# Three Dimensional Printing

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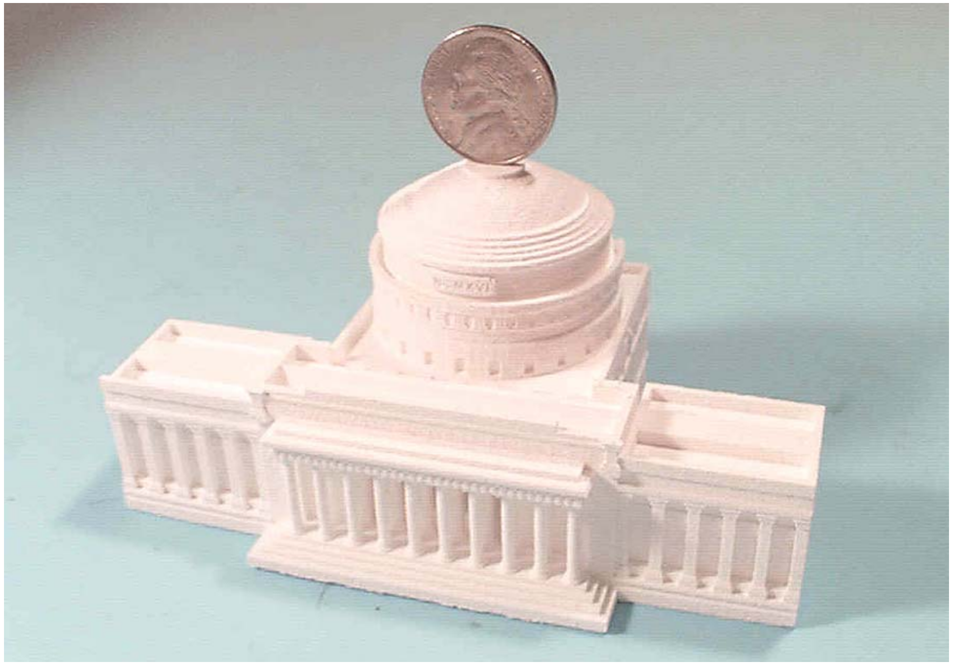

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14. ABSTRACT
3D Printing is an SFF Process which creates parts in layers. Each layer is formed by spreading powder and selectively joining the powder by ink-jet printing of a binder material.

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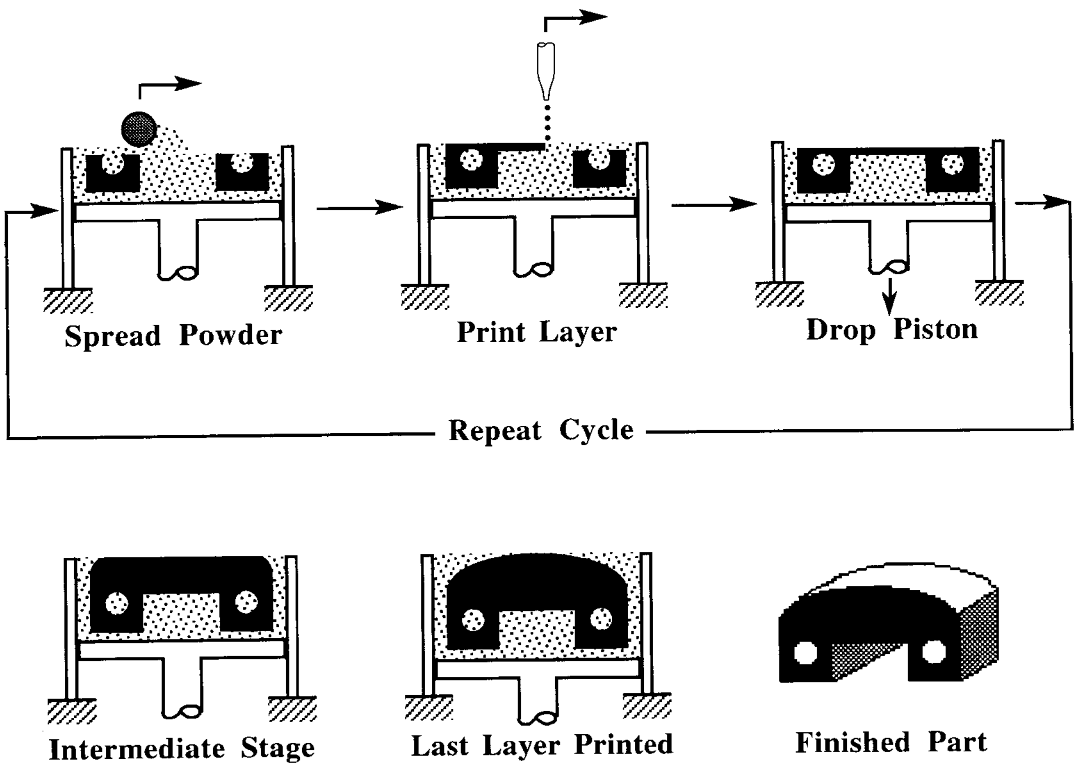
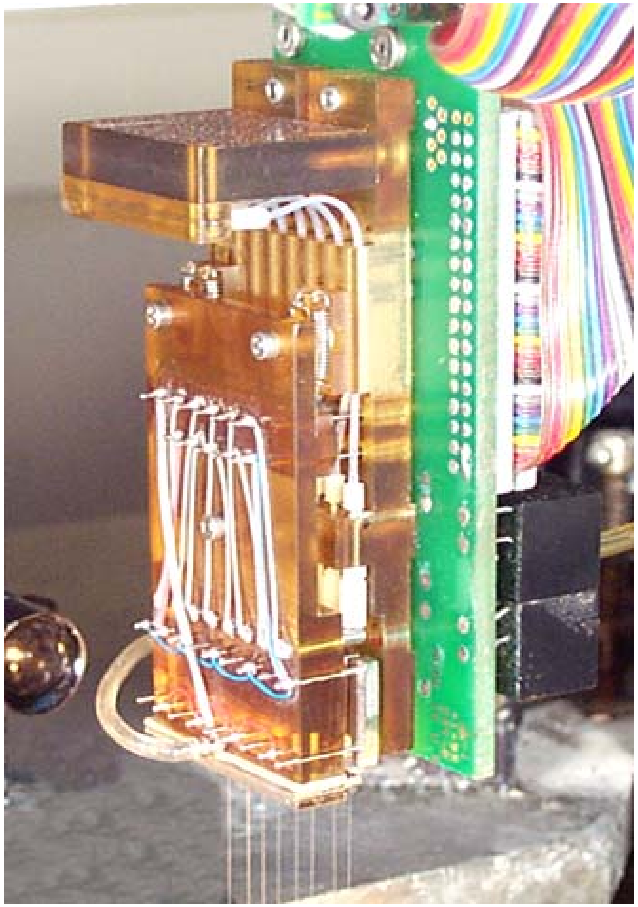
# The 3D Printing Process

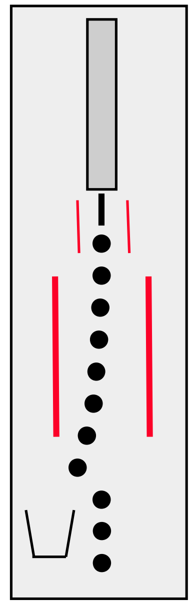


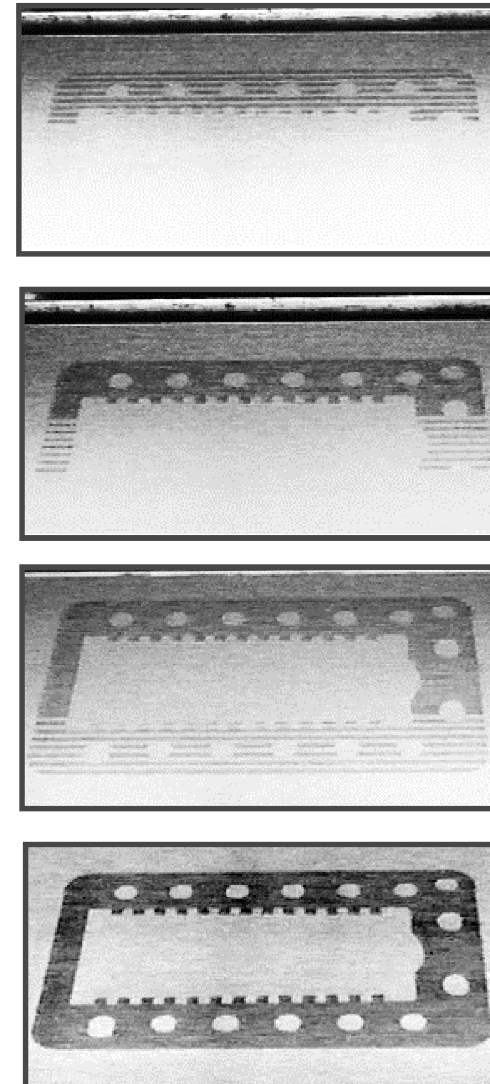

- Any material as a powder
- Scaleable with multiple nozzles
- Local Composition Control

3D Printing is an SFF Process which creates parts in layers. Each layer is formed by spreading powder and selectively joining the powder by ink-jet printing of a binder material.

# MIT's 8-jet Printhead



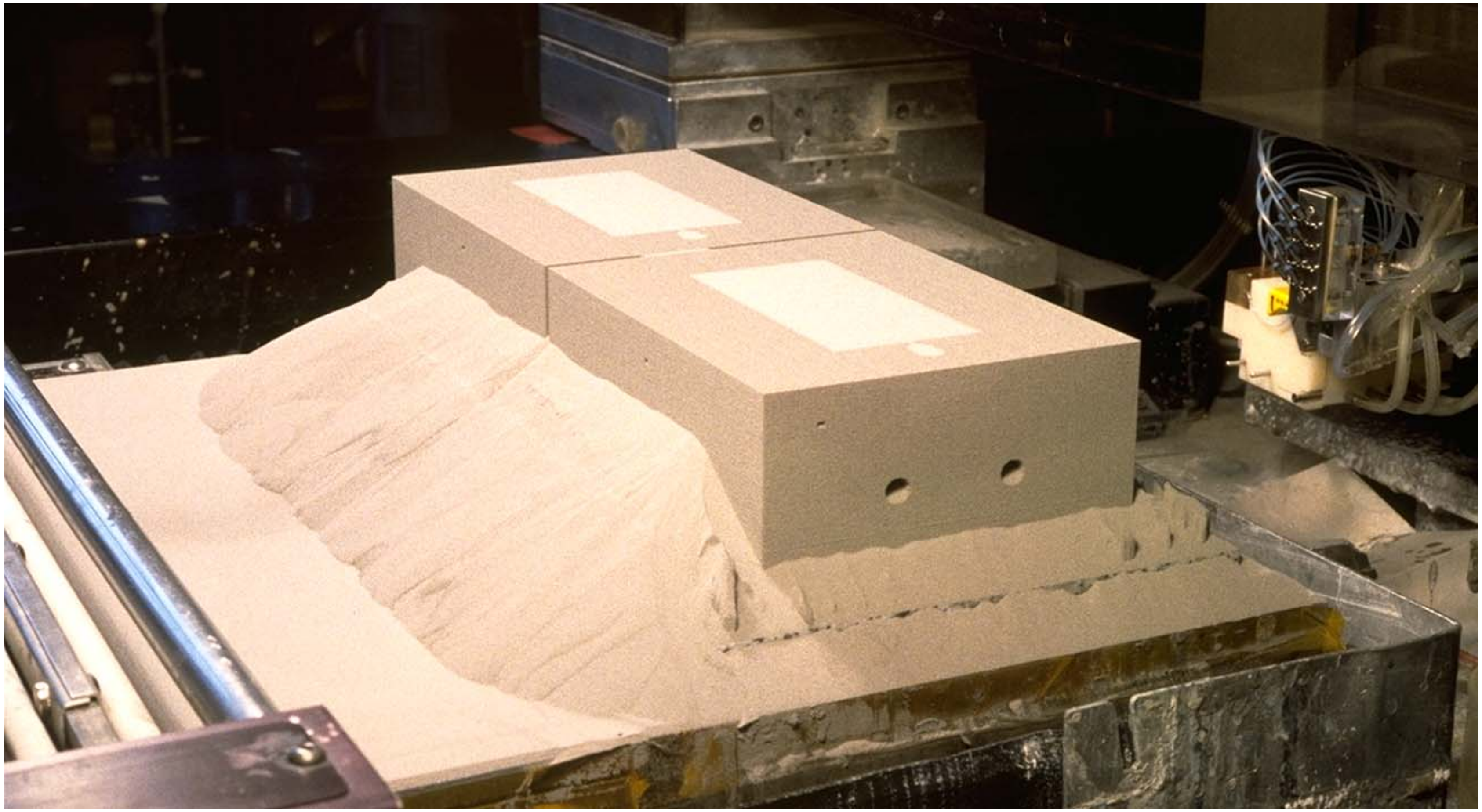




Printing a layer

**Allows for wide range of materials, precise droplet location and scalability.**

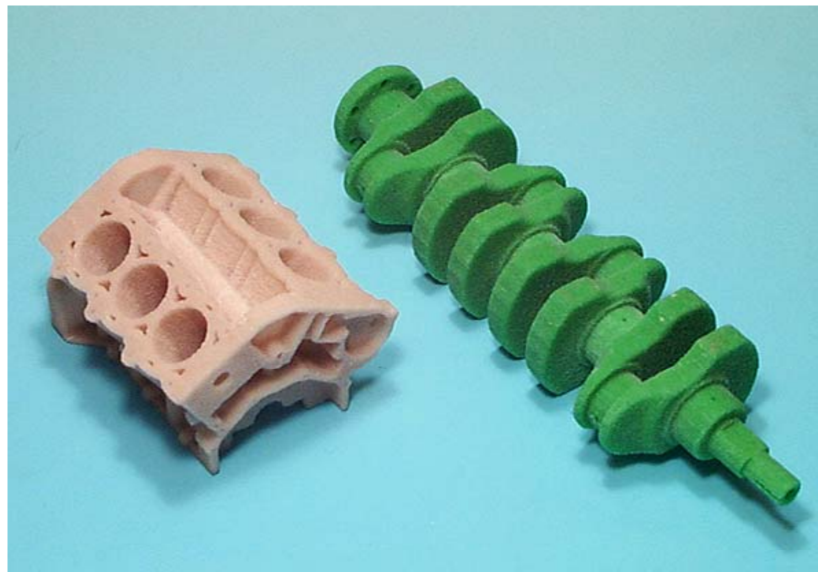
# Removing the Green Part from the Powder Bed



