CTC Industry 4.0
Overview and Lessons Learned from Metal AM Adoption

Bank of America Merrill Lynch

digitalbridge 2019
PITTSBURGH'S INDUSTRY 4.0 CONFERENCE

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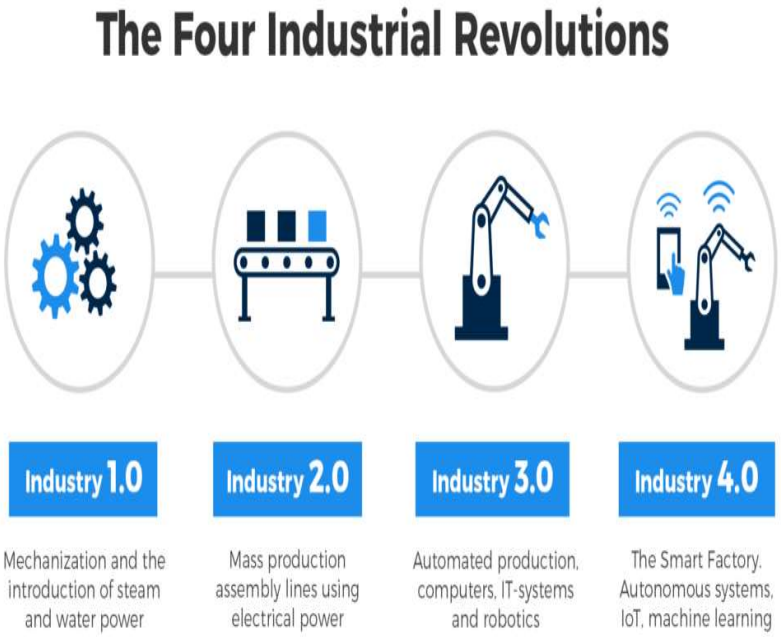
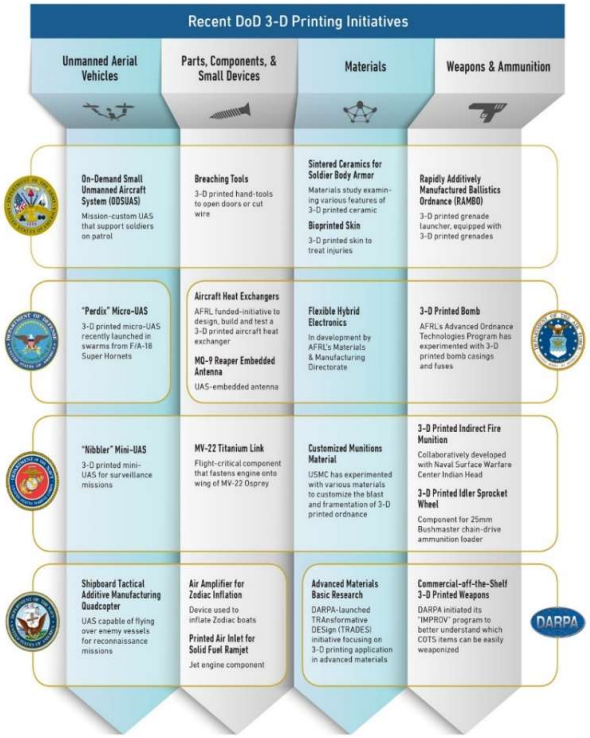
What is Industry 4.0 ?

