Metals: An Overview of Processes and Materials

AM-Dagen, Kista
September 19, 2013
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A little background...

Additive Manufacturing; shaping objects by successive addition of material... New Technology?
First modern system: Stereo Lithography: patent 1986, first sold machine in 1987
"Rapid Prototyping": several systems launched through the late 1980s and the early 1990s
"Rapid Tooling": producing tools based on "RP" technology ex. Keltool, Wibatool, early DMLS...
"Rapid Manufacturing": producing end-use parts based on "RP"-technology, -found some applications but did not really take off
-Well, perhaps it wasn't that "Rapid" after all...
Something has happened

3-D printing could remake U.S. manufacturing

More goods come from 3-D printing

Digital magic could remake, revive U.S. manufacturing

A third industrial revolution

AN AMERICA BUILT TO LAST

...and apparently more is coming!
AM in metals: New manufacturing opportunities...

Successive addition of material brings freedom of design

- AM is an enabling technology:
  - More complex products
  - More intelligent design
  - Enhanced functionality
The key: successive adding of material

Definition (ASTM & ISO):

*additive manufacturing (AM), n*—a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.

The AM process is characterized by how the material is "added"; i.e. brought together and joined together
Nota bene!

- Successive addition of materials is indeed not necessarily a "Rapid" process
- The true merits of AM are in flexibility and versatility
- Highly complex geometries and single objects can be produced economically
- Individual variation of products; geometry, materials…
- The inherent freedom of geometry enables a radical decrease of the number required process steps to produce the final product
How to add material: AM in one or several steps

Additive manufacturing (AM)

Single-step AM processes
- Fusion of similar material(s)
  - Metallic
  - Polymer
  - Ceramic

Multi-step AM processes
- Adhesion of dissimilar materials
  - Secondary processing such as sintering and/or infiltration
    - Metallic
    - Ceramic
    - Composite
Single step AM in metals

1. Type of material
   - Metallic

2. State of fusion
   - Melted state
     - Solid state
     - Solid + melted state
   - Sheet material

3. Material feedstock
   - Filament/wire material
     - Powder material

4. Material distribution
   - Deposition nozzle
   - Powder bed

5. Basic AM principle
   - Selective deposition of material to a substrate
   - Selective fusion of material in a powder bed

6. Source of fusion
   - Electron beam
     - Laser
     - Ultrasound

7. Process category
   - Directed Energy Deposition
     - Powder Bed Fusion
     - Sheet Lamination

8. Technologies
   - EBFFF Sciaky
   - LENS Optomec
   - EBM Arcam
   - SLM (Various)
   - DMLS EOS DM20
   - Ultrasonic consolidation
Example process categories: "powder bed fusion"

- Powders
- Layers: point wise melting and solidification
  - Thin layers – High resolution
- Tension
  - More layers – more tension
- Heated chamber?
- Support!
Powder bed fusion: EBM

- Selective melting with an E-beam
- Fast process!
- Hot chamber process reduces tension
  - Difficult to remove powder from hollow sections
- Commercial materials:
  - Titanium Ti6Al4V
  - Titanium Ti6Al4V ELI
  - Titanium Grade 2
  - CobaltChrome ASTMF75
Material Properties; Arcam Ti6Al4V – Wrought Ti6Al4V

<table>
<thead>
<tr>
<th></th>
<th>Arcam Ti6Al4V</th>
<th>Wrought Ti6Al4V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength (Rp 0,2)</td>
<td>910–960 MPa</td>
<td>860–965 MPa</td>
</tr>
<tr>
<td>Ultimate Tensile Strength (Rm)</td>
<td>970–1030 MPa</td>
<td>930–1015 MPa</td>
</tr>
<tr>
<td>Rockwell Hardness</td>
<td>30–35 HRC</td>
<td>30–35 HRC</td>
</tr>
<tr>
<td>Elongation</td>
<td>12–16%</td>
<td>10–14%</td>
</tr>
<tr>
<td>Fatigue strength@600 MPa</td>
<td>&gt;10,000,000 cycles</td>
<td>&gt;1,000,000 cycles</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>120 GPa</td>
<td>114 GPa</td>
</tr>
</tbody>
</table>
Powder bed fusion: CONCEPTLaser

- Laser based system
- Different machines for different application areas
- Support structure or hybrid manufacturing
- Commercial materials
  - Maraging tool steels
  - Stainless steel
  - Inconel 718
  - Titanium, pure and Ti6Al4V
  - AlSiMg
  - Cobalt-chrome
  - Precious metals
Powder bed fusion: EOS

- Laser based system (200-400W)
- One machine for all metal applications
- Support system or hybrid manufacturing
- Commercial materials:
  - Maraging tool steel
  - Stainless steels
  - Cobalt-chrome
  - Inconell 625 & 718
  - Titanium Ti6-4
Powder bed fusion: SLM Solutions

