From Waste Steel to Matériel: Additive Manufacturing Enabled Agile Manufacturing

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G. Mudd, 2009, Sustainability of Mining
Project Team

Worcester Polytechnic Institute (WPI)
1) Sorting and characterization of waste
2) 3D printing test structures
3) Investment casting using 3D printed structures
4) Post process protocols

Army Research Labs (ARL)
1) Supply metal scrap representative of FOB
2) Technical data on mobile foundry
3) 3D printing of polymer patterns

Energy Research Company (ERCo)
1) Develop LIBS probe for in situ real time composition analysis
2) Design testing procedure, calibration methods, and melt exposure requirements

Drs. Diran Apelian, Brajendra Mishra, Richard Sisson, and Jianyu Liang

Drs. Brandon McWilliams and Jian Yu

Mr. Robert De Saro and Mr. Joe Craparo
Trends in Ore Grade

G. Mudd, 2009, Sustainability of Mining
Problem Statement

- Energy and time consuming.
- Need to develop a metal recycling process with chemical composition control and monitoring.
- Need a manufacturing process to make high quality steel parts directly from waste metal.

Recommended breakdown of metal waste recipe at FOBs:

- 60% iron
- 36% aluminum
- 4% other

(Visual representation of metal waste composition and parts)
Technical Approach

Proposed manufacturing process for ferrous wastes.

1. 3D Mold Design by Software
2. Casting Simulation by MAGMASOFT
3. SLA Enabled Resin Fabrication
4. Ceramic Coating Shell
5. Burn out, Resin Removal
6. Quality Control
7. Post Treatment
8. Shell Removal
9. Casting
10. Collection and Sorting of the Steel Wastes
11. Impurities Removal
12. Composition Adjustment
13. Molten Metal
Path From Waste Metal to New Alloy

1. **Waste material from ARL**
2. **Sorting & Blending**
3. **Melting & Pouring**
4. **Characterization**
5. **Tensile bars machining**
6. **As-cast ingots**
Waste Metal Database & Composition

Identify

Waste metal Characterization

- Use OSE technology (Optical Emission Spectrometry) to identify waste alloy composition.
- Portable OES (Hitachi High-Tech PMI Master UV Touch) was selected to characterize waste metal chemical composition.
- Established a waste metal database. Visual and dimensional information, as well as chemical composition were recorded.

Waste metal Database

<table>
<thead>
<tr>
<th>Metal Waste</th>
<th>Part Description</th>
<th>Weight (lb.)</th>
<th>Dimensions (inch)</th>
<th>Alloy Recognition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plate with partial rust and painted coating</td>
<td>4.02</td>
<td>9.00” x 8.50” x 2.25”</td>
<td>4340</td>
</tr>
<tr>
<td></td>
<td>Block entirely covered in rust</td>
<td>15.69</td>
<td>6.00” x 6.00” x 5.75”</td>
<td>Non-Specified</td>
</tr>
<tr>
<td></td>
<td>Brake Rotor entirely covered in rust</td>
<td>11.98</td>
<td>10.00” x 2.00”</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td></td>
<td>Small Round Stock partially covered in rust (per piece)</td>
<td>0.28</td>
<td>1.125” x 2.00”</td>
<td>12L14</td>
</tr>
</tbody>
</table>
Waste Metal Blending Model

