3D Printed Tools: Opportunities and Limitations of an Emerging Capability

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Delivering Excellence Through Innovation & Technology
Agenda

- Project: Reducing Automotive CAPEX Entry Barriers through Design, Manufacturing and Materials
- Corolla vs. BMW i3 (lightweighting and low volume cost reduction)
- 3D printing: What are we talking about?
- 3D printing techniques, application limitations and imminent opportunities
  - Directed energy (e-beam, laser, arc) – metals
  - Powder bed – metals, polymers, ceramics
- Case study die analysis (WAAM)
- Outlook or further research (materials, process parameters, software)
The Automotive industry structure is changing – new suppliers too

Industry structure of vehicle manufacturers and automotive suppliers

Vehicle Manufacturers

- Traditional vehicle manufacturers
- The strong getting stronger
- Growth market players

Suppliers

- Traditional automotive suppliers
- The strong getting stronger
- Growth market players

Source: Ricardo analysis
Thermoeconomic’s is being used to optimize manufacturing costs

Total cost \( f \left( \frac{\text{Product}}{\text{Cost}} \right) = \$\text{Materials} + \$\text{Process} + \$\text{Waste} \)
Economics continues to push for light weighting.. but why?

EPA estimated fuel economy mpg:
- 2014: 18 city/22 hwy/18 combined
- 2016: 19 city/26 hwy/22 combined

18% improvement

http://www.ford.com/trucks/f150/

SpaceX Flacon Heavy
~$11,000 per kg

Ford F150

Aluminum-Alloy Body and Steel Frame

$22,000 per kg
Impact of light-weight design and low production volumes on manufacturing cost – BMW i3 and Toyota Corolla

- CAFE fuel economy standards and are driving need to reduce vehicle weight
- Light-weight materials are changing OEM’s approaches to tooling

Objectives:
- Evaluate cost effectiveness of in-production light-weight design
- Identify best practices in light-weighting and opportunities for capital cost reduction

Baseline

Toyota Corolla

Light-weight Design

BMW i3

Selected components:
- Floor Assembly
- Front Door Assembly

Barriers to Entry in Automotive Production and Opportunities with Emerging Additive Manufacturing Techniques
Authors: Piyush Bubna (Ricardo), Michael P. Humbert (UTRC), Marc Wiseman (Ricardo), Enrico Manes (UTRC)
Estimated tooling investment for automotive sub-assemblies

- B-pillar Assembly: $3.6 Million
- Differential Housing: $0.03 Million
- Floor Assembly: $5 Million
- Door Trim Assy: $1.4 Million
- Engine Mount: $0.38 Million
- Door Frame: $4.7 Million
- HVAC Assembly: $2.9 Million
- Headlight: $1 Million
- K-Frame: $2.4 Million
- Clutch Housing: $2.4 Million
Vehicle selection

Toyota Corolla and BMW i3 material usage and annual sales volume

% Material Distribution in Body In White

% Material Distribution in Closure System (Door, Hood, Trunk)

Selected Vehicles

- High volume – 300,000 pa
- Conventional steel body
- Low volume – 16,000 pa
- Combination of steel, Al, plastic & composite
Cost estimation methodology

Cost estimation

Virtual Factory
Equipment and staff to produce parts to order

Tooling

Tooling cost includes:
- Dies
- Fixtures
- Robotic features

Materials

Process Cost
- Equipment amortized costs (for outsourced manufacturing)
- Factory annual operating hours
- Labor (Direct & Indirect)
- Maintenance
- Utilities
- Floor space
- Insurance and taxes
- Supporting plant equipment

The virtual factory can be setup differently for various production volumes
What can 3D printing do for you?

Lightweighting - *Exergy*

The art of placing the minimum amount of the right material in the volume to achieve form, fit and function.
3D printing: What are we talking about?

3D printing is not new endeavor – principle found in nature

The basic principles of additive manufacturing has been at play for millennium

SEDIMENTARY ROCK FORMATION

SEDIMENTARY ROCK

METAMORPHIC ROCK FORMATION

BEDDING PLANES
3D printing: What are we talking about?

Even creatures get in on the act

- Crustaceans
  - Oysters
  - Clams
  - Snails
3D printing: What are we talking about?

Precision placement of materials is seen in beehives

– Bees – Direct energy approach
Directed Energy Deposition - wire feed electron beam

- Sciaky electron beam wire feed
  - High deposition rate
    > 10 pounds per hour
  - Well suited to large structures
  - Titanium, tool steel and stainless steel
  - Requires a high quality vacuum as the operating atmosphere

This Component is 22 Inches in Diameter and 12 inches Tall.

Pictures of the Successive Building of an EB Wire-Feed INCO 718 Deposited Engine Case.
3D printing: What are we talking about?