- 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



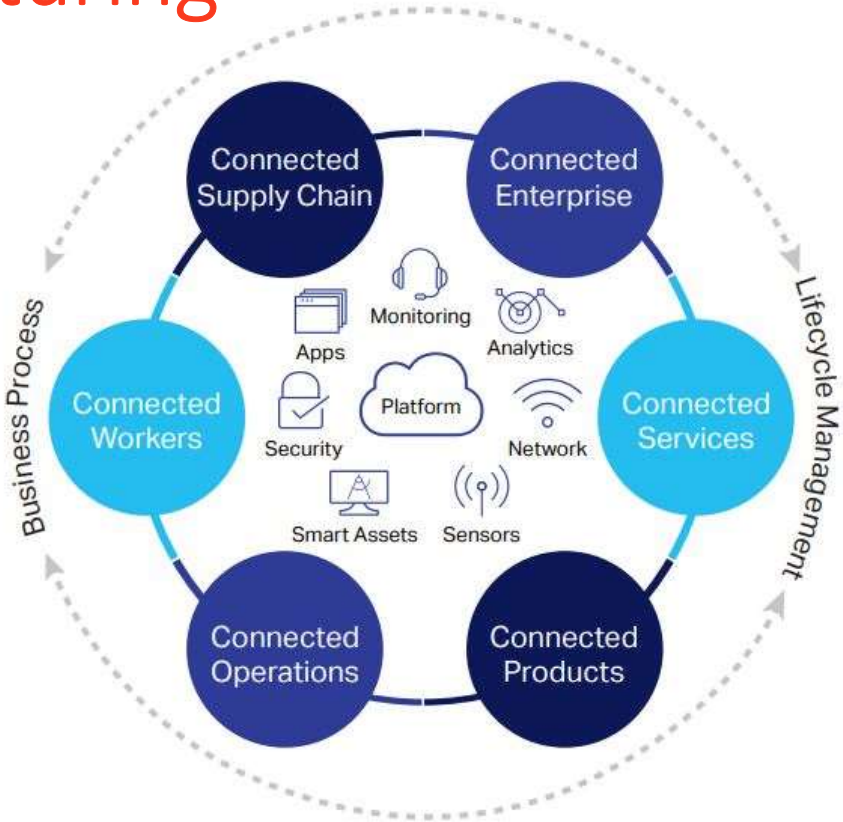
Additive Manufacturing

- 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^{HL}

- 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

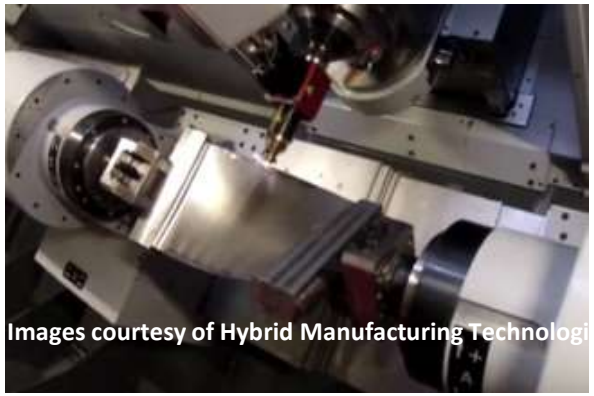
- 16"W x 14"D x 16"H build chamber
- Three tip sizes (0.005", 0.007", and 0.010")
  range of detail or run time
- Materials: PC, PC/ABS, ABS, and ABSi

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

Additions to cylindrical piece

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:**
  - **Robotically 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)**

