CTC Industry 4.0
Overview and Lessons Learned from Metal AM Adoption
What is Industry 4.0?

- Subset of the 4th Industrial Revolution
- Started in Germany in 2011
- Evolving at a pace which is difficult to define
- Buzzword which SME and Global Corporations are working to define
- Flashpoint on Capitol Hill, particularly for the Defense Department
Additive Manufacturing

• Over $1Billion committed investment from the Defense Department for AM

• Private sector investment significantly more with only estimates on growth

• Proven weight savings, cost savings, quality proven in strength, performance, currently flying Air Bus flight critical parts, Military Aircraft

• Driven by composite powder variants layer by layer to meet any objective in 3D and 4D dimensions
Digital Manufacturing

- Referred to as Computer Integrated Manufacturing (CIM)
- Virtual manufacturing implementation during critical design review (CDR)
- The “Smart Factory” enables manufacturers through machine sensors and tooling, to provide workers with real-time data about the processes they are executing
- Provides disruptive capabilities for supply chains and distribution services (think Amazon)
Robotics and Automation

- Automated behavior-based work cells, become behavior-based factories
- Automation empowers the workforce, improves safety, efficiency and output
- $40 Billion in Robotics industrial investments anticipated by 2024
- Humans and Robots are finally sharing workspace, previously not possible
AI (Machine Learning)

- AI is the ability to process massive amounts of data in milliseconds.
- Machine Learning is the intersection of computer science and statistics, involving use of AI and data management.
- AI is disruptive for banks, medical data, insurance, and more
- Machine Learning is self-regulating and self-optimizing, learning as it goes and adapting to changes in the operating landscape (as tasked)
SLM 280<sup>HL</sup>
- 280 x 280 x 350 mm (~11” x 11” x 14”)
  build chamber
- 400W IR Fiber laser
- 200 °C heated build plate
- Real-time laser power display
- Automated layer control system
- Upgradable, open parameters
- Materials: Stainless/Tool Steel, Cobalt-Chrome, Aluminum, Titanium, Inconel

Hybrid Manufacturing
- 120” x 40” x 30” mill/build chamber, 5 axis
- 1000W IR fiber laser
- In process melt pool monitoring/adjustment
- Fine and medium cladding heads
- Combines additive and subtractive
- Materials: stainless steel, tool steel, cobalt-chromium, Inconel, more...

Stratasys Fused Deposition Modeling (FDM) Vantage SE
- 16”W x 14”D x 16”H build chamber
- Three tip sizes (0.005”, 0.007”, and 0.010”)
  range of detail or run time
- Materials: PC, PC/ABS, ABS, and ABSi

VRC Gen III Hybrid High Pressure Cold Spray System
- Portable, Self-contained system
  ~(8’ x 3’ x 6’)
- Handheld operations or integrate with robotic spray booth
- Max gas parameters –
  1000 psi / 900 °C
- Materials: aluminum, copper, nickel, titanium, Inconel, tantalum, and more..
- Applications: dimensional repair, near-net part production, performance coatings
Hybrid Additive Manufacturing Services

AMBIT Hybrid System with HAAS VF-11

Capabilities

- Gas utilization:
  - Argon or nitrogen as shielding gas
  - Separate gas control for shield, laser and powder delivery

- Applied material:
  - Includes non-reactive alloys: stainless steels, tool steel, cobalt chromium, Stellite, Inconel 718 and 625 etc.
  - Ability to develop parameters for new materials
  - Ability to adjust/change parameters as build progresses
  - In-situ process monitoring

- Applicable substrates:
  - Most metallic alloys
  - Can be applied to flat surfaces, cylindrical surfaces (outside and limited inside diameters) and complex-shaped geometries

- Equipment utilization
  - Laser directed energy deposition, 1000 W
  - 5-axis mill, 120” x 40” x 30” work envelope
  - Dual powder feeder
  - Fine and heavy cladding heads
  - Typical deposition rate of 1.5–55 lb/hr

Applications

- Substrate material enhancement (corrosion-resistance, wear-resistance, dissimilar metals etc.)
- Dimensional restoration and repair, all in a single setup (similar metal, dissimilar metal, functionally graded additions etc.)
- Additive part build-up, followed by secondary machining to final geometry
Cold Spray Coating Services
VRC Gen III High-Pressure System

Capabilities

- **Gas utilization:**
  - Compressed air (low cost with limited coating capability)
  - Nitrogen (moderate cost with good coating capability)
  - Helium (highest cost with best coating capability)
  - Up to 1000 psi and 750 °C operating conditions

- **Applied material:**
  - Includes aluminum, zinc, nickel, stainless steel, titanium, chromium carbide – nickel chromium, tungsten carbide – cobalt, tungsten copper, copper, tantalum, Inconel etc.
  - Ability to develop parameters for new materials