# Office Modeler;

Z Corp., Burlington, MA

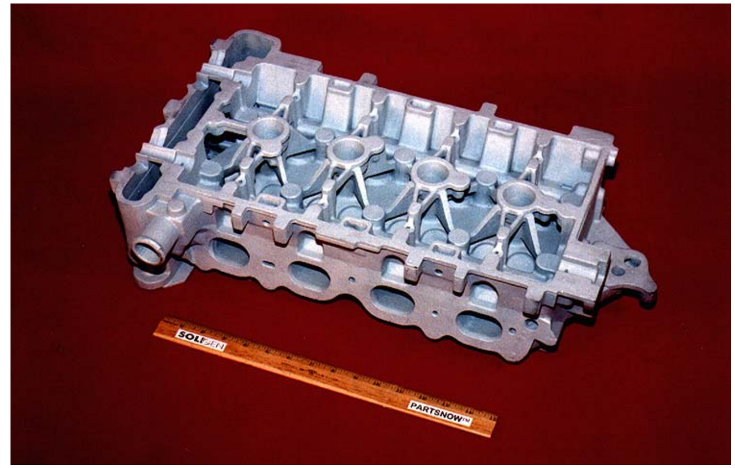
- **Low cost machine.**
- **Office environment (water binder, starch powder or plaster based)**
- **High reliability.**
- **FAST**

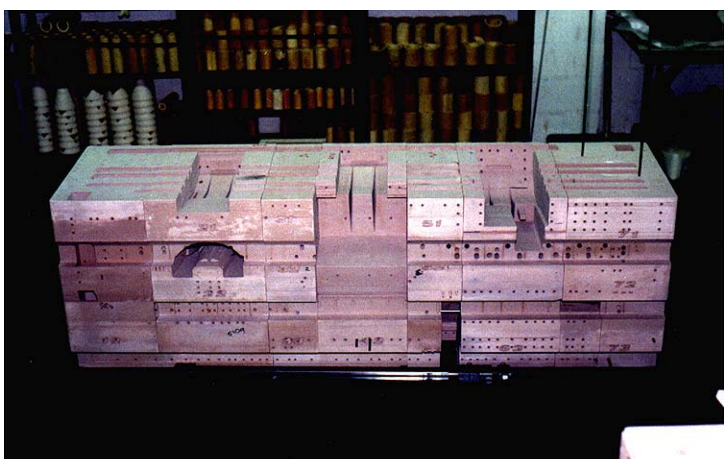


# Ceramic Molds for Metal Castings;

## Soligen, Inc. Northridge, CA

- 3D Print Ceramic mold
  - Colloidal silica binder into alumina powder
- Fastest route to a casting.
- Soligen Operates "Parts Now" which accepts files and returns castings.





# Filters;

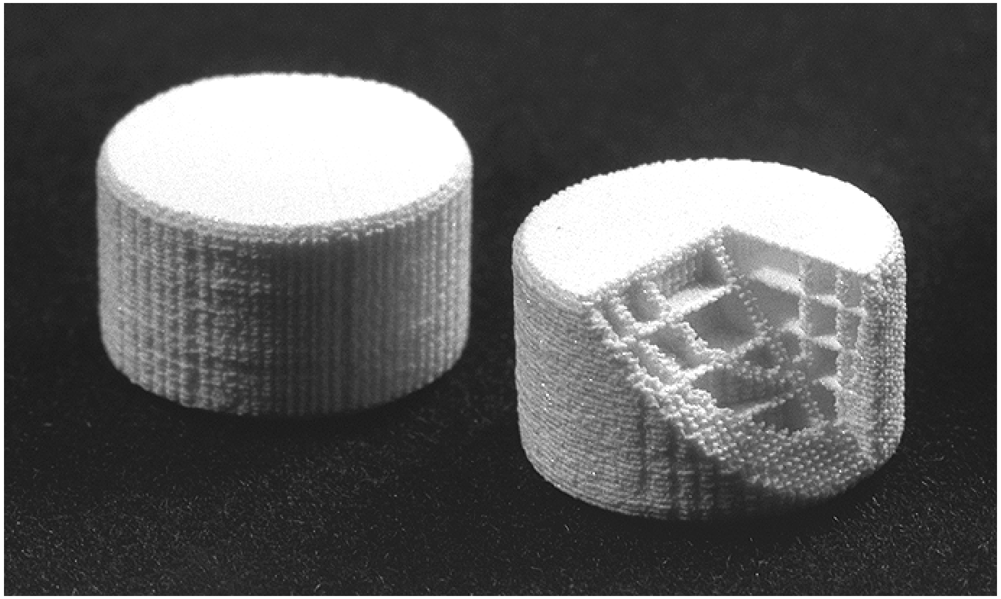
Specific Surfaces,   Franklin, MA

- **Focus: ceramic filters for power plants - high filter area, durable, cleanable.**
- **Successful tests in "bag houses" (2000 hours).  Tests on full scale pilot plant next.  EPRI funded.**

# Medical Applications;

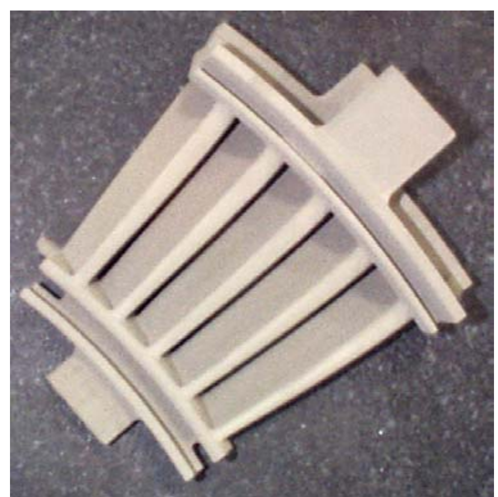
Therics, Inc.  Princeton, NJ

- **Drug delivery devices.**
- **Scaffolds for tissue engineering.**
- **Direct printing of tissue and organs.**
- **Direct printing of metallic prostheses.**



# Direct Printing of Metal Tooling;
ExtrudeHone Corp., Irwin, PA

- **Directly print metal tooling.**
  - **Polymer binder into metal powder.**

# Tooling by Direct Printing

- Colloidal latex binder
- 
- 

Stainless steel or tool steel powder

→ Remove unprinted powder

→ Green part
58% metal
10% polymer
32% open porosity

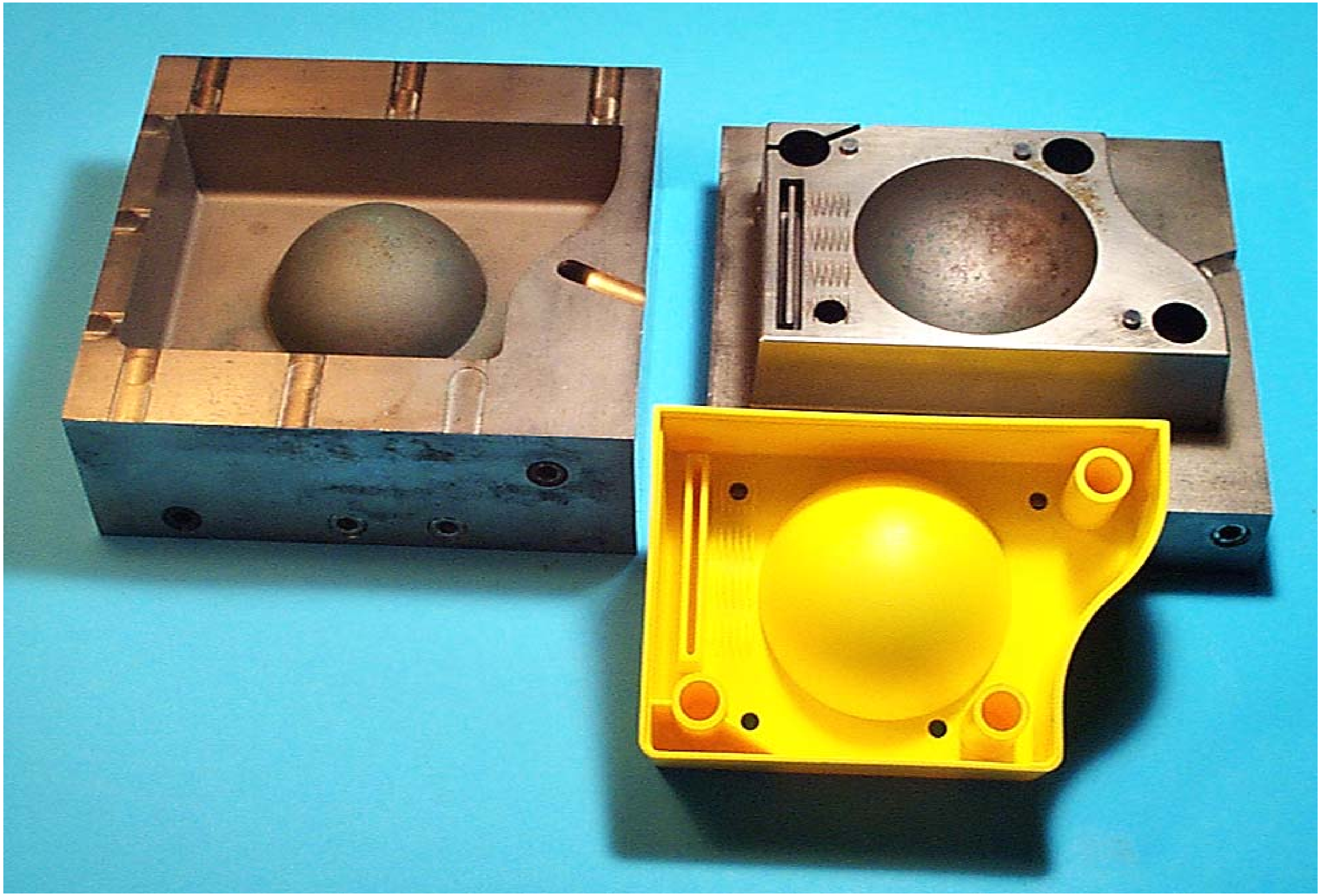
→ Debind by thermal decomposition & pre-sinter to 63% dense

