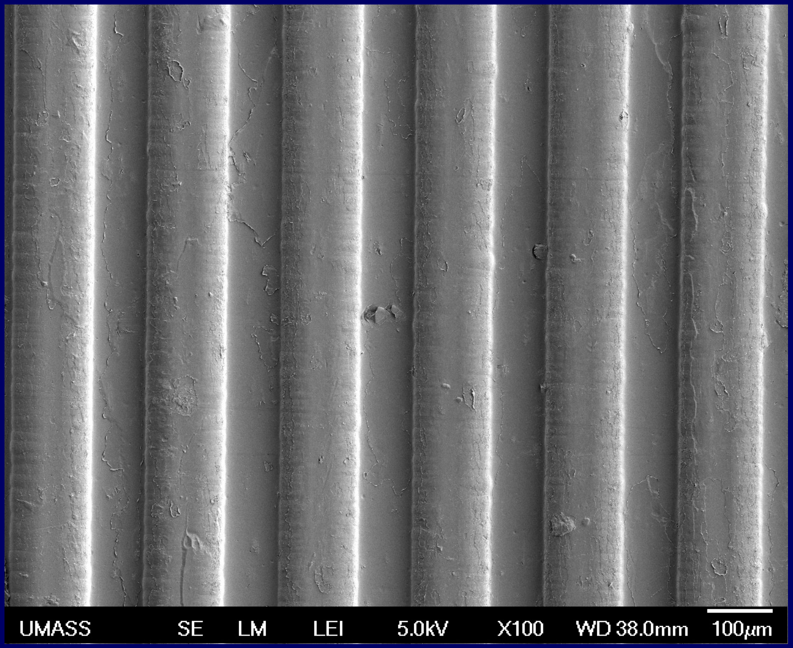
Property	Units	PC	PI-1	PI-2
Thickness	µm	500	400	100
T_g	˚C	151	369	>400
Performance	---	Good	Good	Poor