- Laser based
- Different machines for different application areas
- For example:
  - SLM 500 HL-2x 400W alt.1KW laser & thick layers to reduce tensions
- Some commercial powders, but encourage customers to develop their own materials
  - Successful material applications: Tool steel, Stainless steel, Inconell, Cobalt-chrome, Aluminium, Titanium...
Powder bed fusion: Realizer

- One of the original SLM systems
- Laser based
- Different machines for different applications
- Smaller machines (SLM 50) for small parts and/or precious metals
- Typical metals:
  - Cobalt-chrome (Dental!)
  - Titanium
  - Gold
  - ....
Powder bed fusion: 3D Systems (former Phenix)

- Laser based system, full melting of metal powders of sintering of ceramic powders (Alumina)
- Very small particles, very thin layers, fine surfaces but high tensions (for metals)
- Collaboration with materials developer, but customers may develop their own materials too
  - Stainless steels
  - Tooling steels
  - Non-ferrous alloys
  - Super alloys
  - Precious metals
Single step: Directed Energy Deposition

- Powder or filament (wire)
- Deposition on 2D, - or 3D substrates
- Several commercial processes and some additional only for specific companies
  - LENS (Laser Engineered Net Shaping, Optomec)
    - High Power Laser & Powder
  - DMD (Direct Metal Deposition, -DM3D)
    - High Power Laser & Powder
  - EasyClad (Irepa Laser)
    - High Power Laser & Powder
  - EBFFF (Sciaky)
    - Electron beam, and filament in vacuum chamber
Material Properties;
Yield strength Ti6-4 (LENS & LC)

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>El. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LENS Ti 6-4</td>
<td>848</td>
<td>955</td>
<td>15</td>
</tr>
<tr>
<td>Wrought Ti 6-4 Typical</td>
<td>883</td>
<td>952</td>
<td>14</td>
</tr>
<tr>
<td>LENS 316 Stainless Steel</td>
<td>276</td>
<td>661</td>
<td>67</td>
</tr>
<tr>
<td>Wrought 316 Stainless Steel</td>
<td>289</td>
<td>578</td>
<td>50</td>
</tr>
<tr>
<td>LENS Ni Alloy 625</td>
<td>579</td>
<td>930</td>
<td>38</td>
</tr>
<tr>
<td>Wrought Ni Alloy 625</td>
<td>400</td>
<td>834</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{0.2}$ (MPa)</th>
<th>$\sigma_{UTS}$ (MPa)</th>
<th>E (GPa)</th>
<th>$\delta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Consolidation Ti64</td>
<td>1062</td>
<td>1157</td>
<td>116</td>
<td>6.2</td>
</tr>
<tr>
<td>As cast or annealed</td>
<td>890</td>
<td>1035</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Wrought (annealed bar)</td>
<td>825</td>
<td>895</td>
<td>110</td>
<td>10</td>
</tr>
<tr>
<td>Wrought (solution treated aged bar)</td>
<td>965</td>
<td>1035</td>
<td>110</td>
<td>8</td>
</tr>
<tr>
<td>Wrought (solution heat treated+aged)</td>
<td>1103</td>
<td>1172</td>
<td>-</td>
<td>10</td>
</tr>
</tbody>
</table>
Material's fatigue

Optomec's LENS:

*Test stopped at 162m cycles (587 MPa). Sample unbroken!*

(Graph Source: ASM Metals Handbook, vol 3.)
# Hardness and surface finish

Accufusion’s Laser Consolidation:

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness</th>
<th>Surface Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellite 6</td>
<td>Rc 58</td>
<td>1.7-7.9</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>Hv 360</td>
<td>7.6</td>
</tr>
<tr>
<td>IN-625</td>
<td>Hv 283</td>
<td>1.8</td>
</tr>
<tr>
<td>IN-738</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>SS 316L</td>
<td>Hv 280</td>
<td>2.0-3.2</td>
</tr>
<tr>
<td>SS 420</td>
<td>Rc 53</td>
<td></td>
</tr>
<tr>
<td>Al 4047</td>
<td></td>
<td>1.9</td>
</tr>
<tr>
<td>CPM-9V</td>
<td>Rc 50</td>
<td>1.0-6.1</td>
</tr>
<tr>
<td>H-13</td>
<td>Hv 660</td>
<td>2.4-3.1</td>
</tr>
</tbody>
</table>
Multi-step AM process

- Type of intended product material
  - Metallic, Ceramic and Composite

- Principle for adhesion
  - Thermal reaction bonding
  - Chemical reaction bonding

- Material feedstock
  - Composite material sheet
  - Powder bed
  - Component in the bulk
  - Print head
  - Vat