→ Infiltrate to full density with copper alloy

→ Finish

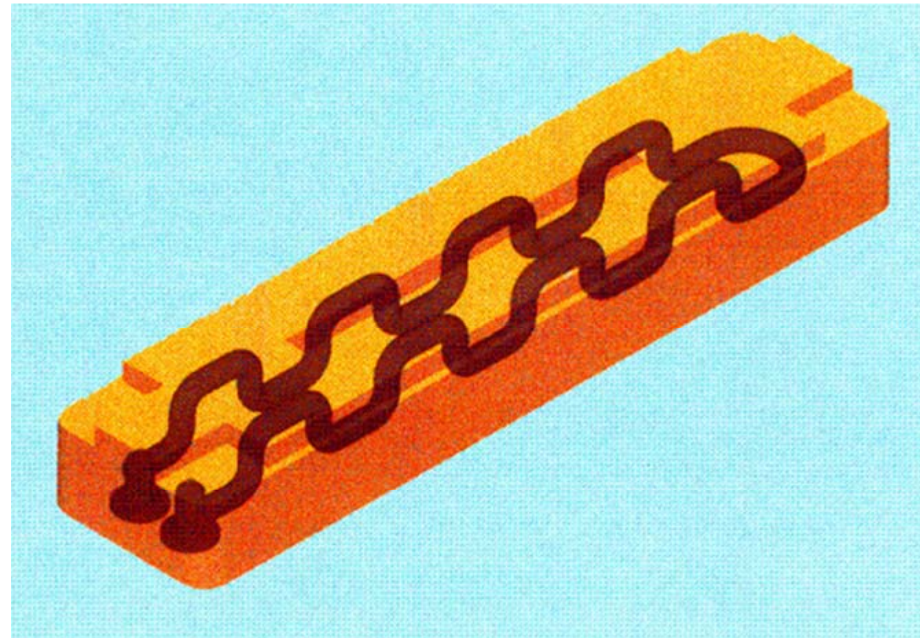
→ Tool Insert

# Finished Tool and Molded Part



# Conformal Cooling in an Industrial Application

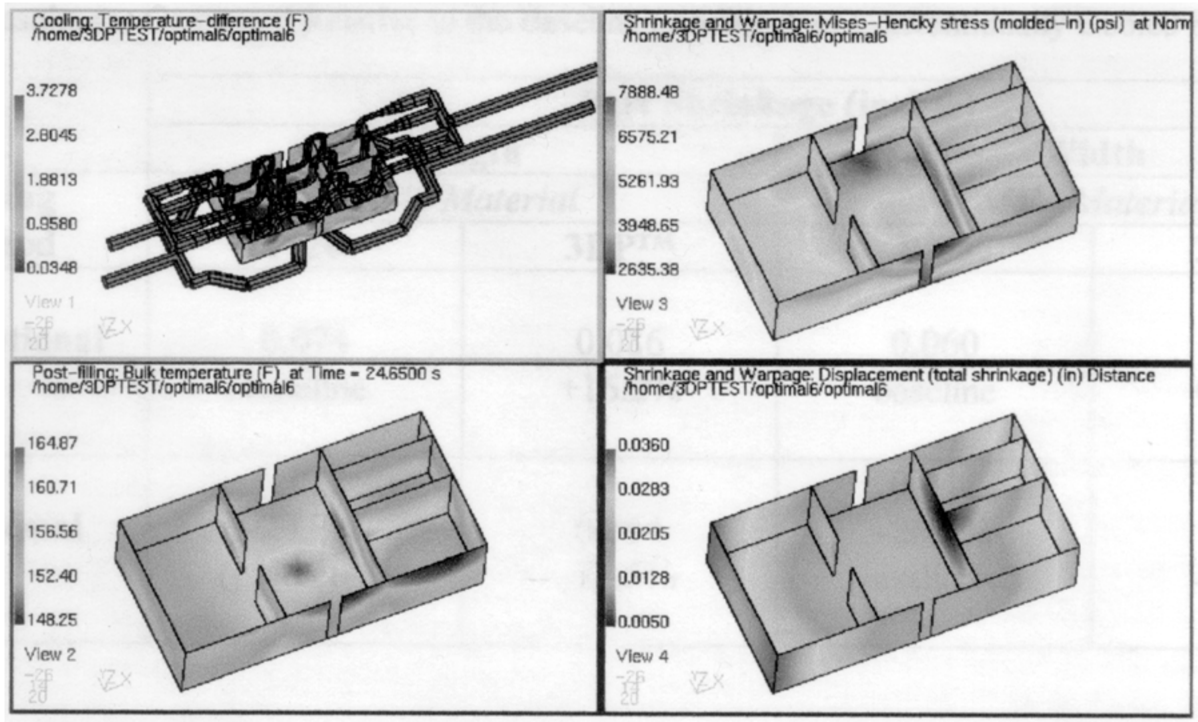
**Tool made by 3D Printing with serpentine cooling channel**



**Improvement over Production Tool**

| | Cycle time | Part Distortion |
|---|---|---|
| **Condition #1** | **15%(limited by sprue)** | **9%** |
| **Condition #2** | **0%(limited by sprue)** | **37%** |

# Conformal Cooling; Data from Design of Expt's

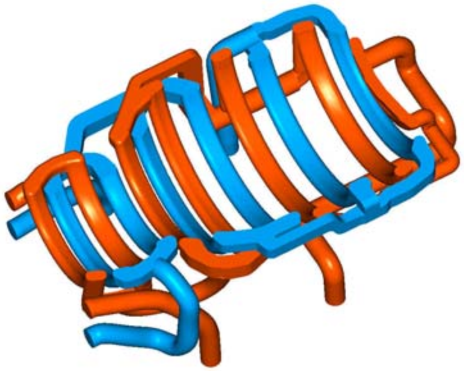


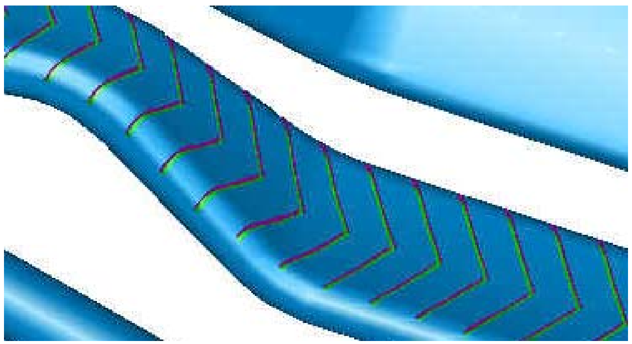

- **Typically**
  - **20% reduction in cycle time**
  - **15% reduction in shrinkage**

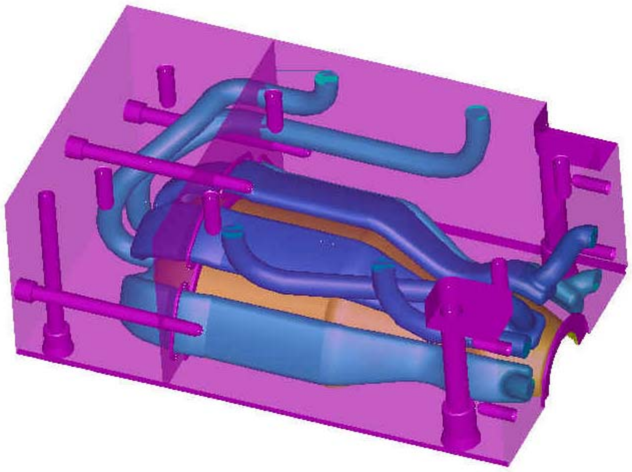
Schmidt et al, "Conformal Cooling vs Conventional Cooling: An Injection Molding Case Study with p-20 and 3DP tooling, MRS 4/00

# Partnership in Technology

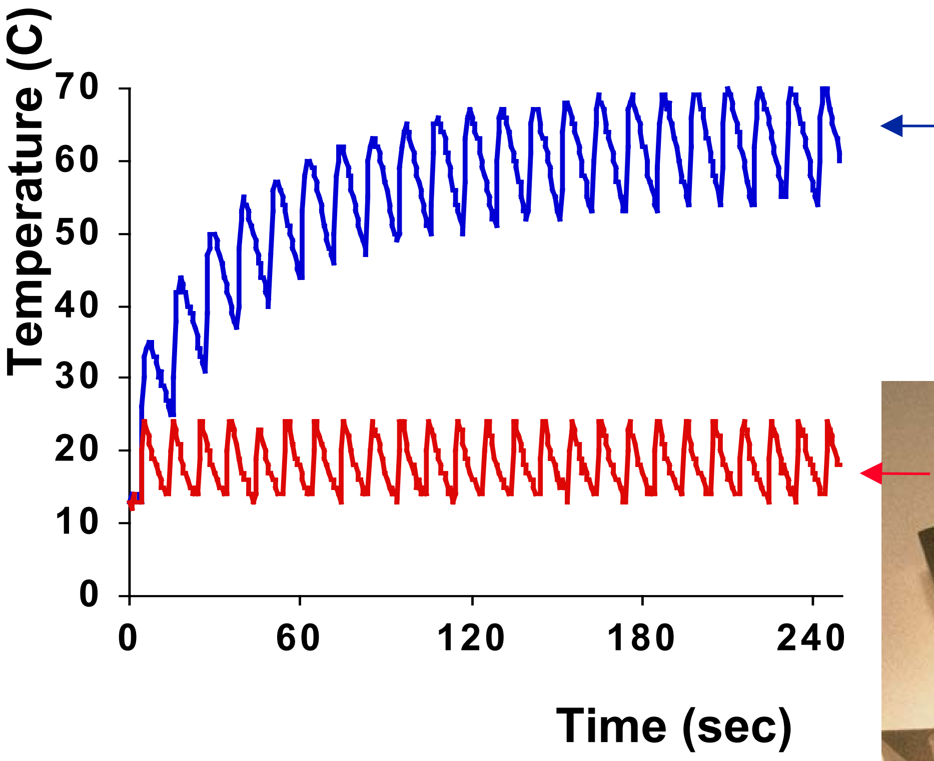
- **Blow Mold Cavities**
  - ***MoldFusion*™ First Design**
    - Two conformal and opposing flow circuits
  - ***MoldFusion*™ Second Design**
    - Two conformal linear flow circuits
    - Turbulence chevron features

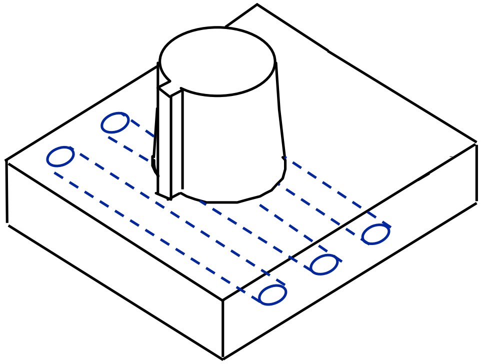


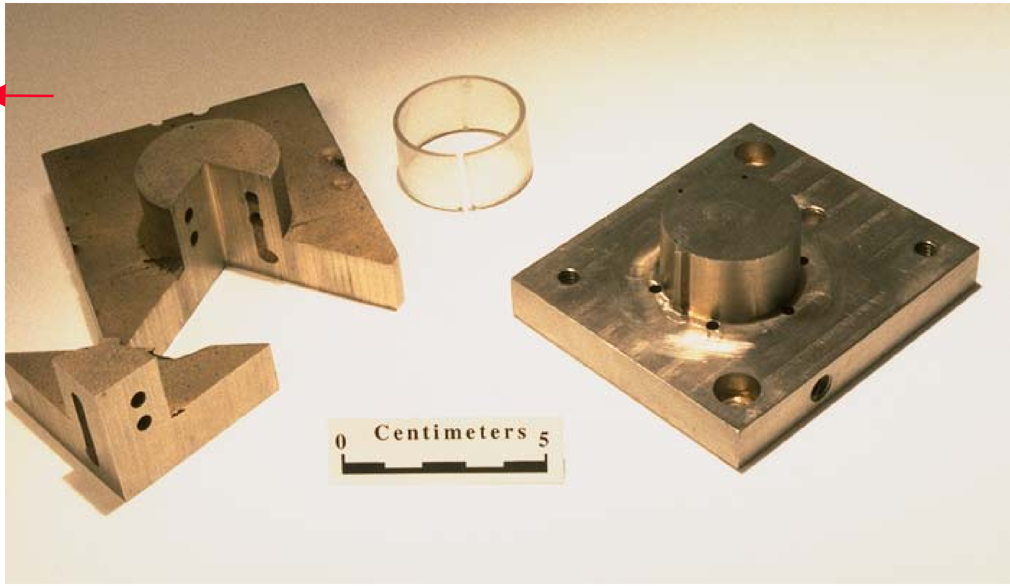




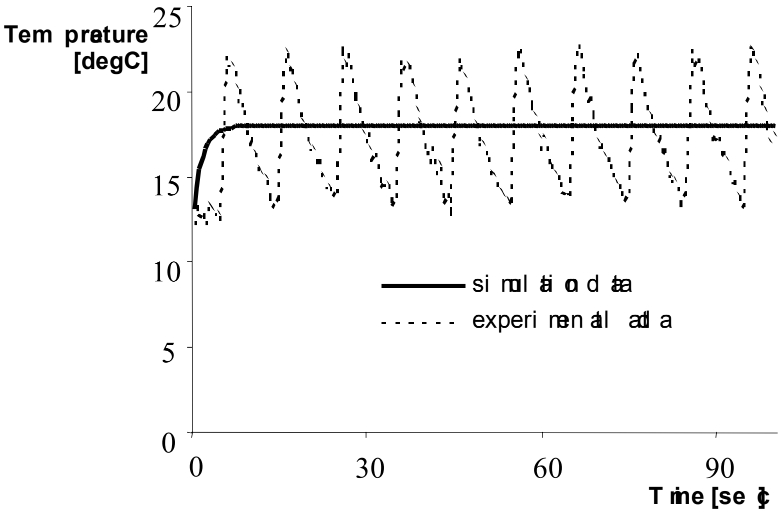
# Demonstration of Performance:Conformal Cooling