PI-1 was better than PI-2 in transferring pattern

Parts Molded from PI Hybrid Tooling



PS

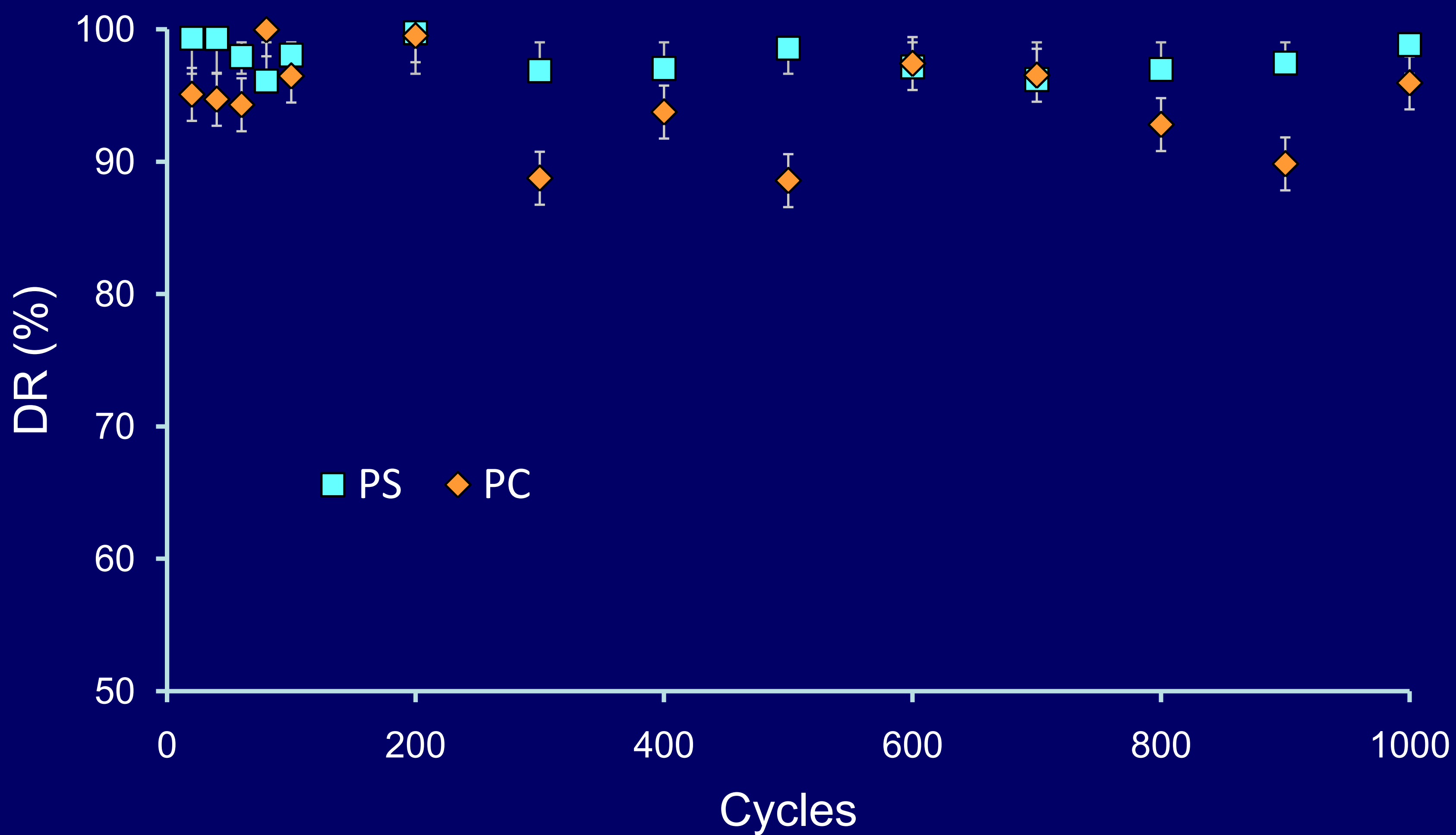


PC

- Molded parts' surfaces were not damaged
- No loss in feature definition over 1000 cycles

Kim et al., *Proc. Ann. Tech. Conf. Soc. Plast. Eng.*, 2143 (2010)

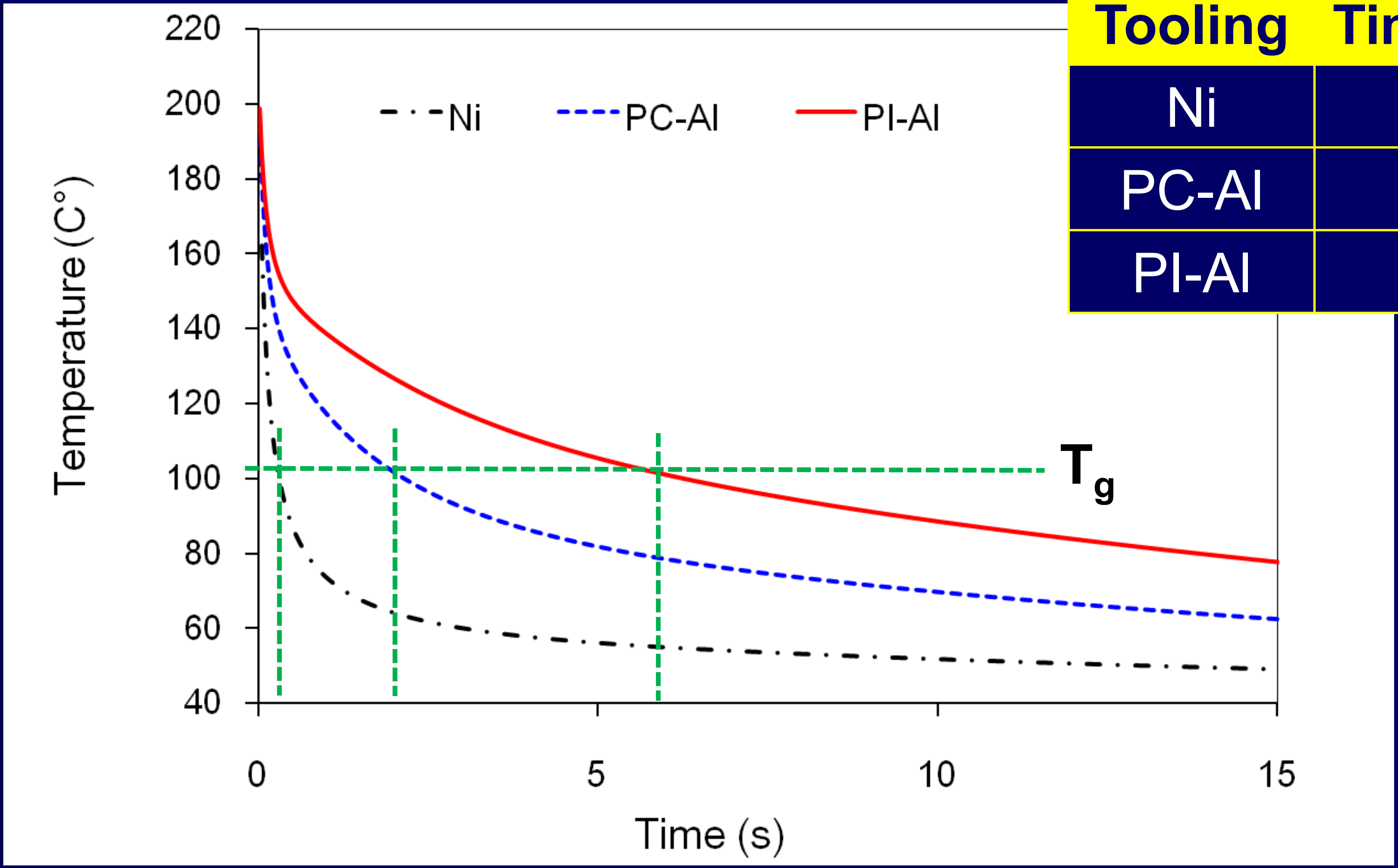
Effect of Molding Cycles on DR



PI-based tooling provided consistent DRs for 1000 molding cycles

Kim et al., *Proc. Ann. Tech. Conf. Soc. Plast. Eng.*, 2143 (2010)