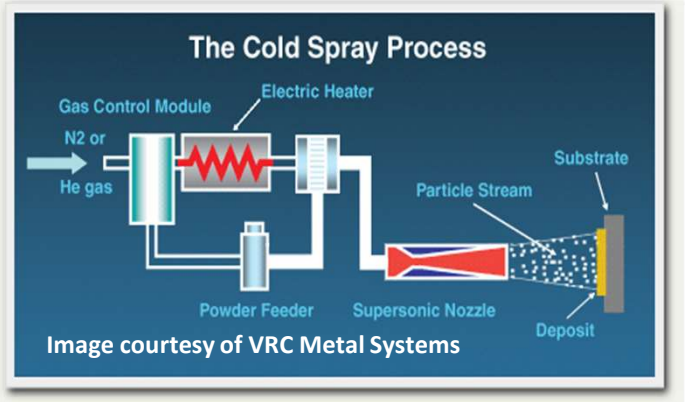


Image courtesy of VRC Metal Systems

Selective Laser Melting Services

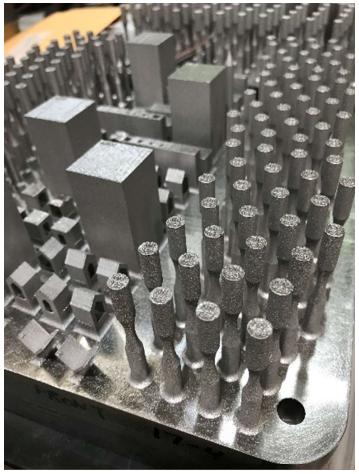
SLM Solutions Group 280HL

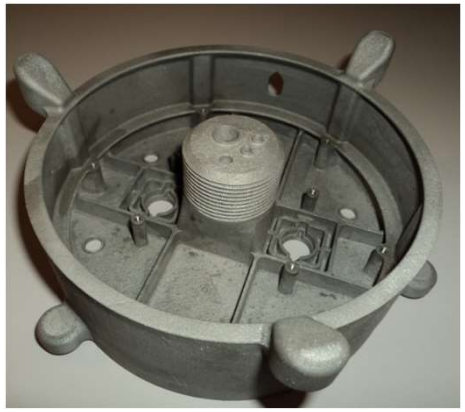
Capabilities

- **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**

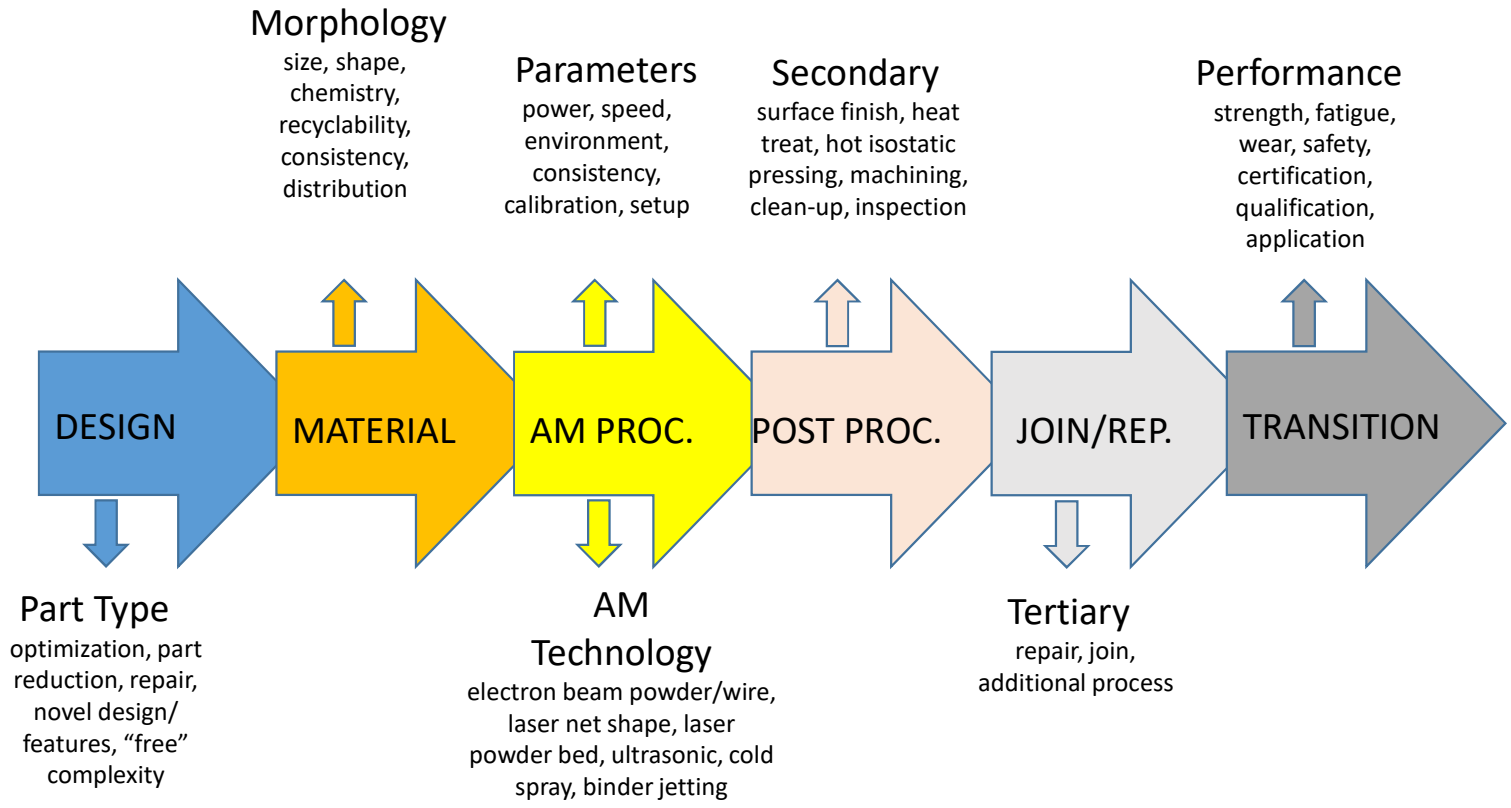




Additive Manufacturing Services

- 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 costumer 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

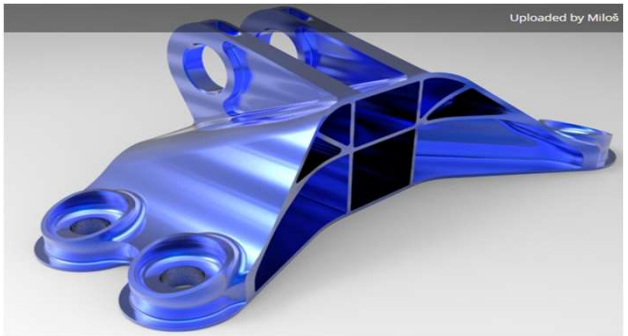
Considerations in AM Production Stages



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



https://grabcad.com/library/m-kurniawange-jet-engine-bracket-version-1-2-1