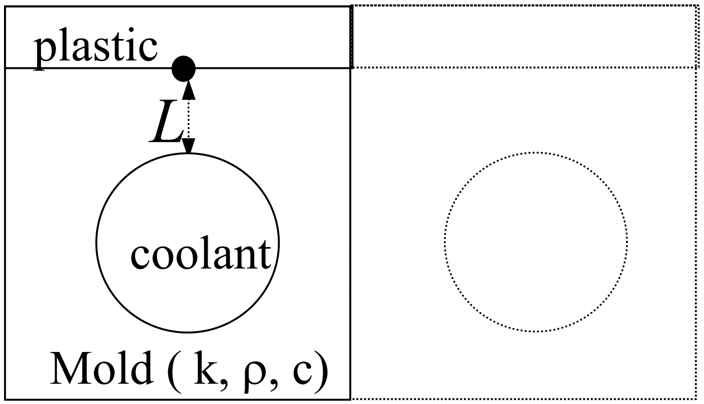




# Conformal Cooling Condition



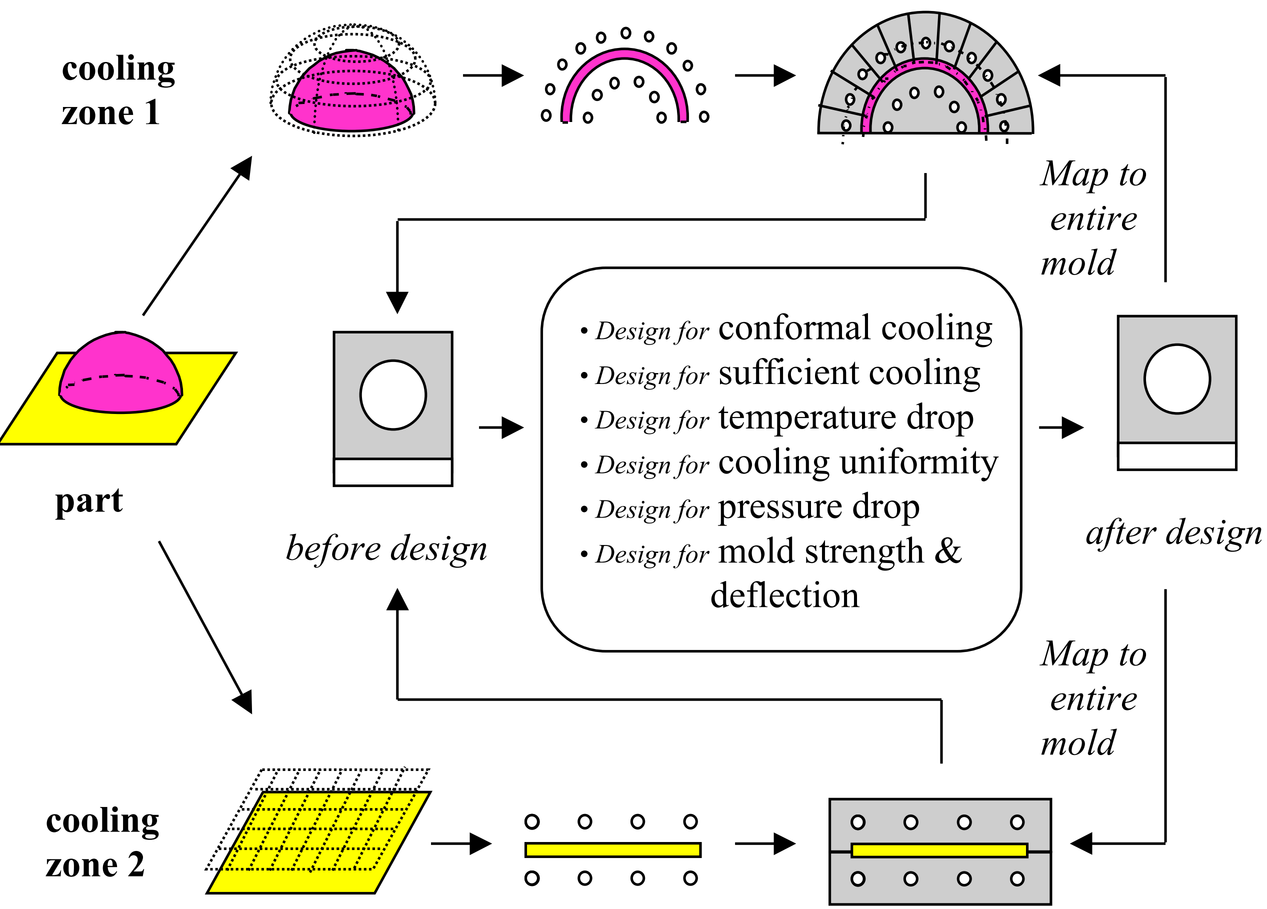



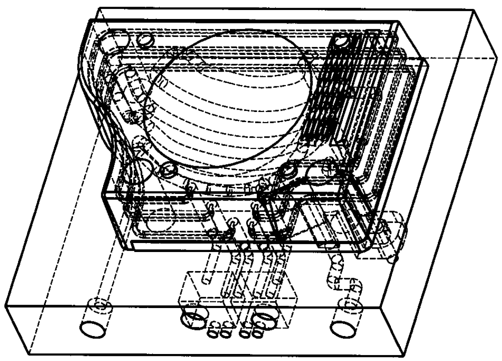

One cooling cell

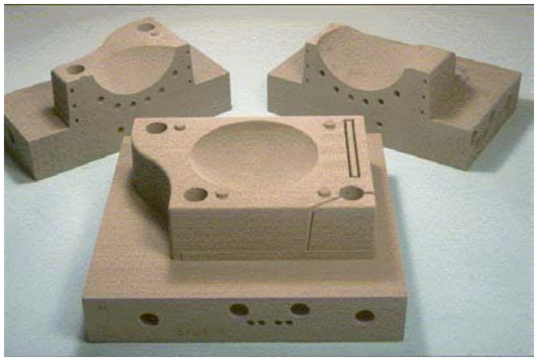
Adjacent cooling cell

$$\frac{L^2}{k} < \frac{\text{Cycle Time}}{\rho\ c}$$

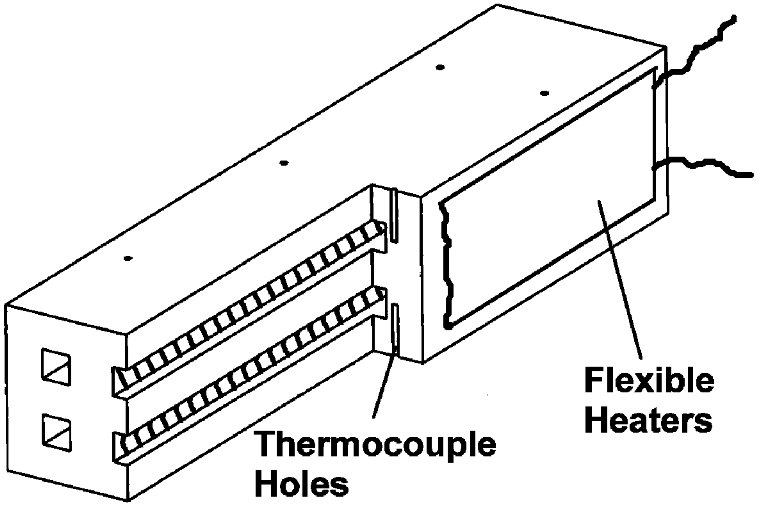
# Conformal Cooling Channel Design Methodology