Temperature at the Tooling Surface

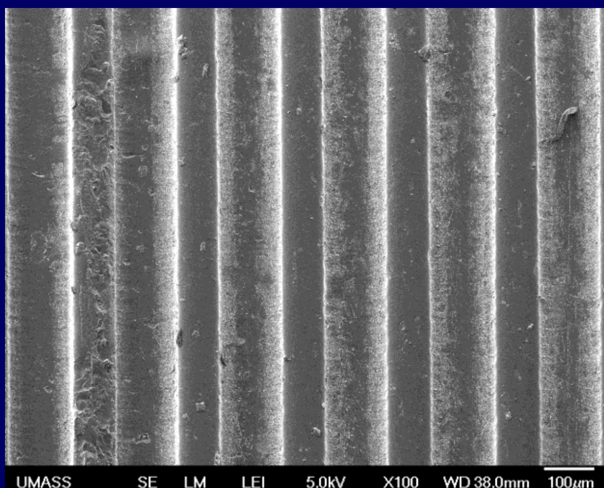


Tooling	Time (s)
Ni	< 1
PC-Al	~ 2
PI-Al	~ 6

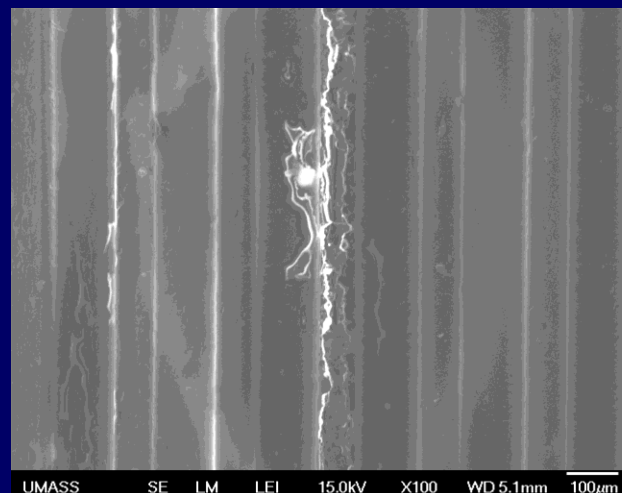
Slower cooling enhanced replication

Kim et al., *Proc. Ann. Tech. Conf. Soc. Plast. Eng.*, 2143 (2010)

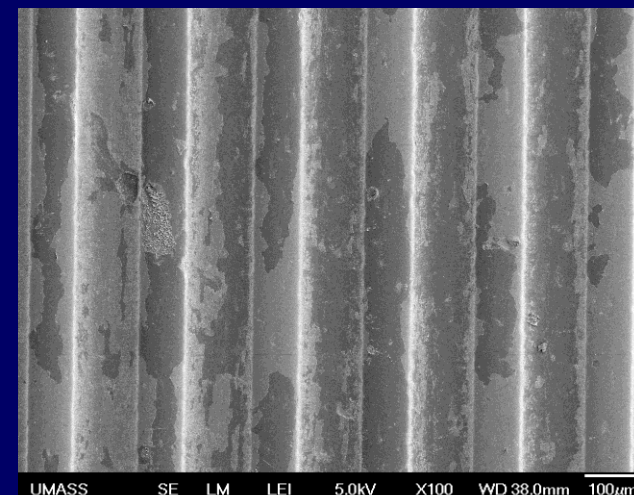
Effect of Molding on Hybrid Tooling



Before molding



After 1000 PS molding

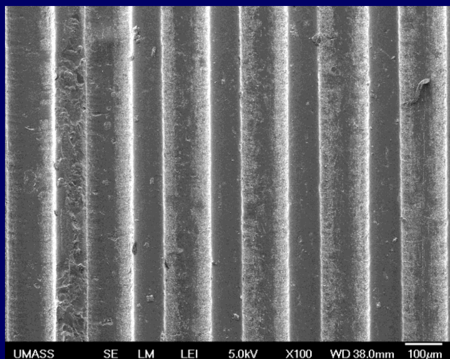


After 1000 PC molding

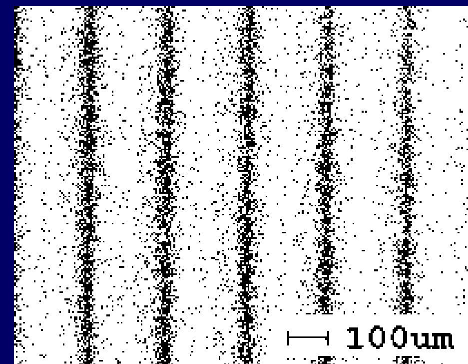
Tooling surface was not deformed, but showed defects

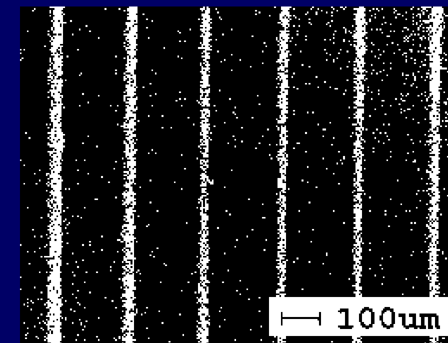
Kim et al., *Proc. Ann. Tech. Conf. Soc. Plast. Eng.*, 2143 (2010)