- Material distribution
  - Sheet stack
  - Powder bed
  - Component in the bulk
  - Print head
  - Vat

- Basic AM principle
  - Fusion of stacked sheets
  - Selective bonding of material in a powder bed
  - Solvent reactive curing
  - Light reactive photopolymer curing

- Process category
  - Sheet Lamination
  - Powder Bed Fusion
  - Binder Jetting
  - Vat Photopolymerization

- Produced by AM processing
  - Green bodies/composite material parts joined by polymer adhesion

- Consolidation by secondary processing
  - Furnace sintering, with or without infiltration

Digital Metal
Multi-step: Binder jetting

- Powder layer being "glued" together forming a green body
- The metallic material properties are produced in a secondary furnace process; (sintering, with or without infiltration)
- Infiltration means composite materials
  - Several material systems are possible...
Cost of manufacturing
Practical benefits
Comparing alternative technologies;

Benefits of AM:
• Freedom to create new geometries
• Excellent material properties*
• Variable material composition*
• Minimized material consumption

Benefits of CNC machining
• High production speed for massive parts
• High surface quality and precision
• "All" familiar materials
• Familiar technology
The Best of Two Worlds? Hybrid Manufacturing

Electronics Housing in 316SS

• Tough to cast, long lead time: 52 weeks to cast
• Hybrid route: machined disk with details added by LENS
• Delivery Time: 3 Weeks.
• Superior Design: reduced weight
• Design changes implemented during development

Hybrid Manufacture gives Time Compression & 30% Cost Reduction

Size: 30cm diameter
Courtesy: Sandia National Laboratories
Implementation: Hybrid build style

“The part of the geometry that could be done by CNC, should be done by CNC”

- Then add complexity by building it on top of the CNC geometry
Industrial needs; initial case study:
Insert for a bracket to an office chair
Industrial needs; initial case study:
Insert for a bracket to an office chair

Results:
• Cooling time for conventional insert and “old” design 70 sec.
  – Estimated cooling time with new design approximately +25 sec. = 95 sec.
• Cooling time with new design and conformal cooling insert: 48 sec.
• Cost of machining AM produced insert similar to conventional production, however the cost of AM makes this an expensive insert

Industrial need: reduced cost of production by AM closer to final shape
The concept of the hybrid cell: Principle and hardware

An integrated solution for combination of AM with CNC milling
The concept of the hybrid cell: Workflow

Working principle:

Pre-machining:
- Bottom surface
- Basic perimeter

CNC milling:
- Clamping
- Positioning to find 0-point and coordinates

AM building:
- Rinsing from chips and cutting fluid
- Heat treatment
- Quality control
- Clamping and positioning in the AM unit
- Fill and level powder

Finishing machining:
- Rinse from powder (recirculate)
- Remove from AM unit
- Heat treatment
- Re-clamping and positioning in the CNC unit

Final processing:
Polishing, coating, etc.
Clamping and fixation: Positioning and precision

- Max deviations; x-direction: 2 µm, y-direction: 3 µm, z-direction: 5 µm
# Clamping and fixation: CNC milling

<table>
<thead>
<tr>
<th></th>
<th>Side milling</th>
<th>Slot milling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth-of-cut, $a_p$</td>
<td>5.0 mm</td>
<td>3.0 mm</td>
</tr>
<tr>
<td>Engagement, $a_e$</td>
<td>4.0 mm</td>
<td>20.0 mm</td>
</tr>
<tr>
<td>Spindle speed, $N$</td>
<td>6000 r/min</td>
<td>3000 r/min</td>
</tr>
<tr>
<td>Cutting speed, $v_c$</td>
<td>380 m/min</td>
<td>190 m/min</td>
</tr>
<tr>
<td>Feed speed, $v_f$</td>
<td>1800 mm/min</td>
<td>900 mm/min</td>
</tr>
<tr>
<td>Feed per tooth, $f_z$</td>
<td>0.1 mm</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Material removal rate, $MRR$</td>
<td>36 cm³/min</td>
<td>54 cm³/min</td>
</tr>
</tbody>
</table>

Stability & Vibrations: OK!
Cutting fluids used in the milling operation would pollute the powder bed in the building chamber!
Base part material

Requirements for injection molding inserts:

- Tool steel quality compatible for AM building
  - Can be hardened and no crack formation during welding
  - Machinability and surface quality

- 3 alternative steel tested:
  - Uddeholm’s Orvar Supreme: (Premium AISI H13), hardening temperature 1020-1030°C
  - DIN W.nr. 1.2709, identical to EOS and ConceptLaser’s AM tool steel, age hardening temperature 490°C
  - Metso’s Marlok C1650, tool steel for die casting aluminum age hardening temperature 490°C
## Base part material