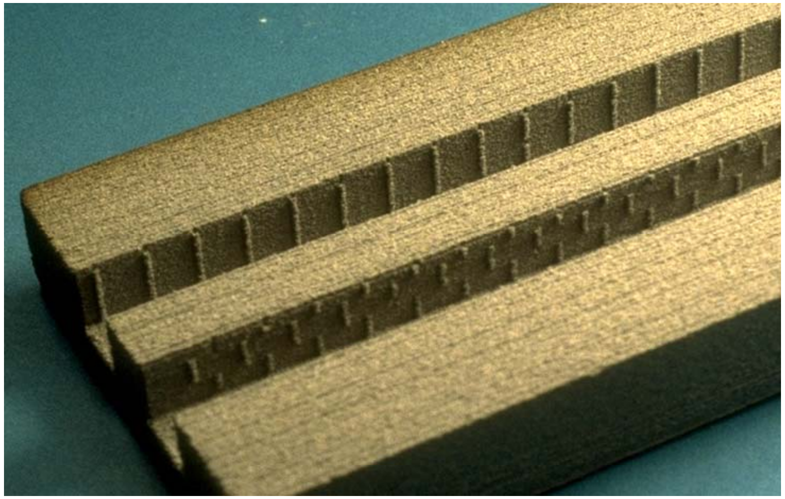


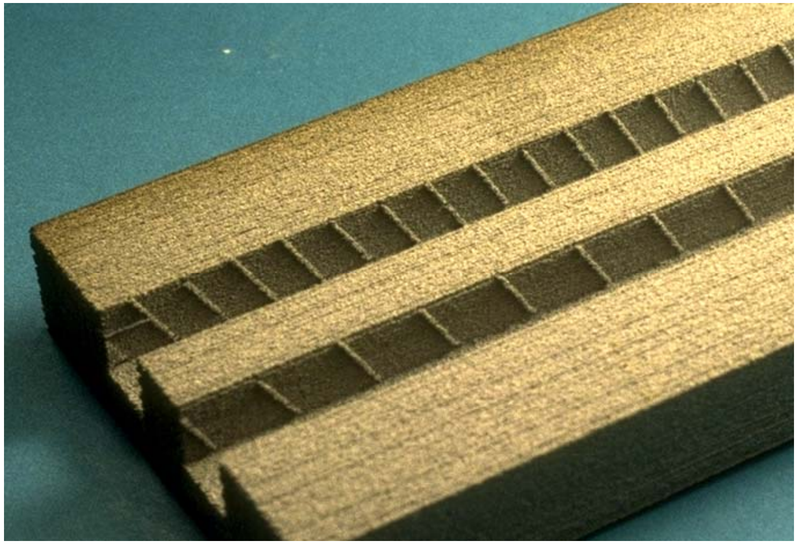



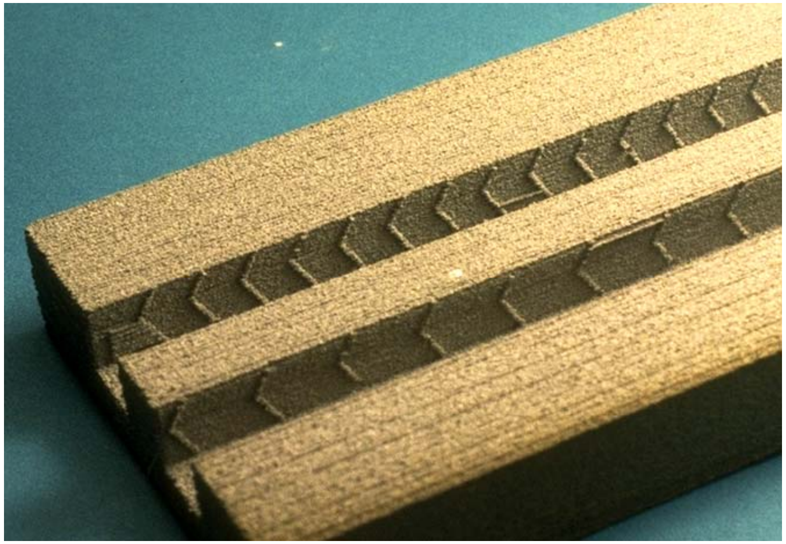


# Surface Textures for Heat Transfer Augmentation

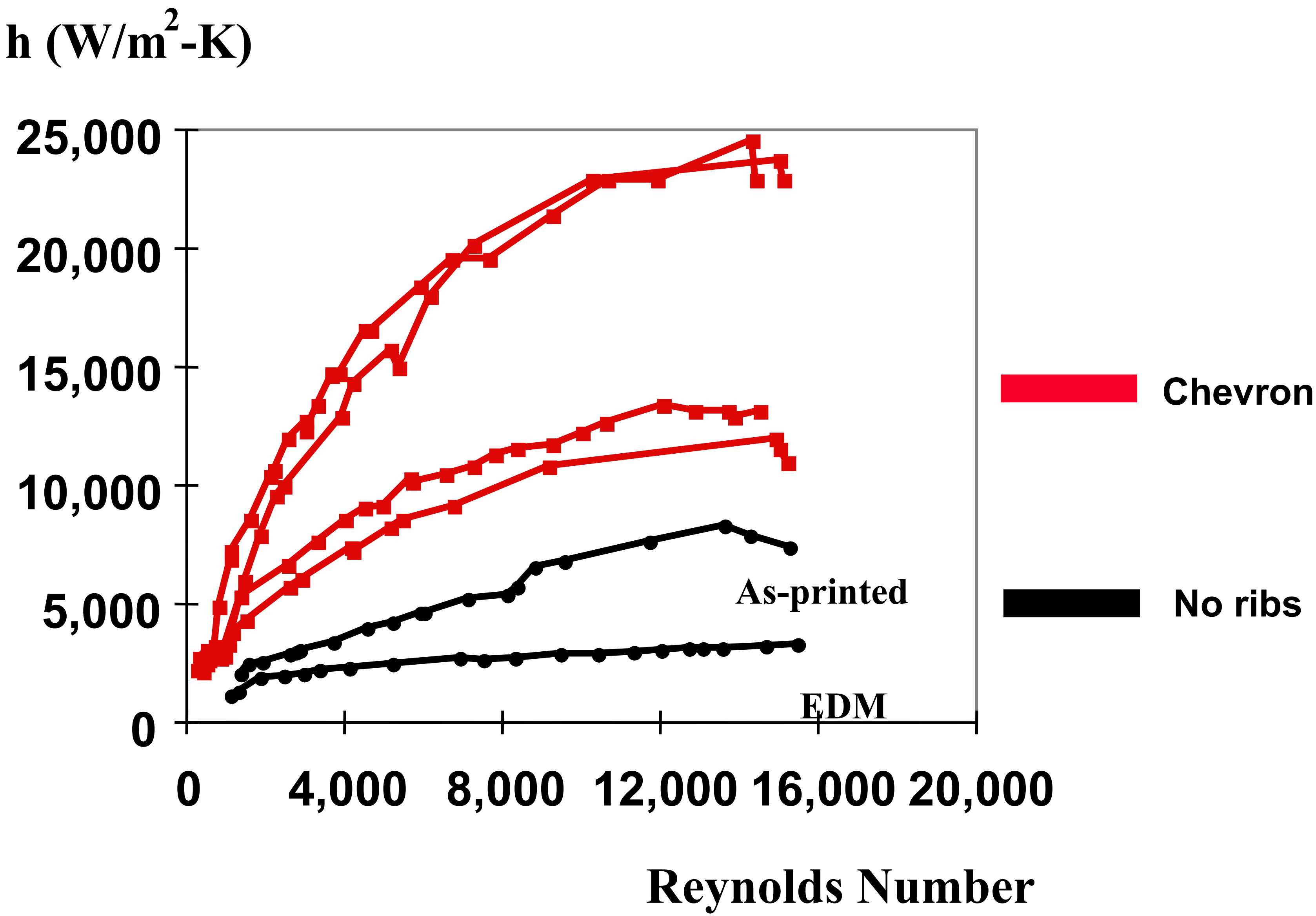


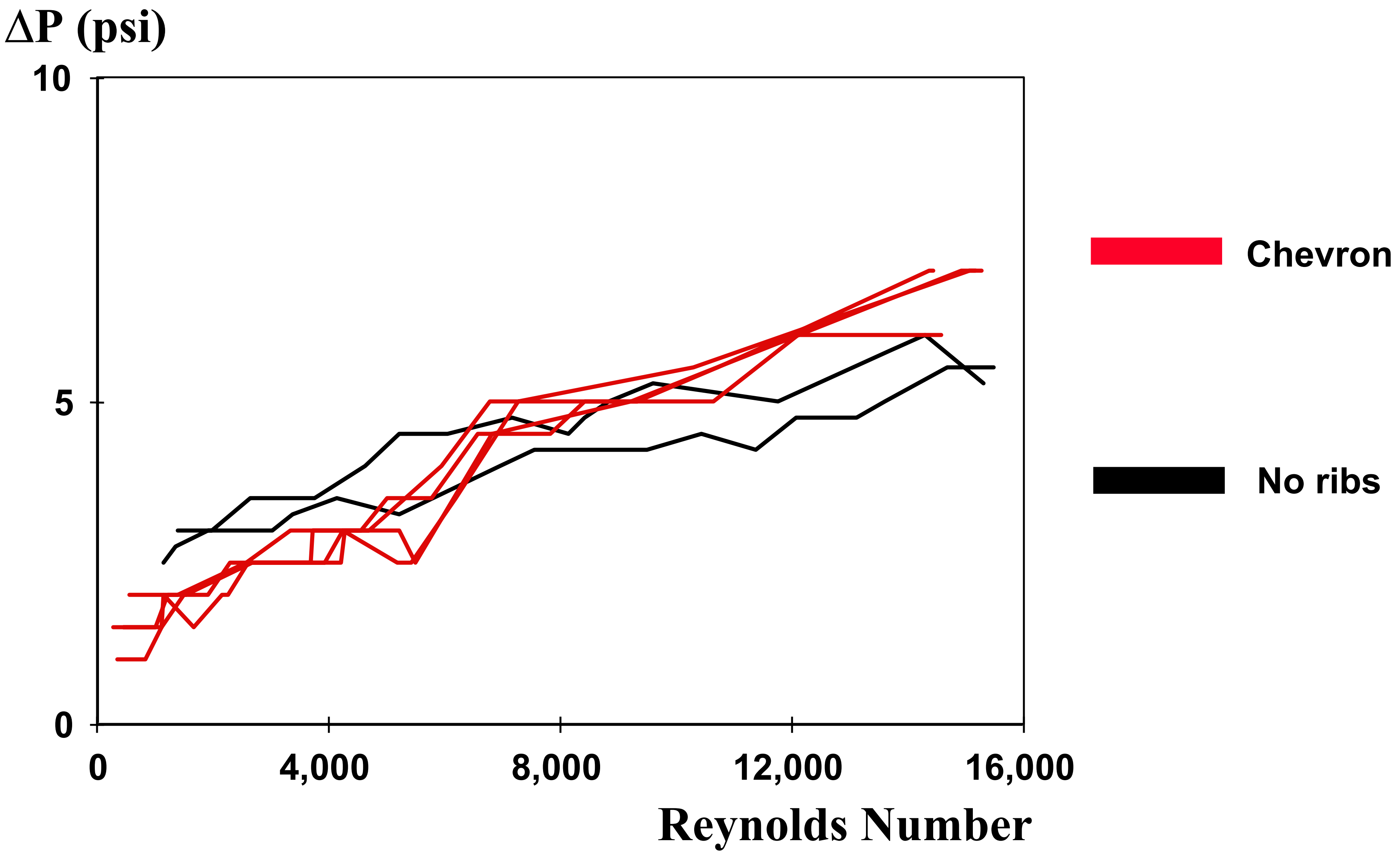




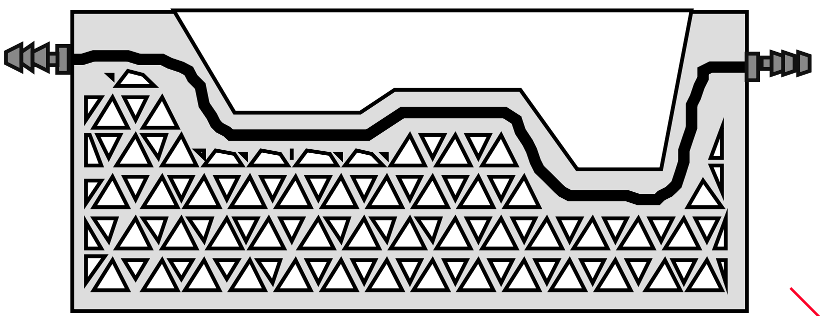
# Heat Transfer Coefficient



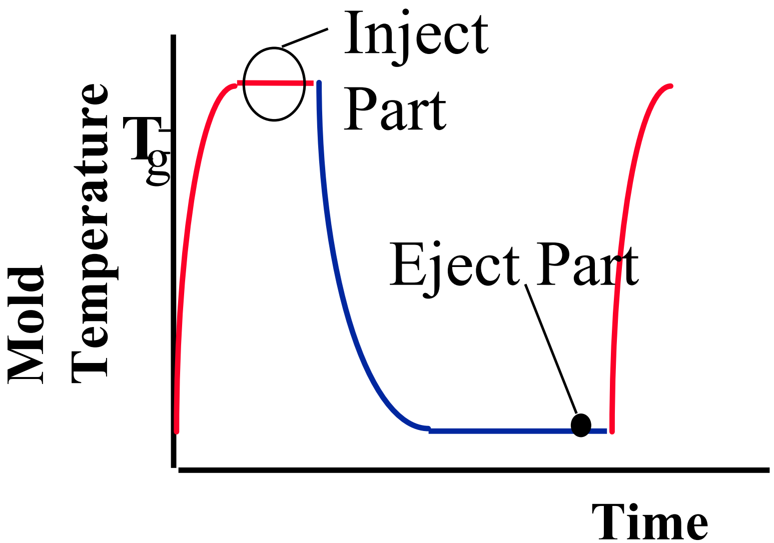
# Pressure Drop (ΔP)



# Rapid Thermal Cycle Tooling

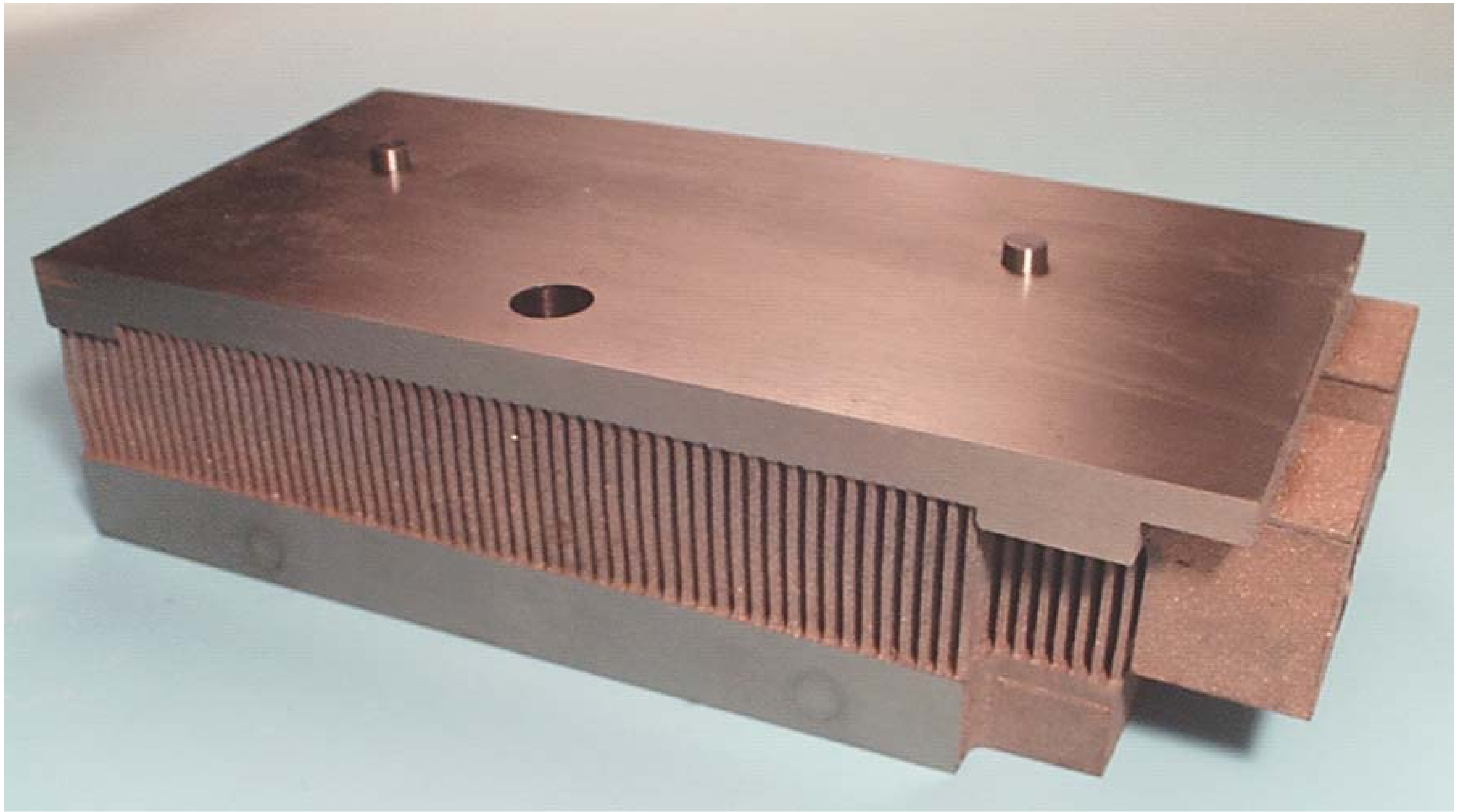


Constant Temperature



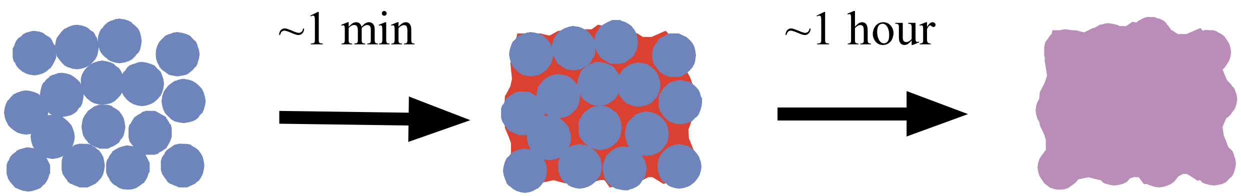

Cycled Temperature

# 3D Printed Tool for Rapid Thermal Cycling



**The tool has cooling/heating channels in the top plate and stands on 2000 posts (which allow for thermal expansion/contraction)**