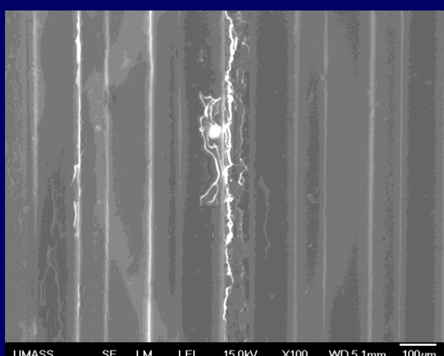
Analysis of Tooling Surface



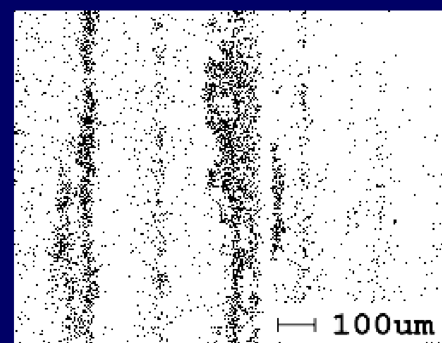
Before molding

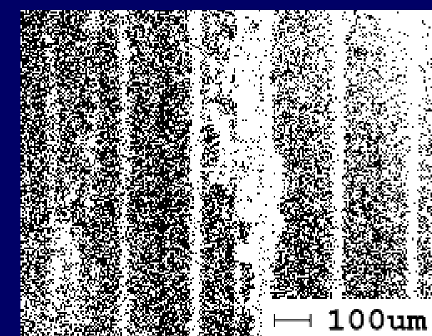


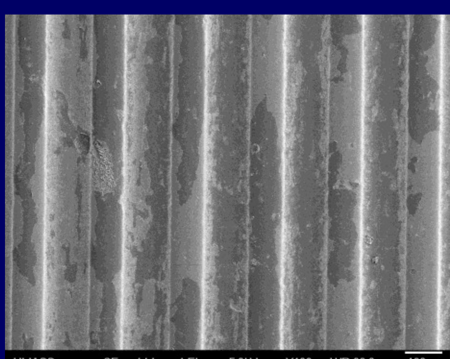




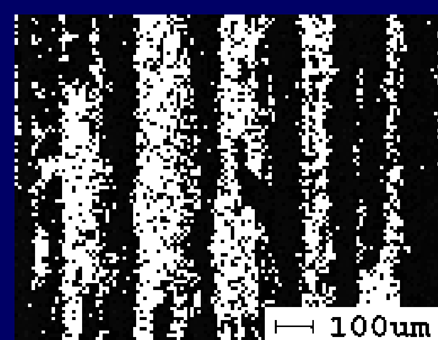
After 1000 PS molding

