Metamorphic Manufacturing (a.k.a. Robotic Blacksmithing):
The Third Wave of Digital Manufacturing

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Digital Manufacturing: Hope & Hype

**First Wave – CNC Removal**
USAF Funding at (MIT) starting in 1949.

**Second Wave – AM Additive**
NSF, etc., early 1980’s
Metals: Primary Engineered Material

- Production → large fraction of energy use
- Application → huge in energy efficiency
  - Light vehicles, efficient engines, advanced construction

Resource Productivity
Dornfeld (2013, blog)
Tekkaya & Lange

M. F. Ashby, 2010
www.grantadesign.com/education/resources
Third Wave: Metamorphic
Proof: Plasticine and Metal

LIFT Prize – $25k offered for a single programmable system that can shape 2 of 3 target parts.

Team Honey Badger, of Ohio State University. Alex Koenig, Bhuvi Nirudhoddi and Brian Thurston
See: RoboticBlacksmithing.com for details.
Team Honey Badger: Detail

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Technical: How

Fundamentals

Plasticine is a hot metal surrogate.

Volume conserved

\[ \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \]

Can make complex shapes by:

→ Squeezing
&
→ Bending

Primary deformation trumps secondary deformation.

How would you make a cube from a piece of clay?

Controlled open die

Primary deformation trumps secondary deformation.

Rotate, shape, repeat...

- Squeeze
- Rotate
- Squeeze
- Rotate
- Squeeze
- Rotate

Final!

Increments

Very simple hydraulic cylinders can offer 40,000 ponds force; ~1” square interchangeable tools and multiple programmed strokes.

20-Ton C-Clamp, 40 kg
20-Ton cylinder, 15 kg
Technical: How

Many focused examples:
Incremental sheet
Incremental bar
Stretchers
Shrink
Flexible profile bending
Flexible ring rolling
Open die forging
Powered hammers
Etc...
Technical: What

Track with time:
- Temperature
- Strain tensor
- Stress tensor

Predict:
- Microstructure
- Damage
- Anisotropy
- Etc…

German anonymous, circa 1606
Technical: Why -- Carbon Footprint


Shape by deformation more efficient than:
- Machining
- Casting
- Powder Metallurgy
- Additive

Also
- Range of materials
- Established Tech.
- No HIPping

Energy to:
- Vaporize
- Melt
- Deform

<table>
<thead>
<tr>
<th>Electricity Usage (J/g)</th>
<th>Process Rate (kg/hr)</th>
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<tbody>
<tr>
<td>1TJ/g</td>
<td>1 mg/hr</td>
</tr>
<tr>
<td>1GJ/g</td>
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<td>1000 kg/hr</td>
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<td>10^6 kg/hr</td>
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Metamorphic!
Technical: Better, Cheaper, Assured

Wrought metals generally have the best properties.

Weld metal lay-ups could provide initially graded compositions.

Metal forming is relatively inexpensive. Dies account for most of the cost and lead time.

**Power** of the forming system largely sets forming time.

Sensing and big data assure each part is within specification.
Policy: *Synthesis, not just Analysis*

Lots to be done to launch a new industry. Public investment needed.

Scientific basis is **not** the key; its synthesizing building, developing standards and communities.

Need to engage our workforce and community colleges.

Demonstrate room for creativity and innovation in manufacturing.

Need to stay in front of Fraunhofer-like collaborations.

Fund translational research centers (See MForesight talk, Thursday).

Fund openly available specialized facilities for training, innovation trials and research.

Don’t get locked out of IP.

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**Press Function:** Multi-purpose double action forming

**Capabilities:**
- Local temperature control
- Double action forming 300x230Ton
- FB35”xSS35”x 24” Daylight
Summary: *We Need Metamorphic Mfg!*

Subtract → Add → Morph. (shape and properties)

Based on fast advancing disciplines
- Robotics
- Integrated Computational Materials Engineering
- Artificial Intelligence
- Sensors
- Control

Can scale naturally to large sizes

Provides exceptional materials properties; extendable to graded chemistry

Naturally provides a path for qualification and certification

Is an opportunity for the USA. Helps balance of trade. Cement this here by:
- Fast innovation
- Skilled workforce (motivated by creative opportunity)
- Unique and accessible equipment
Further Information

LIFT Agile and Low Cost Processing Pillar Docs: [https://lift.technology/pillar/novel-agile-processing/](https://lift.technology/pillar/novel-agile-processing/)

**Key elements of this technology:**

Open die forging: [https://en.wikipedia.org/wiki/Forging](https://en.wikipedia.org/wiki/Forging)


3-D optical dimensional measurement: [https://en.wikipedia.org/wiki/3D_scanner](https://en.wikipedia.org/wiki/3D_scanner)

Thermo-mechanical processing: (huge topic), maybe start at: [https://www.doitpoms.ac.uk](https://www.doitpoms.ac.uk), here’s a book: [http://www.sciencedirect.com/science/bookseries/14701804/11](http://www.sciencedirect.com/science/bookseries/14701804/11)

Daehn and Taub *Manufacturing Letters* Publication: [https://doi.org/10.1016/j.mfglet.2018.02.014](https://doi.org/10.1016/j.mfglet.2018.02.014)
Robots -- Way better than humans

Stronger.

Better sensors.

Faster decisions.

Can Learn!

Can record everything.

No attitude.

Other examples:
Making pizza
laying bricks
Robo-dogs
Robo-Soldiers

Example: Japanese Robot Sumo
Movie from: https://www.youtube.com/watch?v=QCqxOzKNFks
See rules at: http://robogames.net/rules/all-sumo.php