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

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

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

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

Contact Information:
Concurrent Technologies Corporation (CTC)
Michael L. Tims; 814-269-2515; tims@ctc.com

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

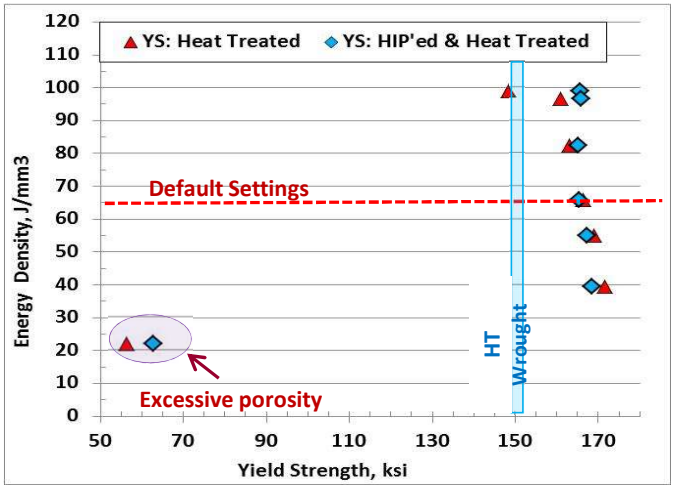
Scenario: Setting Balanced Performance Parameters via JMP Linear Regression Software

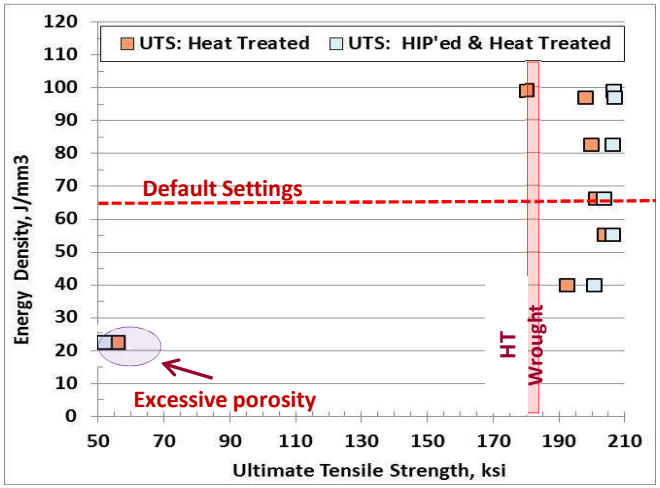
Weighted Values (User Defined)							
Density (g/cc)	Hardness (-)	Roughness (µin)	Build Time (min)	Per Part Turn (min)	Yield Strength (ksi)	UTS (ksi)	Elongation (%)
1	1	-1	0	-1	1	1	1