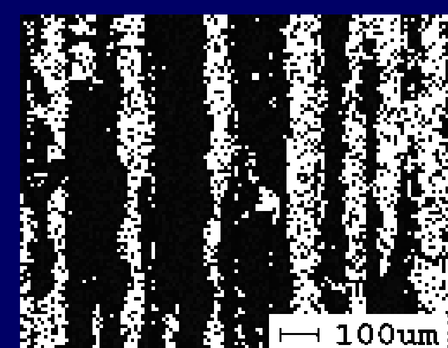






After 1000 PC molding



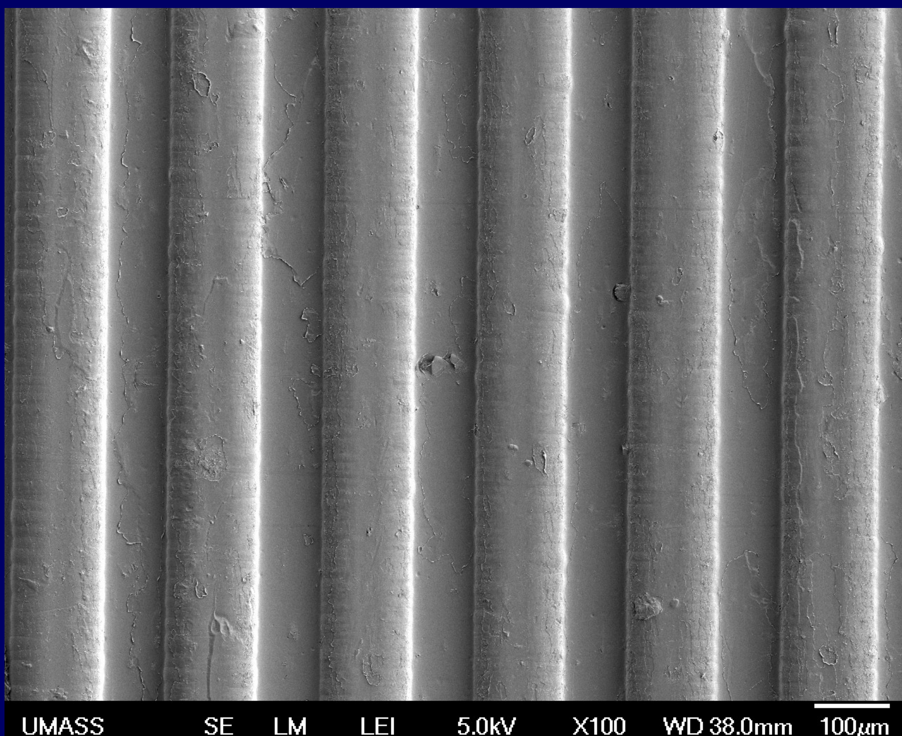


SEM

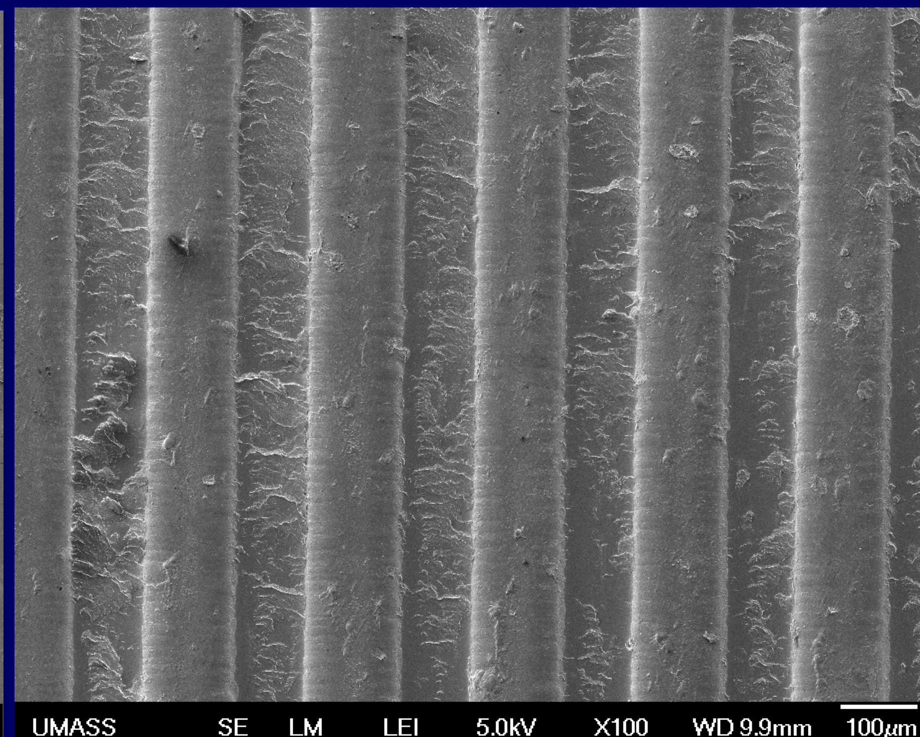
C

Al

Polymer Only Tooling?



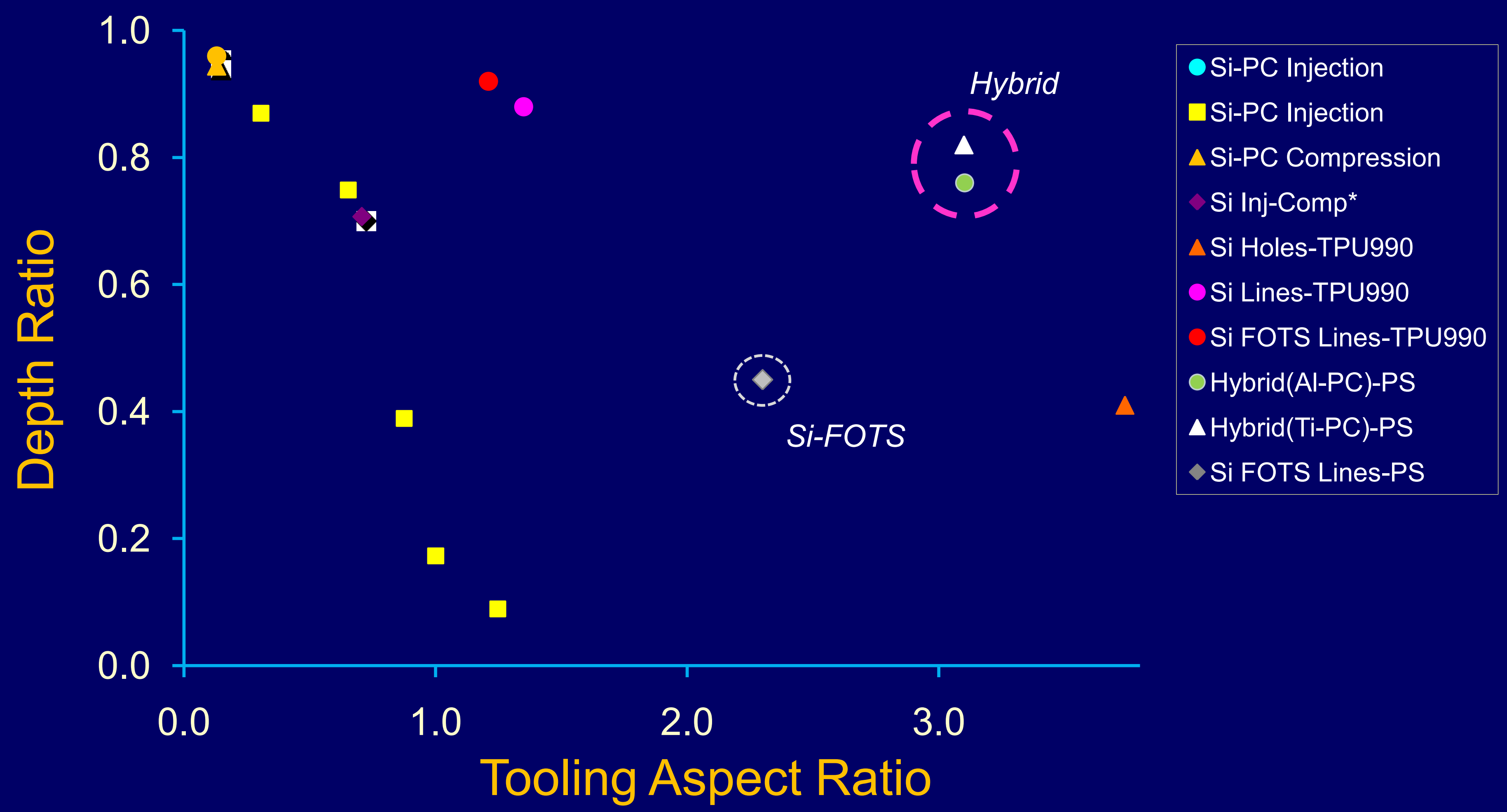
with PI-Al hybrid tooling
(after 1,000 cycles)