- Created a blending model for heat calculation and composition adjustment

### Steel 1 Carbon Steel 45 ksi YS

<table>
<thead>
<tr>
<th></th>
<th>CE</th>
<th>DI</th>
<th>% C</th>
<th>% Si</th>
<th>% Mn</th>
<th>% P</th>
<th>% S</th>
<th>% Cr</th>
<th>% Mo</th>
<th>% Ni</th>
<th>% Al</th>
<th>% Co</th>
<th>% Cu</th>
<th>% V</th>
<th>% Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery</td>
<td></td>
<td></td>
<td>0.9</td>
<td>0.95</td>
<td>0.95</td>
<td>1.0</td>
<td>1.0</td>
<td>0.97</td>
<td>0.99</td>
<td>0.99</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Target Composition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aim</td>
<td></td>
<td></td>
<td>0.40</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td></td>
<td>0.60</td>
<td>0.15</td>
<td>0.40</td>
<td>0.50</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td></td>
<td>0.50</td>
<td>0.90</td>
<td>0.30</td>
<td>0.60</td>
<td>1.20</td>
<td>0.035</td>
<td>0.035</td>
<td>0.50</td>
<td>0.20</td>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Composition</td>
<td></td>
<td></td>
<td>0.43</td>
<td>0.89</td>
<td>0.147</td>
<td>0.506</td>
<td>0.768</td>
<td>0.021</td>
<td>0.013</td>
<td>0.190</td>
<td>0.054</td>
<td>0.343</td>
<td>0.015</td>
<td>0.005</td>
<td>0.180</td>
</tr>
<tr>
<td>Heat Size (lb.)</td>
<td></td>
<td></td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Waste Parts

<table>
<thead>
<tr>
<th>Name</th>
<th>Remain</th>
<th>Added (lb.)</th>
<th>Fraction</th>
<th>Dimensions</th>
<th>% C</th>
<th>% Si</th>
<th>% Mn</th>
<th>% P</th>
<th>% S</th>
<th>% Cr</th>
<th>% Mo</th>
<th>% Ni</th>
<th>% Al</th>
<th>% Co</th>
<th>% Cu</th>
<th>% V</th>
<th>% Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>#3-35 Plate with Square Hole</td>
<td>45.400</td>
<td>54.600</td>
<td>0.780</td>
<td>27.75&quot; x 15.125&quot; x 1.0&quot;</td>
<td>0.136</td>
<td>0.050</td>
<td>0.809</td>
<td>0.017</td>
<td>0.008</td>
<td>0.077</td>
<td>0.014</td>
<td>0.084</td>
<td>0.019</td>
<td>0.003</td>
<td>0.188</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>#4-15 Big Thread Barrel 5</td>
<td>32.780</td>
<td>10.000</td>
<td>0.143</td>
<td>4.5&quot; x 24&quot;</td>
<td>0.355</td>
<td>0.320</td>
<td>0.739</td>
<td>0.055</td>
<td>0.022</td>
<td>0.879</td>
<td>0.284</td>
<td>1.870</td>
<td></td>
<td>0.017</td>
<td>0.090</td>
<td>0.052</td>
<td></td>
</tr>
<tr>
<td>#3-32 Big L Beam</td>
<td>27.810</td>
<td>5.000</td>
<td>0.071</td>
<td>3.0&quot; x 3.0&quot; x 64.0&quot;</td>
<td>0.087</td>
<td>0.270</td>
<td>0.972</td>
<td>0.002</td>
<td>0.048</td>
<td>0.123</td>
<td>0.037</td>
<td>0.189</td>
<td></td>
<td>0.009</td>
<td>0.284</td>
<td>0.022</td>
<td>0.015</td>
</tr>
</tbody>
</table>
The Use of ML Tool

Original Data Source

High quality data from large SFSA’s formulation, processing and properties database

Data Driven Analysis

Learn relations between factors. Data regression analysis by fuzzy neural network

Steel Chemical Composition
Tempering Factors (Temperature, Time)
Mechanical Properties (Hardness, YS, TS, EL...)

Critical Diameter (DI)
Carbon Equivalent (CE)

Prediction

Predict usable parameters for desirable performances

Alloy Formula
Heat Treatment Schedule

Validation

Experimental Validation

Model Optimization
Artificial Neural Network Model for Metal Recycling

- 20,000+ cast steel data from SFSA.
- Chose 86XX (2100 data points) to study relation between chemical, HT conditions, and mechanical properties.