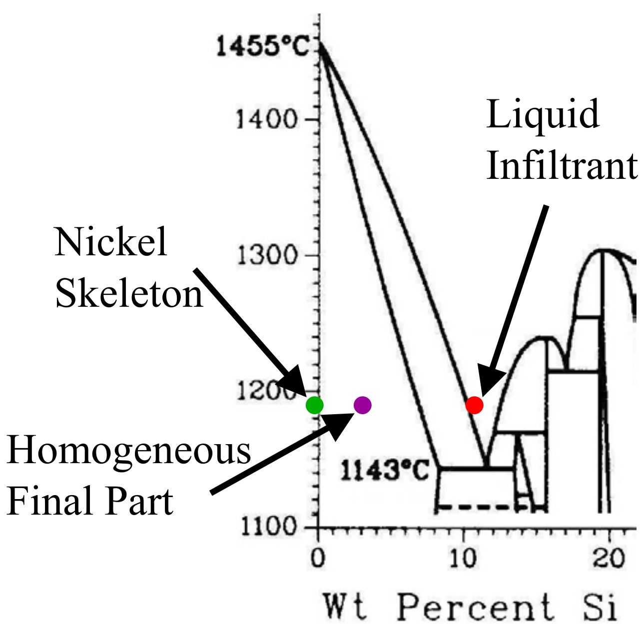
# Homogeneous Metal Parts by Infiltration




Porous skeleton of nickel or other high temperature material

Infiltration using same material containing a melting point depressant (MPD)

Diffusion of MPD into skeleton creates a solid homogeneous part




**~1 kg infiltrated part (Ni–4Si)**

# Infiltration Distance

- **Capillary limit**

$$h = \frac{1}{\rho g} \cdot \frac{2\gamma}{r}$$

**>0.5 m typical for 100 μm powder**

- **Premature freezing of infiltrant can choke liquid flow**

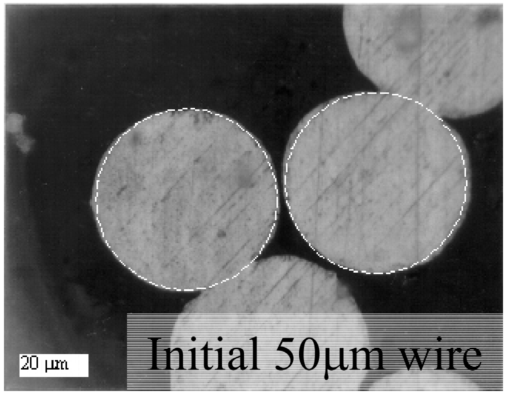
Skeleton made of ~ 50–150 μm powder (both cases)

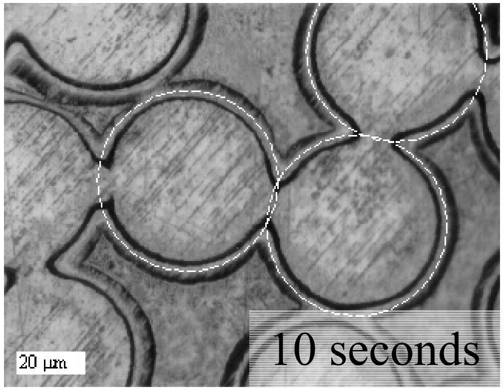
Ni infiltrated with Ni-10Si

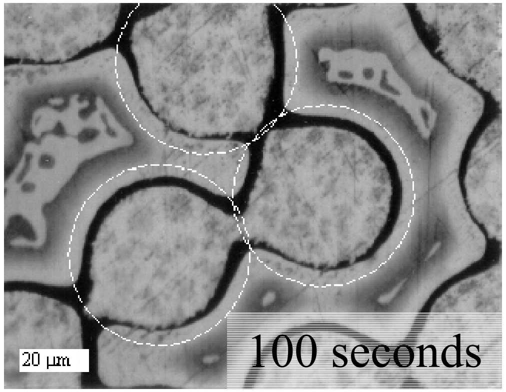
Steel infiltrated with Cu

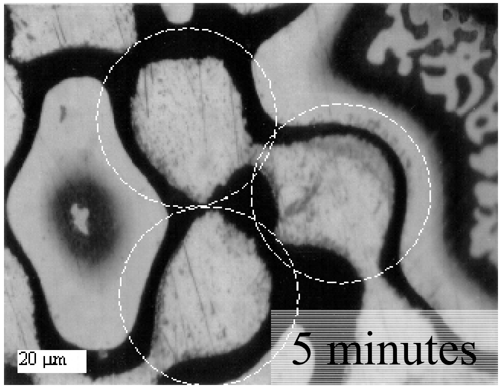
# Solidification Time Sequence

- Wire bundle infiltrated and quenched at various times
- Ni wire w/ Ni–10Si infiltrant
- Infiltrated at 1200°C



# Solidification Time Sequence

- Wire bundle infiltrated and quenched at various times
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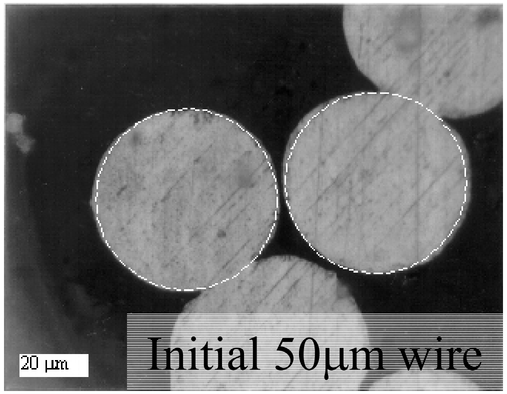
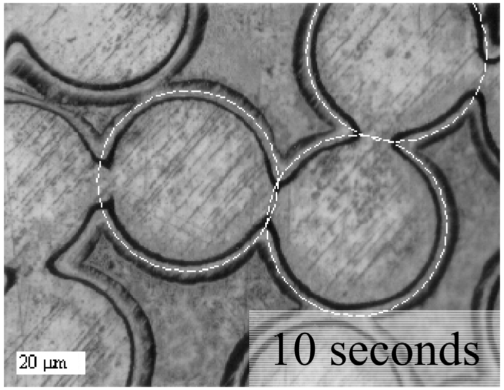
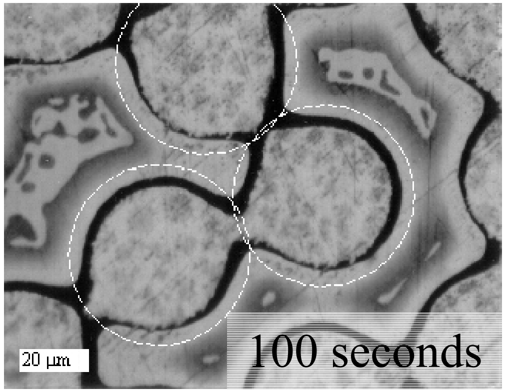
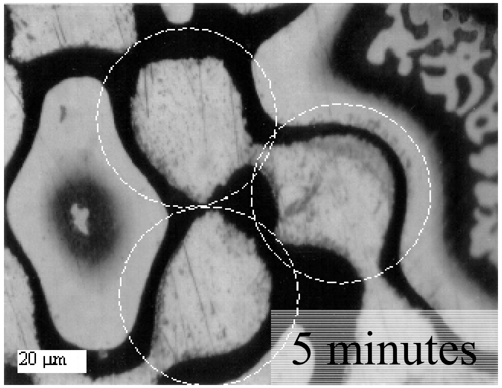


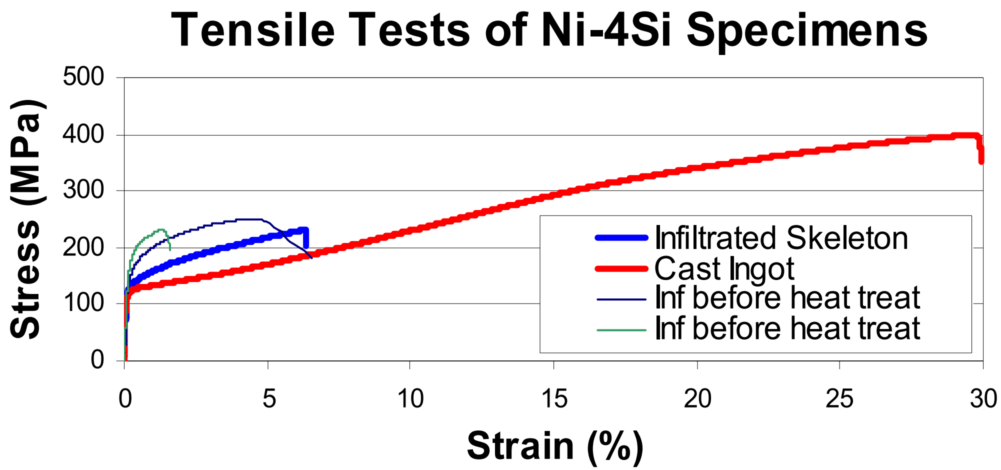



# Mechanical Properties

Infiltrated

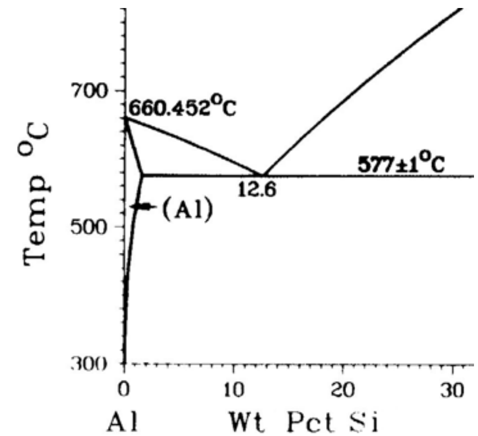


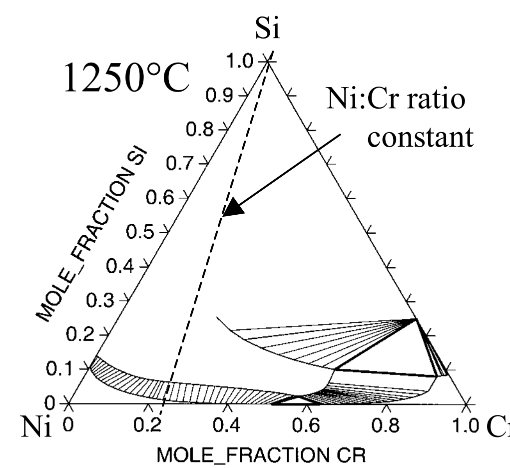

- Infiltrated skeleton held 12 hrs at 1200°C for homogenization
- Cast ingot of same composition
- Hopefully Cr or other elements will provide more strengthening

Cast ingot

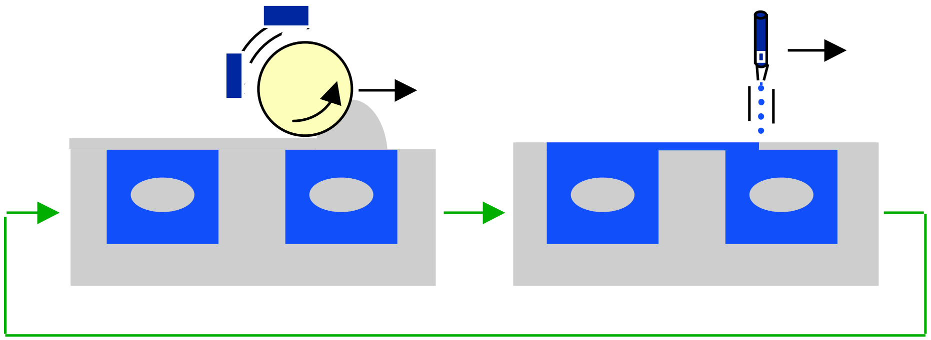
# Other Material Systems

- **Al–Si**
  - Low solubility (no freeze-off)
  - Similar to cast microstructure
  - Pure Al infiltrated w/ Al–12Si at 625°C achieved 93.5% density
- **Ni–Cr–Si**
  - solid solution strengthening
  - keep constant Ni:Cr ratio during diffusional solidification
- **Steel?**