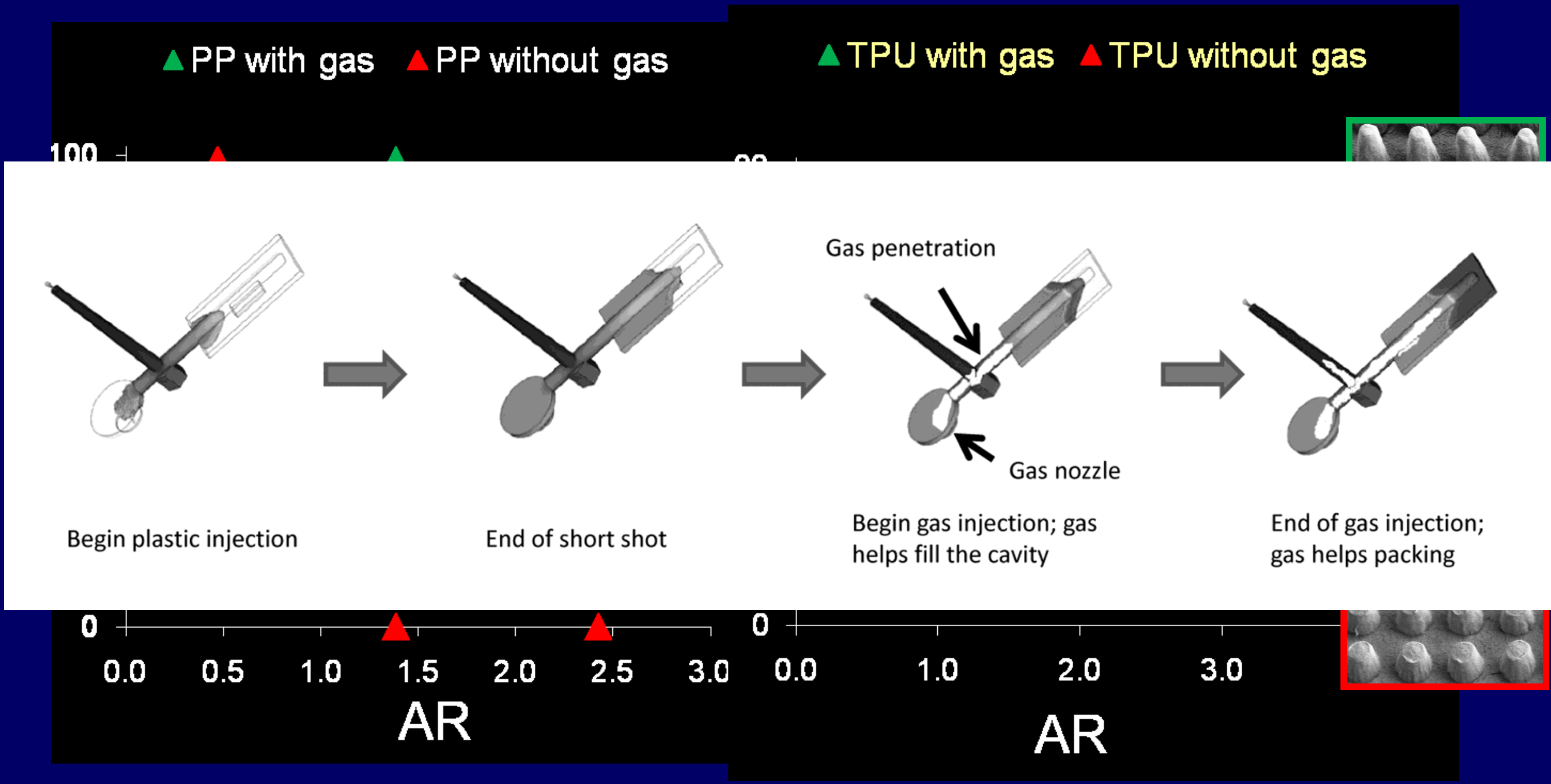
with PI “hybrid” tooling
(after 100 cycles)