![Base part material](image)

### Form for milling with no coolant

<table>
<thead>
<tr>
<th>Activity</th>
<th>Orvar Supreme</th>
<th>Wnr.1,2709</th>
<th>Marlok</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flattening</td>
<td>X</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Dowel pin holes</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Clearance hole for screws</td>
<td>X</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Pocket for clamps</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Counterbored clearance hole</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Pockets for positioning</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Contour milling (outside radius)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threaded hole for water cooling</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This form is to be filled out during the milling process:

- 1 = very bad millability
- 2 = bad millability
- 3 = good millability
- 4 = very good millability

The form follows the process, and is delivered to Erik Menke, together with the testparts when they are done.
Substrate preparation

• Flat milling produces a glossy surface;
  – Low-friction for powder spreading
  – Reflective to laser beam
• Standard procedure: Sand blasting, -unsuitable for the hybrid cell
• Hybrid cell procedure: Extra sharp cutting tool inserts "scratch" the substrate
  – Provides an exact z = 0 -point for starting the AM building
Substrate preparation

- Edge radius: 0 – 0.1 mm;
- Cutting depth: 0.1 mm;
- Feed rate: 0.05 mm/O
Adhesion to substrate and AM material quality
Marlok powder applied to AM building?

Tensile bars have been produced and tested in as-built condition:

- Ductile fracture
- Generally small variation of test results between specimens
- Young’s modulus and tensile strength in AM built condition is slightly less than reported in material data sheet, while elongation and contraction is slightly higher than reported in the material data sheet.
- Testing in heat treated condition remains:
  - Annealed condition
  - Hardened condition
  - Geometrical distortions during the hardening operation?
Integrated control systems: Powder bed AM and 5-axis CNC

- CNC and AM control systems are fundamentally different
  - (Example: TNC430 Heidenhain controller v.s. a PC running MS windows)
- Input for CNC is an executable program, input for AM is a solid model file...
- No way to interact with M2 control program during processing
Control system interaction

However:

- Critical data can be communicated between the machine units by TCP/IP, which enables:
  - Measurement data from CNC to AM machine
  - Automation of AM start-up procedure
  - Monitoring AM operation
OMOS:
Optimized Manufacturing Operation Sequence
AMT for repair and add-ons
(such as small features or alternative materials)

LENS component repair in action;
Low heat input – low distortion
and heat affected zone

POM’s DMD 44R/66R
6 axes performance and large
work envelope
AMT repair, examples

Rotor repaired by LENS

Airfoil T700 engine (Black Hawk)
Base material: AM355 steel
Repair material: Stellite 21
Repair of T700 Blisk Leading Edge

Material: AM355; a Cr-Ni-Mo stainless steel for high temperature applications

Parts characterized by premature failure due to abrasion and are highly susceptible to foreign object damage

• Leading edges of the airfoils machined back to remove wear damage
• LENS deposits abrasion-resistant material on to 0.2mm wide leading edge
• Finally; dimensions of the airfoil were restored back to blueprint tolerance

• Low Cycle Fatigue Testing (mimics flight conditions): 5,000 rpm 50,000 rpm 5,000 rpm; 5,000 times (11 s/cycle):
Part passed test without incident.
New industrial standards

Needed for multiple industrial applications:

- ASTM International F42: in progress since 2009
- ISO TC261: in progress since 2011
- CEN: new initiative starting up

Standards are good, but we don't necessarily need three of them…

- Collaboration agreement between ASTM and ISO signed
- CEN initiative will be coordinated with ISO TC261
- Opportunity! –Make your voice heard, join SIS/TK563!
AM at SINTEF Raufoss Manufacturing AS

Present research:

- CRI Norman: Advanced manufacturing methods
  - Background and support for new projects
- BIP HYPRO: Case studies and application for Norwegian manufacturing industry
- IC2: EU project for innovative Injection molding and tooling industry
- BIP Duocombe: New hybrid process incorporates AM parts within injection molding products
- Diginova: EU collaboration project mapping for the future "Innovation for Digital Fabrication"
- SASAM: EU-project; Support Action for Standardization of AM
Final remarks:

2011 the total revenue of the AM business was estimated 1.9 bill. USD
  • With present, two digit growth rate it would reach excess of 7.5 bill. USD by 2020; But
  • If the most principal issues can be solved the market is could exceed 100 bill. USD by 2020.

Additive manufacturing is not going to replace all other manufacturing methods" in the foreseeable future, But:
  • It is a vital, complimentary, technology that enables and stimulate innovation, from business model to actual products and services
    • There is hardly a sector of society that will not be impacted

AM is growing fast, investments are there, the potential is huge, BUT
  • It takes knowledge to be a part of it