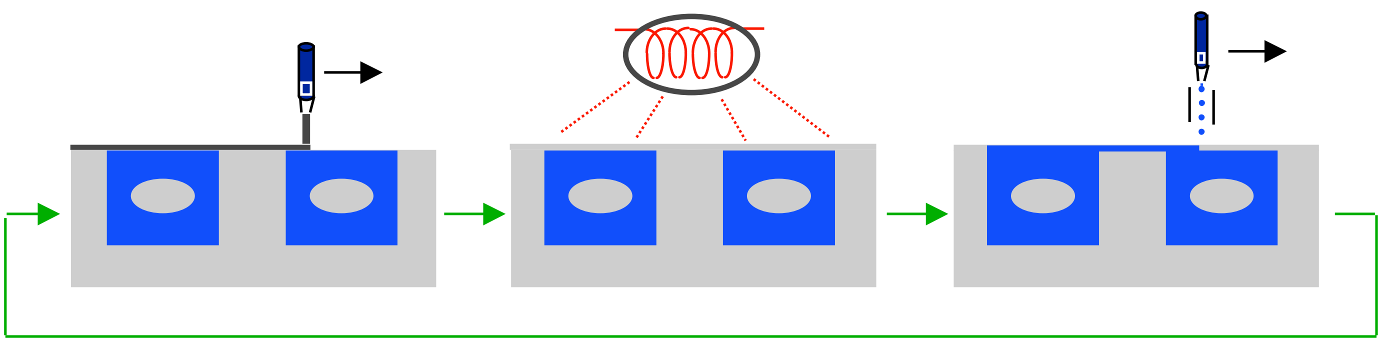



# 3D Printing: Dry vs. Wet Layer Spreading



**Dry**

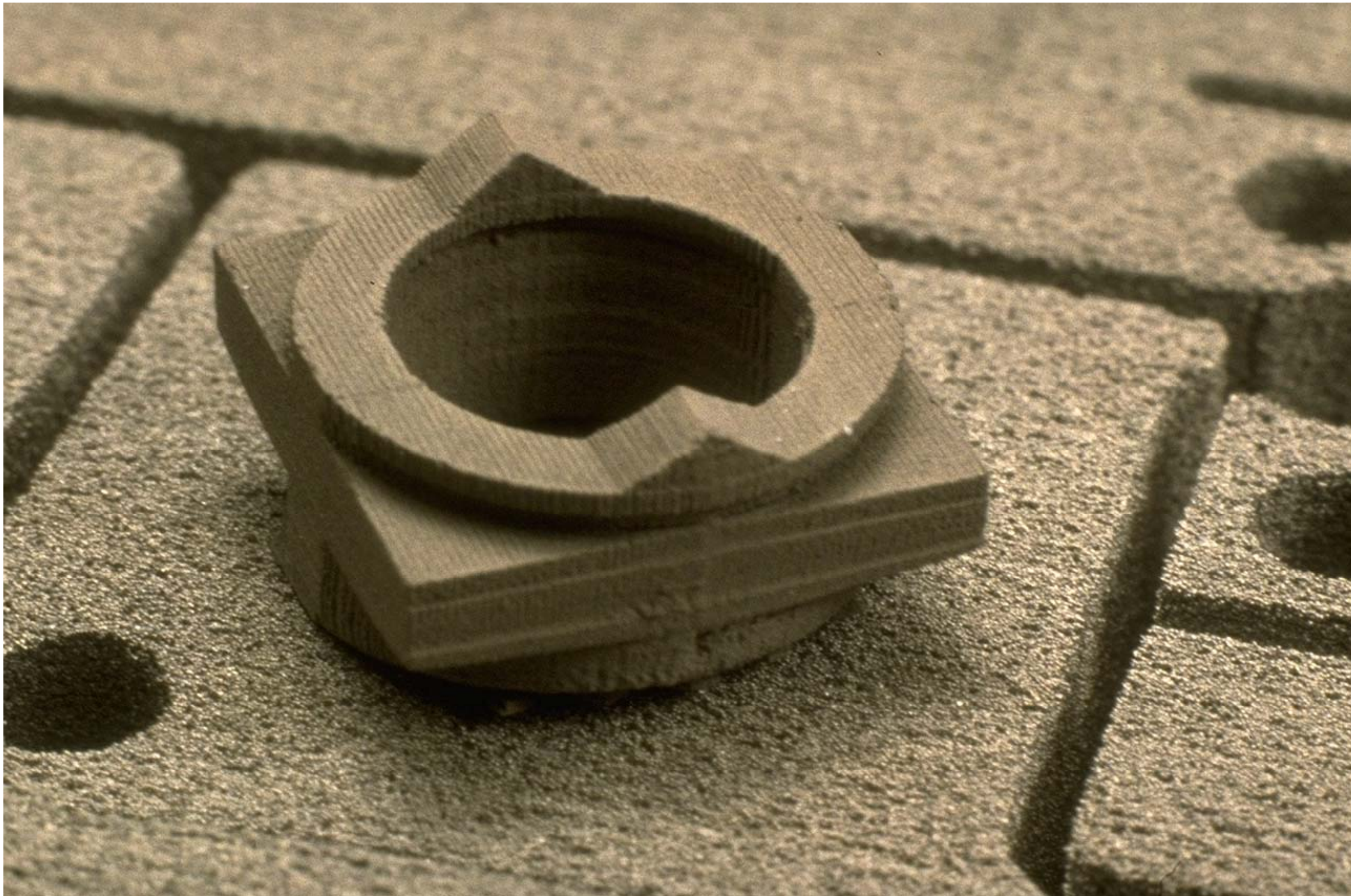
- **Spherical as small as 10 μ**
- **Acycular as small as 20 μ**



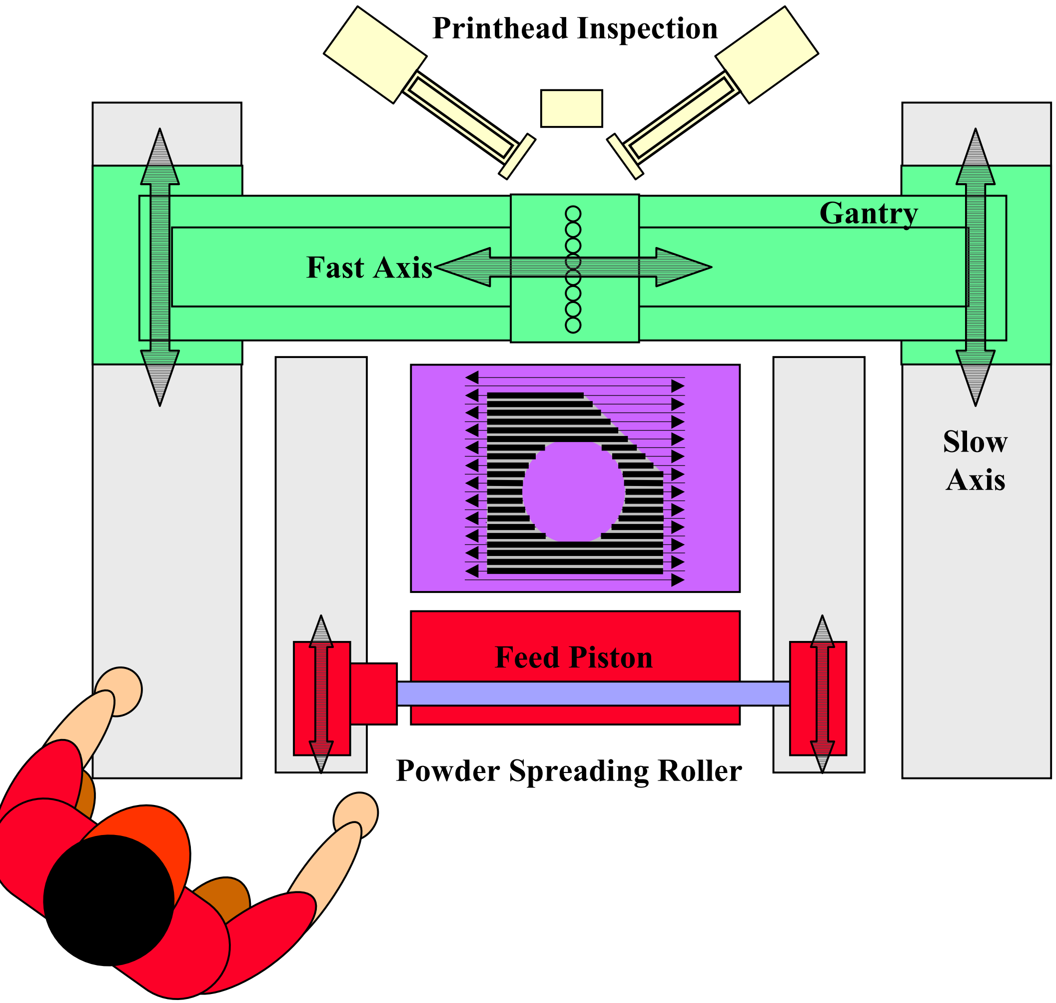
**Wet**

- **Anything that can be slurry processed**

# Parts with Fine Metal Powder



# Architecture 1: Stationary Bed, Raster Print

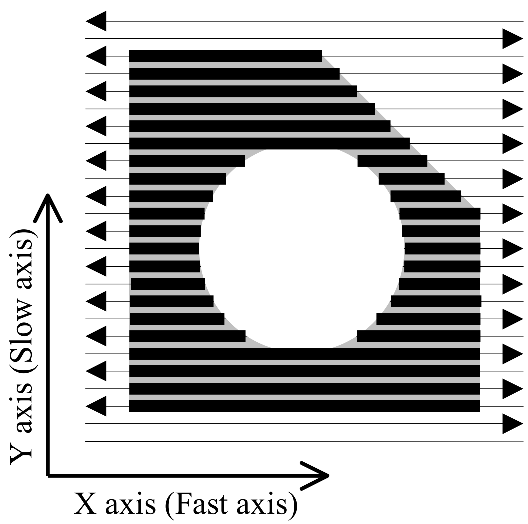



Z Corp.

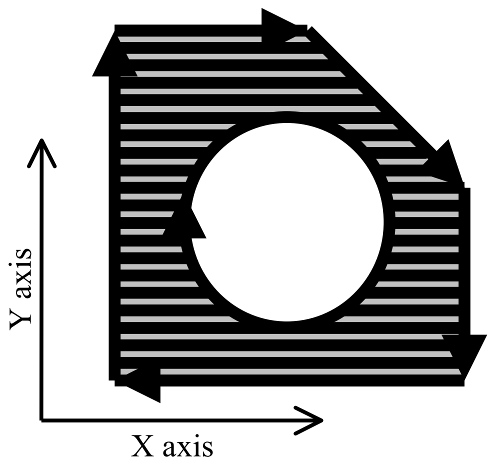

ExtrudeHone Corp.

# Small Parts; Distinguishing Features

- **Powder beds are small , light (<1 kg) and often cohesive.**
  - ⇒ **Move powder bed**
- **Perimeter is short**
  - ⇒ **Vector Print the perimeter.**