Directed Energy Deposition - wire feed electron beam

Sciaky
Directed Energy Deposition – wire arc welding

- Wire-arc based processes: MIG welder style system
  - Lower cost than laser and electron beam systems, but typically produces lower quality deposits
  - Integrated industrial welding robots and setups are very cost effective

Thermal stress management

0.6 metre x 0.6 metre titanium frame for BAE Systems
http://waammat.com/about/demo-parts

Materials Science and Technology
http://www.tandfonline.com/doi/pdf/10.1179/1743284715Y.0000000073
3D printing techniques, application limitations and imminent opportunities

Additive manufacturing technologies speed vs detail vs capital cost

- Wire Arc Additive Manufacturing (WAAM)
- Electron Beam Wire Deposition
- Directed energy (Laser Applied Powder)
- Laser Engineered Net Shaping (LENS)
- Polyjet; Material jetting
- Binder Jetting
The tool making challenge for hot forming Boron steel

- Lower production volumes
- More capabilities
- Shorter lead times
- Lower cost
- 3D geometry
3D printed dies: Approaches to low volume manufacturing

Door Skin Tooling – Conventional Stamping Dies

- Stamping of the front door outer skin is completed in 4 stations:
  1. Blanking – one die set ($40k)
  2. Forming – one die set ($125k)
  3. Trim + pierce – one die set ($75k)
  4. Check fixturing/gauges ($7.5k)

TOTAL COST TO MANUFACTURE
~ $0.25 million

- Durability – 1.5 million hit durability (tool steel)
  - Capable of 300,000 per annum volume for 5 years without being replaced

Teardown Images: Courtesy of A2MAC1 LLC
Part dimensions are 1.13 m x 0.74 m x 0.1 m depth of draw
   - Plate dimensions (each) are 1.43 m x 1.04 m x 0.15 m (15% increase)

Volume of material added to each die:
   - Assume equal distribution between male and female die
     - 54,000 cm\(^3\) added to plate for each die (587.4 kg)

Cost: WAAM machine ($20.16/hour) Material ($33.00/hour)

Total cost for the Forming die set $100,000

Conventional Stamping die set costs $125,000 to manufacture

20% cost savings
Material Jetting Technologies
Binder jetting creates casting cores and molds

BENEFITS:
- combined production of different mold sizes
UNPACKING:
Removing the unprinted particulate material and the side walls
Thank You

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Front Door Tooling - Additive

- Cost to use WAAM machine is $20.16/hour
- Material cost (tool steel wire) is assumed to be $33.00/hour

<table>
<thead>
<tr>
<th>Starting plate cost (w/ D2 steel)</th>
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<tbody>
<tr>
<td>Plate height (cm)</td>
<td>143</td>
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<tr>
<td>Plate width (cm)</td>
<td>104</td>
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<tr>
<td>Plate thickness (cm)</td>
<td>15</td>
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<tr>
<td>Volume (cm³)</td>
<td>223,080</td>
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<tr>
<td>Mass (kg)</td>
<td>1762.3</td>
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<tr>
<td>Material cost ($/kg)</td>
<td>1.65</td>
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<tr>
<td>Plate cost</td>
<td>$2,908</td>
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<thead>
<tr>
<th>Additive manufacturing cycle time (deposition time required on WAAM equipment)</th>
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<tr>
<td>Mass to be deposited (kg)</td>
<td>587.4</td>
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<tr>
<td>Deposition rate (from above)</td>
<td>2.0</td>
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<tr>
<td>Buy-to-fly ratio (estimate for amount of finish machining necessary)</td>
<td>1.15</td>
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<tr>
<td>Total deposition time (hr)</td>
<td>337.8 hr</td>
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<tr>
<td>Time to load/unload system (hr)</td>
<td>1.5 hr</td>
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<tr>
<td>Additive machine cost</td>
<td>$6,840</td>
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<td>Additive material cost</td>
<td>$11,146</td>
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<th>Post processing considerations</th>
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<tr>
<td>Mass of material to be removed via milling (kg)</td>
<td>88.1</td>
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<tr>
<td>Rough cut milling rate (kg/h)</td>
<td>47.4</td>
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<tr>
<td>Finish cut milling rate (kg/h)</td>
<td>0.1896</td>
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<tr>
<td>% of material roughed</td>
<td>85%</td>
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<td>Milling set up and clean up time (h)</td>
<td>0.25</td>
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<td>Milling total time (h)</td>
<td>71.54</td>
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<tr>
<td>Milling cost ($/h)</td>
<td>$100.00</td>
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<tr>
<td>Total finish machining time (hr)</td>
<td>71.5 hr</td>
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<tr>
<td>Total finish machining cost ($)</td>
<td>$7,154</td>
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Total cost for a male OR female die is $49,948
Forming die set costs $99,896
A traditionally manufactured die set costs $125,000 to manufacture
  - 20% cost savings