Tooling without metal coating produced scaly surfaces

Comparison of Tooling Materials



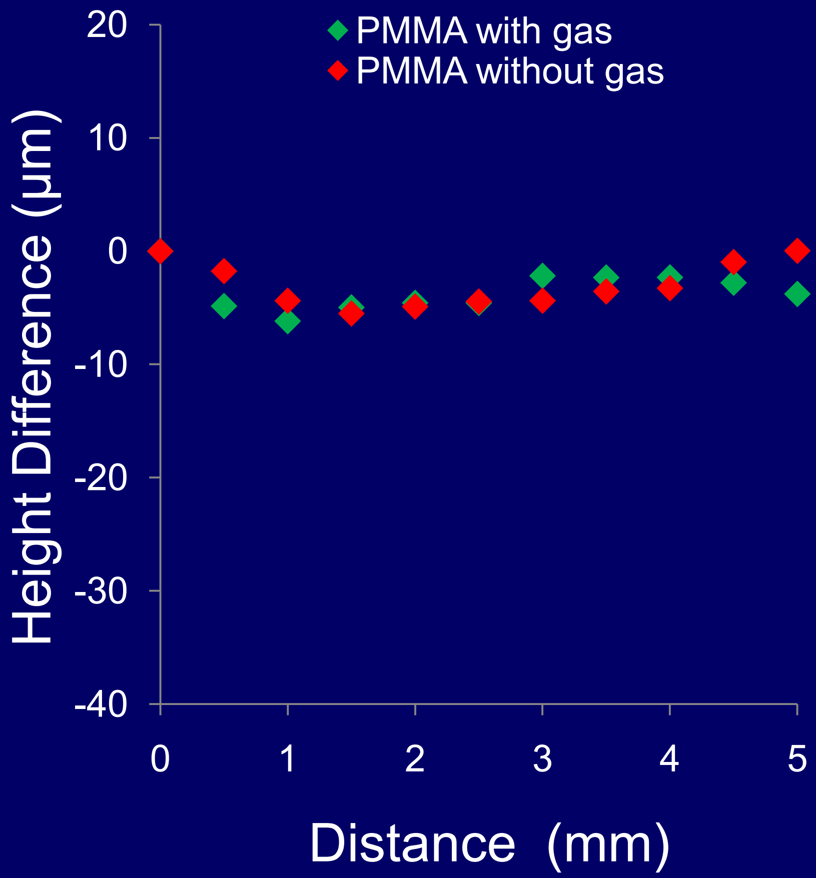
5. Effect of Gas Assisted Injection Molding

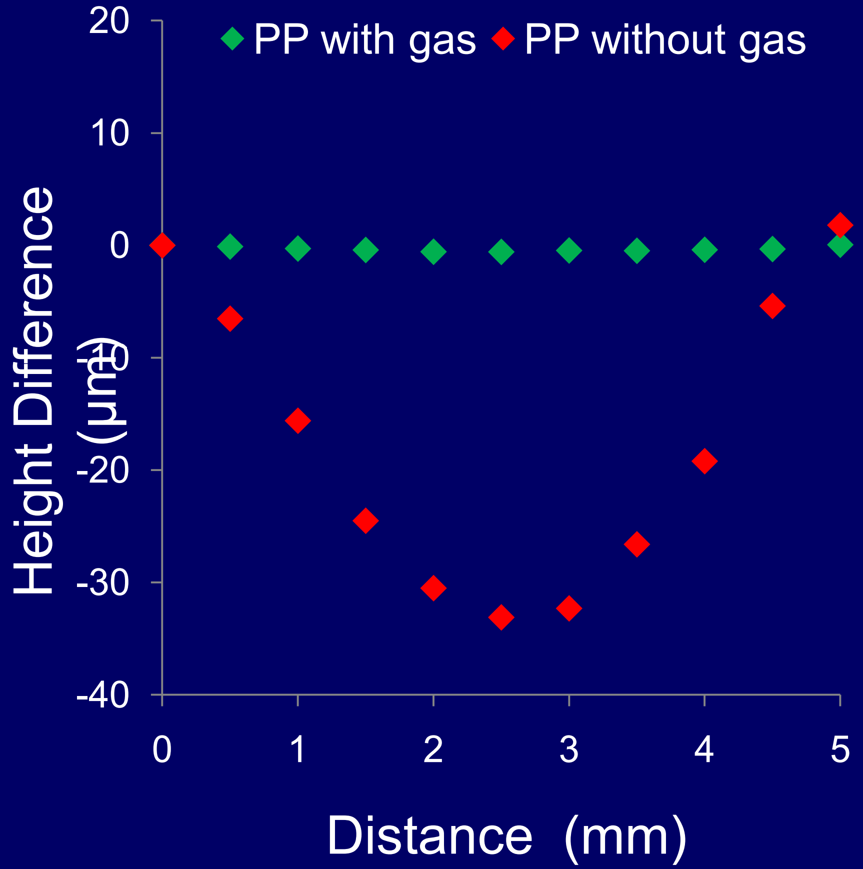


GAIM improved depth ratio

Yoon et al., *Plastics, Rubber and Composites: Macromolecular Engineering*, accepted (2010)
Palanisamy et al., *Proc. Ann. Tech. Conf. Soc. Plast. Eng.*, 1316 (2009)