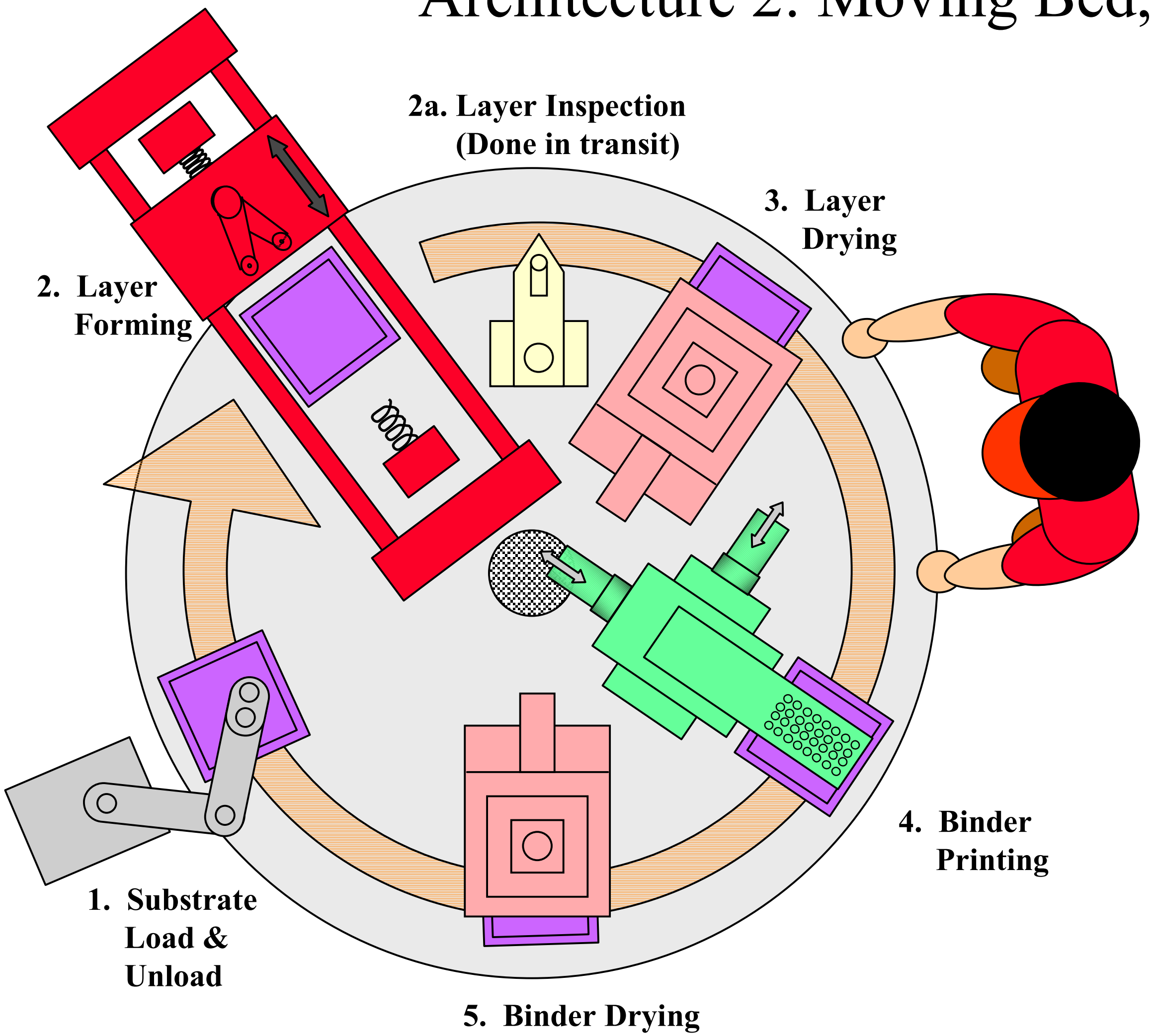



**Raster printing**




**Vector printing**

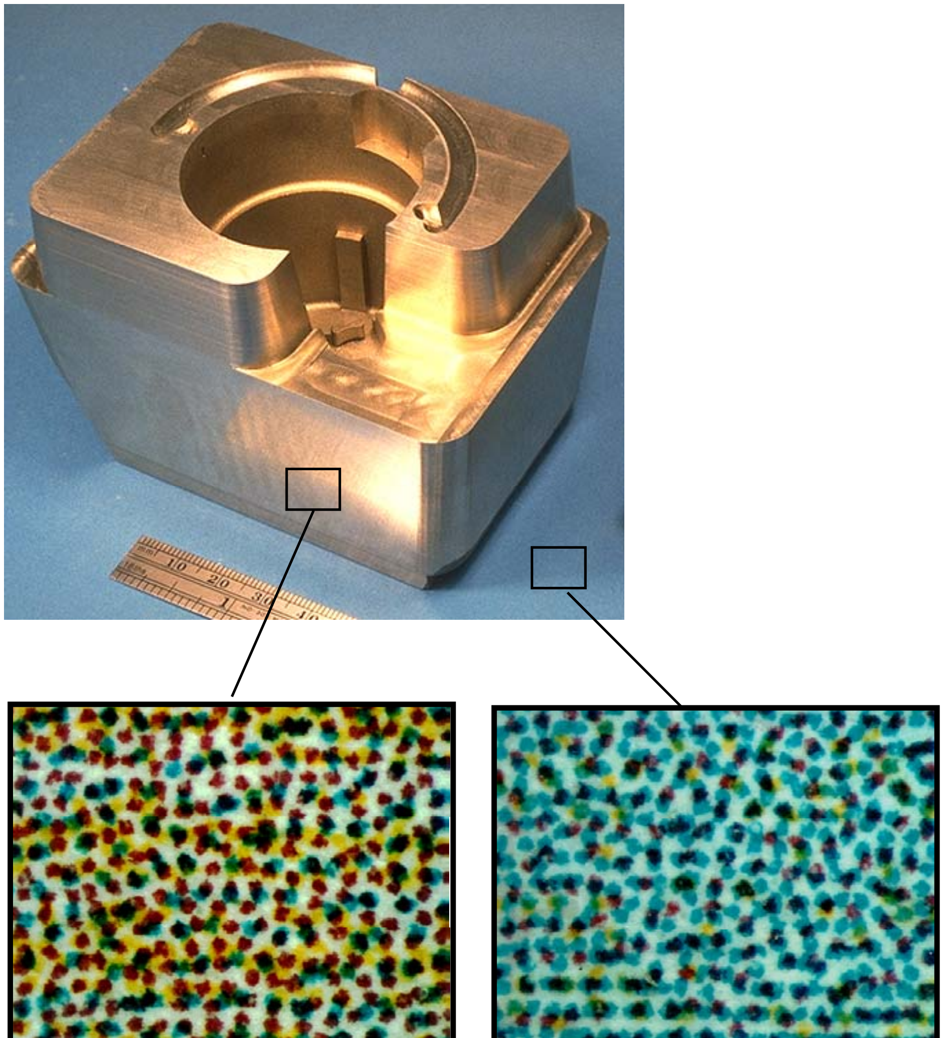
# Architecture 2: Moving Bed, Vector Print

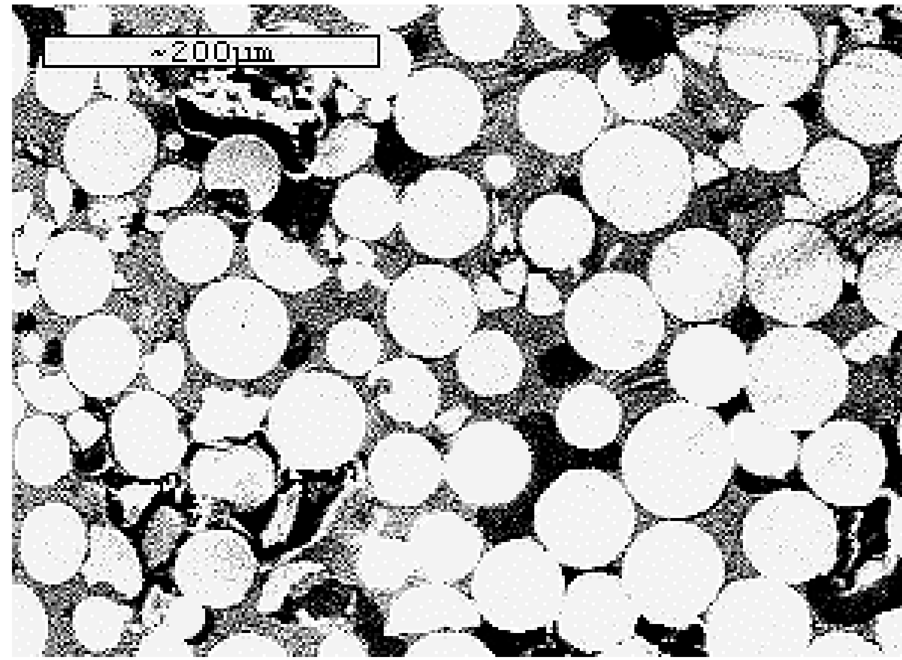



- **All stations in use all the time.**
- **Automation ready.**
- **Improved surface finish.**

# Barrium Titanate Parts made by 3DP with Slurry

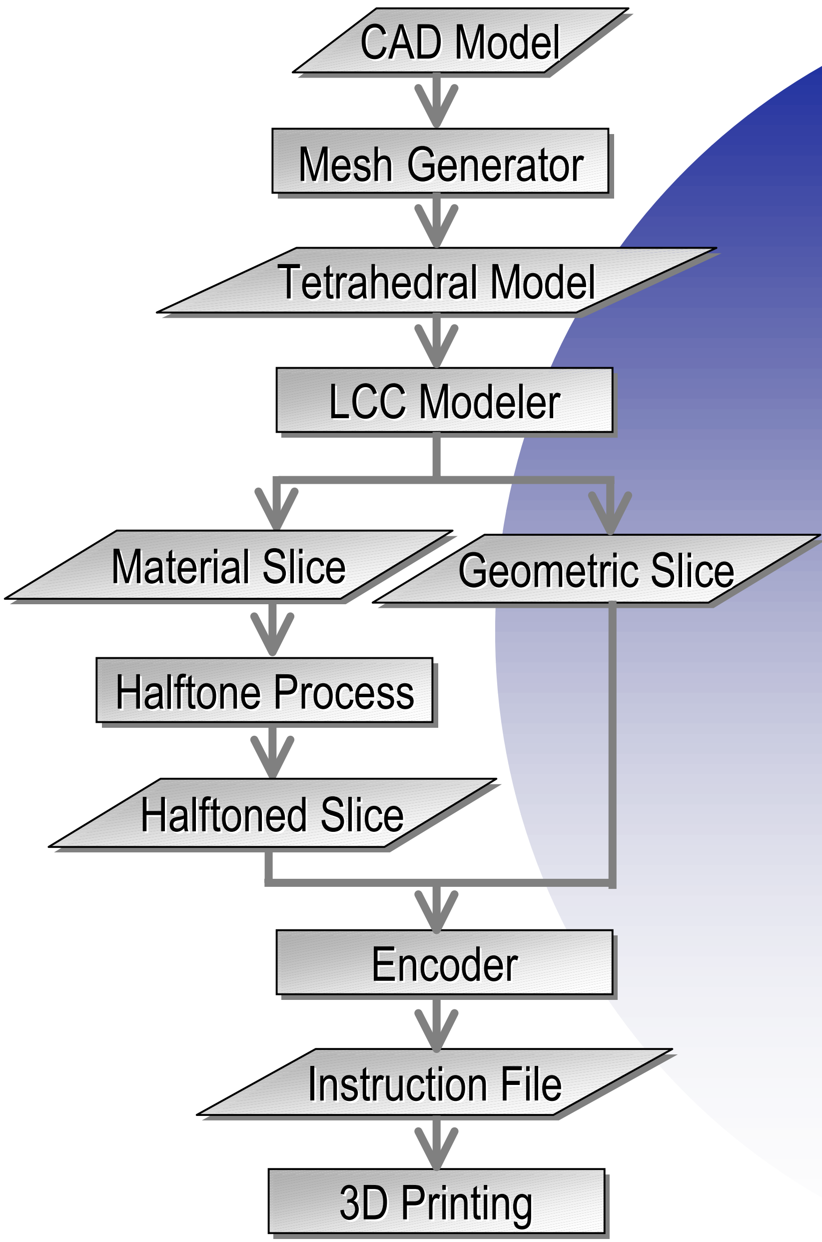
# Local Composition Control; Like Color ink-jet Printing, but with Materials

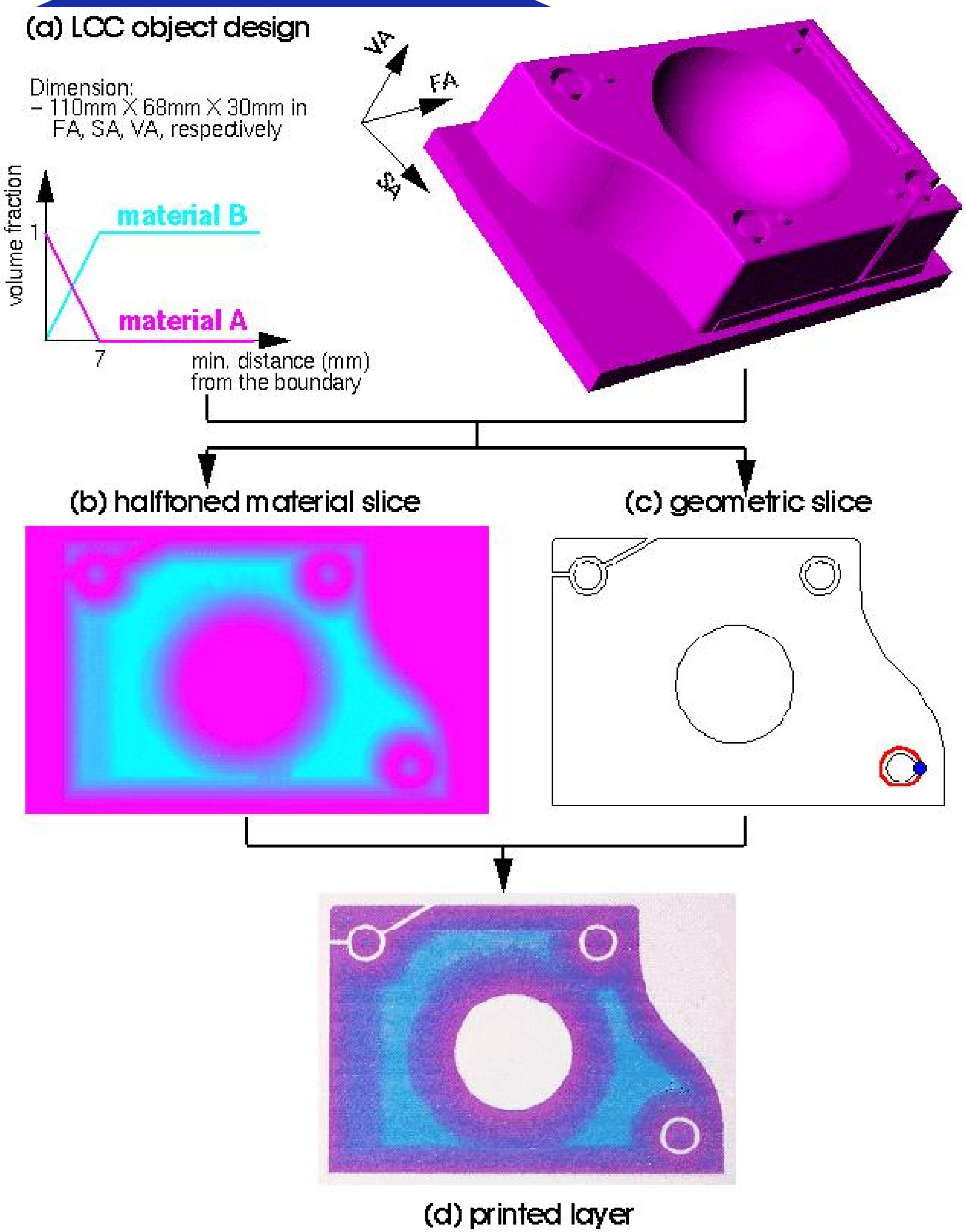





Titanium Carbide slurry printed in Moly powder; 83% dense

# Information Flow



# Summary: 3DP for Thermal Management

- Cooling/heating channels - high complexity
- Surface textures
- Macro cellular structures
- Locally controlled porosity
- Locally controlled thermal conductivity