Calculated Parameter Settings from JMP							
Fill Pattern	Volume Boarder Power Output (W)	Volume Area Power Output (W)	Volume Area Scan Speed (mm/sec)	Hatch Spacing (mm)	Platform Heating (°C)	Powder Layer Thickness (µm)	Mean Build Cross-Sectional Area (mm^2)
Stripe	75	221	725	0.1125	200	30	6000

Predicted Results							
Density (g/cc)	Hardness (-)	Roughness (µin)	Build Time (min)	Per Part Turn (min)	Yield Strength (ksi)	UTS (ksi)	Elongation (%)
7.884	281.1	83.0	859.2	115.0	90.7	108.6	32.1

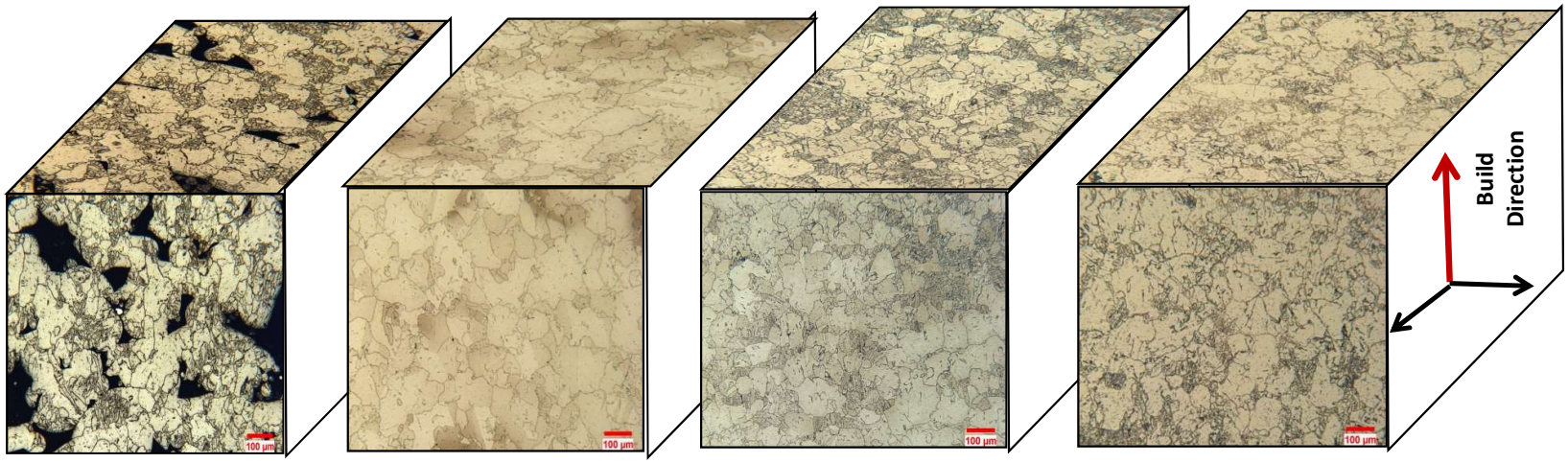
Heat Treatment & HIP + Heat Treatment - Effects on the Yield and Tensile Strength





- 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



E = 21.98 J/mm³
ρ = 7.254 g/cm³

E = 39.56 J/mm³
ρ = 8.278 g/cm³

E = 65.93 J/mm³
ρ = 8.269 g/cm³

E = 98.9 J/mm³
ρ = 8.254 g/cm³

- **Microstructural Analysis Observations:**
  - HIP'ing and heat treatment did not eliminate the porosity of the bars produced below 30 J/mm³
  - Practically complete healing of the porosity was achieved after HIP'ing in all bars produced using energy densities above 40 J/mm³

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