Effect of Gas Assisted Inj. Molding





GAIM eliminated sink marks in polypropylene parts

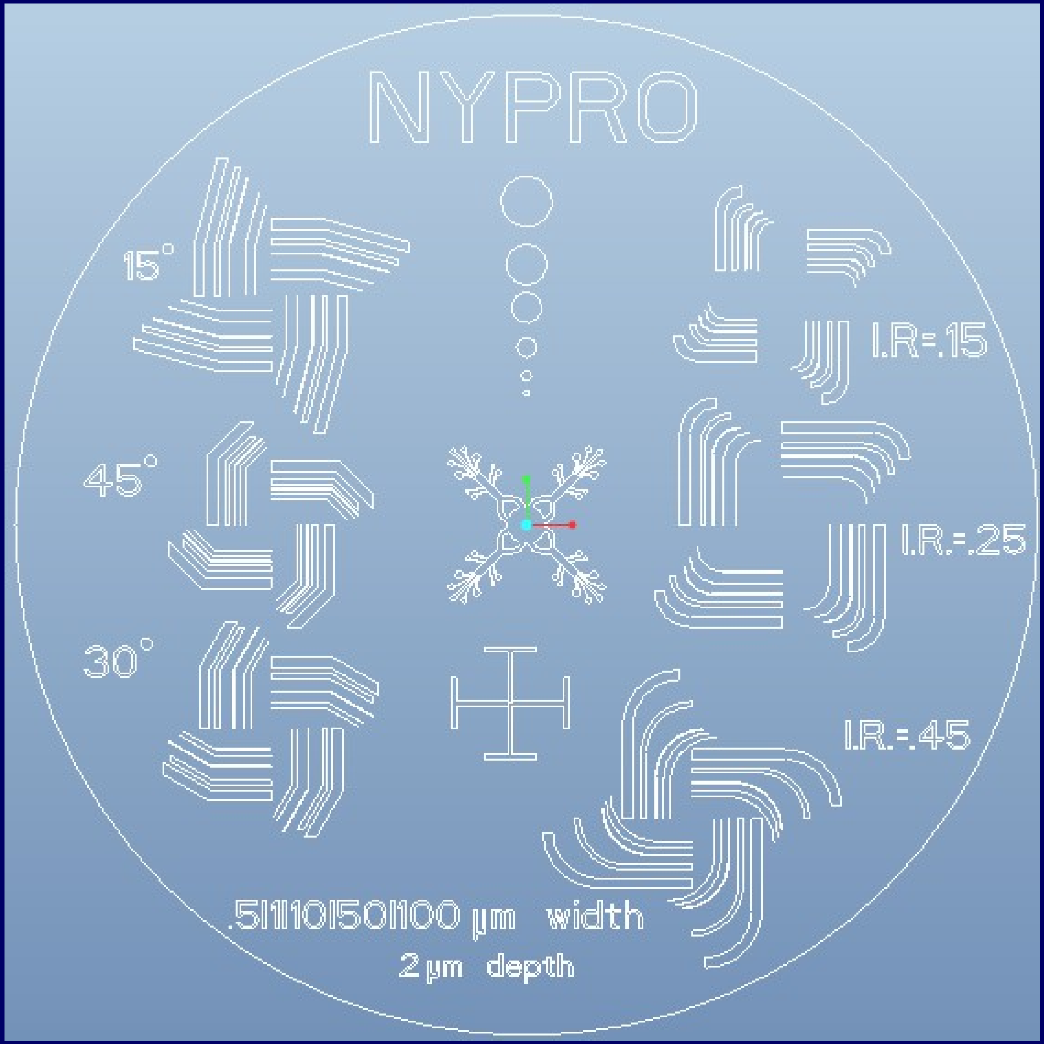
Yoon et al., *Plastics, Rubber and Composites: Macromolecular Engineering*, accepted (2010)
Palanisamy et al., *Proc. Ann. Tech. Conf. Soc. Plast. Eng.*, 1316 (2009)

Conclusions

- Gate location – often produces hesitation
- Vacuum venting – improves feature definition
- Tooling features
  - Positive features provide better replication than negative features
  - Smaller features are more difficult to replicate
- Tooling materials
  - Retarding heat transfer enhances replication
- Gas assisted injection molding
  - Improves replication, particularly with semi-crystalline polymers

Path Forward

- Effects of feature angles, radii, and size
- Impact of surface roughness
  - Silicon, steel



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- Nypro, Inc.
- Nissei America, Inc.; Metrigraphics; Bayer Corp.
- Sung-hwan Yoon, Joey Mead, Stephen Johnston, Jun Lee, Michael Alabran, Brian Beaudoin, Daniel Dempsey, Nicholas George, Younghyo Kim, Jeffrey Rawson, Purushotham Padmanabha, Prabhu Palanisamy, Chinnawat Srirojpinyo, Rajkumar Thiruvenkataswamy, University of Massachusetts Lowell
- Jin-Goo Park, Hanyang University, South Korea
- David Carter, The Charles Stark Draper Laboratory
- Shinji Matsui, University of Hyogo (Japan)
- Nam-Goo Cha and Xugang Xiong, Northeastern University
- Keun Park, Seoul National University of Technology
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