- **Applicable substrates:**
  - Includes aluminum, steel, stainless steel, magnesium, nickel, copper, etc.
  - Can be applied to flat surfaces, cylindrical surfaces (both inside and outside diameters) and complex-shaped geometries

- **Equipment utilization:**
  - Roboticely manipulated for precise and consistent coating build-up
  - Hand-held manipulation for in-field services or hard-to-reach areas
  - Approximate working envelope of 15’ × 10’ × 8’
  - Deposition rate of 0.4–1.5 lb/min

Applications

- Substrate material enhancement (corrosion-resistance, wear-resistance, electromagnetic interference shielding etc.)
- Dimensional restoration and repair (similar metal, dissimilar metal)
- Additive part build-up of near-net-shape geometries (work-hardened material properties)

Image courtesy of VRC Metal Systems
Selective Laser Melting Services
SLM Solutions Group 280HL

Capabilities
- Build chamber:
  - Inert gasses (nitrogen or argon)
  - Heated build platform, up to 200°C operating conditions
  - Dual optical pyrometers for melt pool monitoring
  - Laser monitoring system
  - Automated layer control system
- Common build material:
  - Includes aluminum, nickel based alloys, stainless steel, titanium, cobalt chrome, tungsten, copper, etc.
  - Ability to develop parameters for new materials
- Applicable components:
  - Complex parts and difficult/impossible features
  - Can be used for repair, but only for certain planar applications
- Equipment utilization:
  - Laser rastering computer controlled
  - Softwares assist with support structure, and determine scan patterns
  - Build volume (280mm x 280mm x 350mm)
  - Build rate of 0.4–1.5 lb/min

Applications
- Complex parts and difficult/impossible features
- Can be used for repair, but only for certain planar applications
Additive Manufacturing Services

• Application of simple, proven materials
  – Part/surface machining for either application
  – Spray/laser application
  – Final machining to desired finish/dimensions
  – Validation of build-up properties conducted upon request (e.g., tensile, bend and adhesion testing, etc.)

• Research and develop for new applications/materials
  – Material identification and metal powder development
  – Process development and optimization
  – Component design
  – Post process development (e.g., final machining, heat treatment, peening, etc.)
  – Comprehensive coating property evaluation based on customer needs and requirements (e.g., scanning electron microscopy and testing for tensile, fatigue, impact toughness, corrosion resistance, electrical impedance, etc.)
  – Finalization of process parameters and procedures for transition to customer or for service continuation
Considerations in AM Production Stages

**Morphology**
- size, shape, chemistry, recyclability, consistency, distribution

**Parameters**
- power, speed, environment, consistency, calibration, setup

**Secondary**
- surface finish, heat treat, hot isostatic pressing, machining, clean-up, inspection

**Performance**
- strength, fatigue, wear, safety, certification, qualification, application

**DESIGN**
- Part Type optimization, part reduction, repair, novel design/features, “free” complexity

**MATERIAL**
- AM Technology electron beam powder/wire, laser net shape, laser powder bed, ultrasonic, cold spray, binder jetting

**AM PROC.**

**POST PROC.**
- Secondary surface finish, heat treat, hot isostatic pressing, machining, clean-up, inspection

**JOIN/REP.**
- Tertiary repair, join, additional process

**TRANSITION**
- Performance strength, fatigue, wear, safety, certification, qualification, application
Examples of CTC’s Externally Funded AM Efforts

• ONR Quality Made – AM Solutions for the Navy
  – ICME, monitor, measure/feedback, and in-situ correction for laser AM powder bed process
• Air Force AM and CMC Integration
  – AM hard point integration for hypersonic missile applications
• Commercial part process development and LRIP
  – Produce demonstration and LRIP metallic AM parts – advanced heat exchangers, aerospace, missile, hypersonic and ground-based applications, etc.
• NMC – Distortion Mitigation for AM Electronic Chassis
  – Develop and validate strategies to mitigate distortion of AlSi10Mg electronic chassis from L-PBF
• NMC – NDI for EBAM of Ti
  – Define limits of inspection techniques under varying part conditions
• NIST – Measurement Science Innovation Program for AM
  – Define limits of inspection techniques for varying L-PBF part shapes
• NMC – Printed Sand Casting Molds for HY Steels
  – Define process limits to ensure castings meet Tech Pub 300, Rev. 2 requirements
• America Makes – EBM Ti-6Al-4V AM Demonstration and Allowables
  – Quantify anisotropic properties for and secondary processing effects on Ti-6Al-4V parts
ONR Quality Made: Integrated Computational Microstructure – Informed Response Tools for High Quality AM Parts

October 31, 2019

Technical Tasks:
- Prepare feed forward algorithm for process control
- Investigate sensors and integrate pool monitoring and layer control sensors to validate process control
- Train control algorithm to predict properties based upon experiments measuring properties, defects and distortion of several metallic alloys of interest to the US Navy: Ti-6Al-4V, 316L and Inconel 625
- Demonstrate technology on minimal viable product
- Integrate developed tools into new L-PBF machine, install system at Navy site, demonstrate system on selected air/sea/ground part, train Navy on use of hardware/software