- Predict accuracy on mechanical properties. (21 results test out of 2100 data)

- Chemical composition
- Normalizing condition
- Austenitizing condition
- Tempering conditions
- Coolant type

Input layer

Hidden layers

Output layer

- Artificial neural network algorithm
- Mechanical properties,

Guidance post-process condition
SLA Enabled IC Process

Ferrous (Iron) Waste Material

Printed SLA Patterns

Ceramic Shell Making

Investment Casting Finished Parts

Applications
Results – SLA Pattern Design and Fabrication

Design Intent
- Start with single part production
- Combine casting tree with the part
- Fabrication entirely through SLA printer

Optimization of SLA pattern design
- Mold holding fixture point (Red circle)
- Vent/Riser to allow air escape (Blue circle)
- Chills to ensure the cast piece is completely cast (Green circle)
Results – Ceramic Shell Production

- Primary slurry recipe:
  a. LUDOX HS30
  b. Distilled Water
  c. Zircon CG, Std
  d. REMET Wet-In Wetting Agent
  e. Fumexol/Burst 100 Antifoam

- 6-Layer Ceramic Shell Attempted

<table>
<thead>
<tr>
<th>Layer</th>
<th>Slurry</th>
<th>Stucco</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Primary</td>
<td>Zircon Sand</td>
</tr>
<tr>
<td>2</td>
<td>Primary</td>
<td>Zircon Sand</td>
</tr>
<tr>
<td>3</td>
<td>Primary</td>
<td>Mulgrain 47 60S</td>
</tr>
<tr>
<td>4</td>
<td>Primary</td>
<td>Mulgrain 47 60S</td>
</tr>
<tr>
<td>5</td>
<td>Primary</td>
<td>Mulgrain 47 22S</td>
</tr>
<tr>
<td>6</td>
<td>Primary</td>
<td>Mulgrain 47 22S</td>
</tr>
</tbody>
</table>

Ceramic shell thickness: 4.1mm
Results – Burnout Optimization

- Burnout schedule for ceramic shell

1. Ramp up to 90°C @ 0.25°C/min, hold for 3 hrs
2. Ramp up to 155°C @ 0.25°C/min, hold for 3 hrs
3. Ramp up to 675°C @ 0.50°C/min, hold for 3 hrs
4. Ramp down to Room Temperature (approximately 25°C) @ 0.75°C/min

Total burnout time ≈ 50h

- Improved burnout schedule

1. Ramp up to 90°C @ 0.50°C/min, hold for 3 hrs
2. Ramp up to 155°C @ 0.50°C/min, hold for 3 hrs
3. Ramp up to 675°C @ 0.75°C/min, hold for 3 hrs
4. Ramp down to Room Temperature (approximately 25°C) @ 1.00°C/min

Total burnout time ≈ 37h
Results – Burn Out

- Surface roughness before burn out
  ![Image of surface roughness before burnout]

- Surface roughness after burn out
  ![Image of surface roughness after burnout]

Ceramic shell after burnout

<table>
<thead>
<tr>
<th>ISO 25178 Height Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sq</td>
<td>17.2 μm</td>
<td></td>
</tr>
<tr>
<td>Ssk</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>Sku</td>
<td>5.11</td>
<td></td>
</tr>
<tr>
<td>Sp</td>
<td>152 μm</td>
<td></td>
</tr>
<tr>
<td>Sv</td>
<td>134 μm</td>
<td></td>
</tr>
<tr>
<td>Sz</td>
<td>286 μm</td>
<td></td>
</tr>
<tr>
<td>Sa</td>
<td>13.1 μm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ISO 25178 Height Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sq</td>
<td>20.2 μm</td>
<td></td>
</tr>
<tr>
<td>Ssk</td>
<td>0.235</td>
<td></td>
</tr>
<tr>
<td>Sku</td>
<td>2.48</td>
<td></td>
</tr>
<tr>
<td>Sp</td>
<td>119 μm</td>
<td></td>
</tr>
<tr>
<td>Sv</td>
<td>91.8 μm</td>
<td></td>
</tr>
<tr>
<td>Sz</td>
<td>211 μm</td>
<td></td>
</tr>
<tr>
<td>Sa</td>
<td>16.7 μm</td>
<td></td>
</tr>
</tbody>
</table>
Thank You!