Objectives:
- Improve quality and consistency of metal laser-powder bed fusion (L-PBF) builds
- Assimilate integrated computational materials engineering (ICME) to control of L-PBF machine
- Enable the Navy to produce and qualify low-volume metallic parts via L-PBF
- Develop demonstration and training tool for use by Navy on L-PBF and process control
- Correct for machine-to-machine variability and equipment degradation in performance

Period of Performance:
The 48-month project started in mid-March 2018

Team Members:
- MRL
- MSC
- ONR
- SLM
- CTC
- University of Pittsburgh
- America Makes
- Navy Labs

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https://grabcad.com/library/m-kurniawange-jet-engine-bracket-version-1-2-1
NMC – Printed Sand Casting Molds and Cores for HY Steels

• Team: OR and VCS Program Offices, Naval Surface Warfare Center, Carderock Division; General Dynamics Electric Boat; ExOne; Naval Undersea Warfare Center Division, Keyport; Bradken; and NMC

• Objectives:
  – Investigated printed sand mold technology to produce complex high yield (HY) steel castings for the Columbia and Virginia Class submarine programs

• CTC Efforts:
  – Used design of experiments to determine prequalification of printed sand molds
  – The team produced castings from printed sand molds and compared results to legacy production methods
  – Identified process and material conditions required for successful implementation of technology for HY steel castings
Examples of CTC’s IR&D AM Projects

• Design of Experiments for Rapid Machine/Material Integration
  – Define critical AM process parameters and optimize AM process
• Embedded Sensors
  – Add strategic sensors to AM components to measure state of in-service functionality
• Hot Isostatic Pressing (HIP) and Quality
  – Repair common defects from AM process; develop robust, low-cost AM processing conditions
• AM Repair/Joining
  – Define issues with joining AM parts to other components in an assembly
• Cyber/Cloud/Big Data and Additive Manufacturing
  – Safe transfer and storage of electronic files
• Powder Morphology, Inconel 625 Recyclability
  – Define limits of powder reuse while ensuring requisite component properties
• Friction Stir Welding (FSW) Additive Manufacturing
  – Rapid production of large functionally graded components
• Carbonyl Process (Gaseous Deposition)
  – Production of seamless, thin-wall components
Scenario: Setting Balanced Performance Parameters via JMP Linear Regression Software

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<th>Weighted Values (User Defined)</th>
<th>Density (g/cc)</th>
<th>Hardness (-)</th>
<th>Roughness (μin)</th>
<th>Build Time (min)</th>
<th>Per Part Turn (min)</th>
<th>Yield Strength (ksi)</th>
<th>UTS (ksi)</th>
<th>Elongation (%)</th>
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<th>Fill Pattern</th>
<th>Volume Boarder Power Output (W)</th>
<th>Volume Area Power Output (W)</th>
<th>Volume Area Scan Speed (mm/sec)</th>
<th>Hatch Spacing (mm)</th>
<th>Platform Heating (°C)</th>
<th>Powder Layer Thickness (μm)</th>
<th>Mean Build Cross-Sectional Area (mm²)</th>
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Heat Treatment & HIP + Heat Treatment -
Effects on the Yield and Tensile Strength

- Energy density of approximately 20 J/mm\(^3\) produced builds with very low yield and tensile strength. Excessive porosity (open) not healed by HIP was the main cause.

- The HIP'ed + heat treated and heat treated builds made with energy densities above 40 J/mm\(^3\) had yield and tensile strengths larger than the wrought alloy.

- Both HIP'ed + heat treated and heat treated builds had practically similar yield and tensile strength regardless of any SLM process variables used.
Microstructure – HIP + Heat Treated

- Microstructural Analysis Observations:
  - HIP’ing and heat treatment did not eliminate the porosity of the bars produced below 30 J/mm$^3$.
  - Practically complete healing of the porosity was achieved after HIP’ing in all bars produced using energy densities above 40 J/mm$^3$. 

$E = 21.98$ J/mm$^3$  
$\rho = 7.254$ g/cm$^3$

$E = 39.56$ J/mm$^3$  
$\rho = 8.278$ g/cm$^3$

$E = 65.93$ J/mm$^3$  
$\rho = 8.269$ g/cm$^3$

$E = 98.9$ J/mm$^3$  
$\rho = 8.254$ g/cm$^3$
Lessons Learned in Metal AM

- Powders are not the same from different manufacturers
- Machines are not the same from the same manufacturer
- Codified design rules are emerging – more details needed
- Parts must be designed with AM in mind
- AM process must be designed with the part in mind
- AM is NOT typically a DIRECT substitute for established manufacturing alternatives
- Post processing is “always” needed after AM building
- Metal AM is still developing rapidly
- Alloy selection is limited, but will grow
- Standards are being developed for the AM industry