AM Capabilities for Thermal Management with a comprehensive study of **IN625 Powder Reuse*** and the effect on tensile properties

*** STUDIED ACROSS SEVEN (7) EOS M280 MACHINES OVER THE COURSE OF EIGHT MONTHS WITH MORE THAN 800 BUILDS***

Frederick Claus
Business Development Manager – Aerospace and Defense
Stratasys Direct Manufacturing

arpa·e CHANGING WHAT'S POSSIBLE

High Efficiency High Temperature Modular Power Utilizing Innovative Designs, Materials, and Manufacturing Techniques

AGENDA

- Stratasys Direct Manufacturing – Technologies and Services
- Validating Additive Metals Process for Production Parts
- Additive Capabilities for Thermal Management
- Applications
- Challenges and Future Work

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About Stratasys Direct Manufacturing

Stratasys Direct Manufacturing is one of the largest providers of additive and conventional manufacturing solutions:

- 7 U.S. manufacturing facilities
- 12 manufacturing technologies
- 600+ employees
- Certifications: ISO 9001, AS9100
- ITAR registered
- Over 25 years experience

Your Team

Our experienced team of project engineers is committed to your success with:

- Design support for additive manufacturing
- Technical direction and recommendations
- Material, technology and build optimization for quality, speed and reduced cost
- Material and Manufacturing Process development

Stratasys Direct Manufacturing Technologies and Services

Technologies

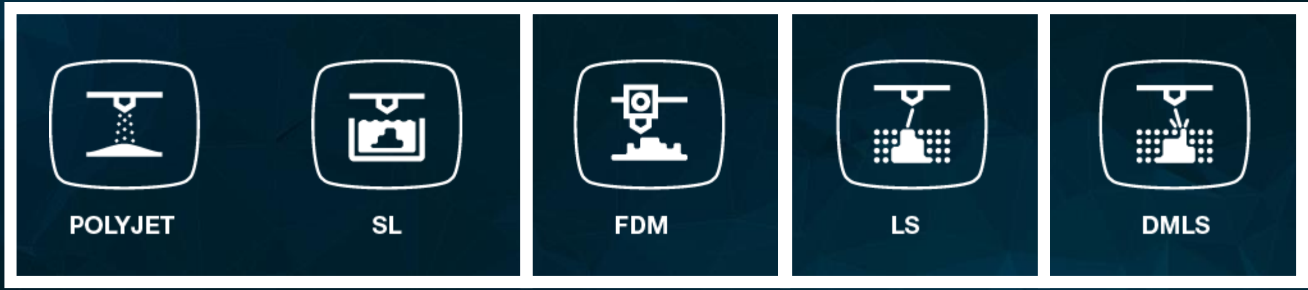
PolyJet & Stereolithography
Photo-curable Resins

Fused Deposition Modeling
Plastic extrusion

Laser Sintering
Laser Based Plastic Powder Bed Fusion

Direct Metal Laser Sinter
Laser Based Metal Powder Bed Fusion

ADDITIVE



CONVENTIONAL

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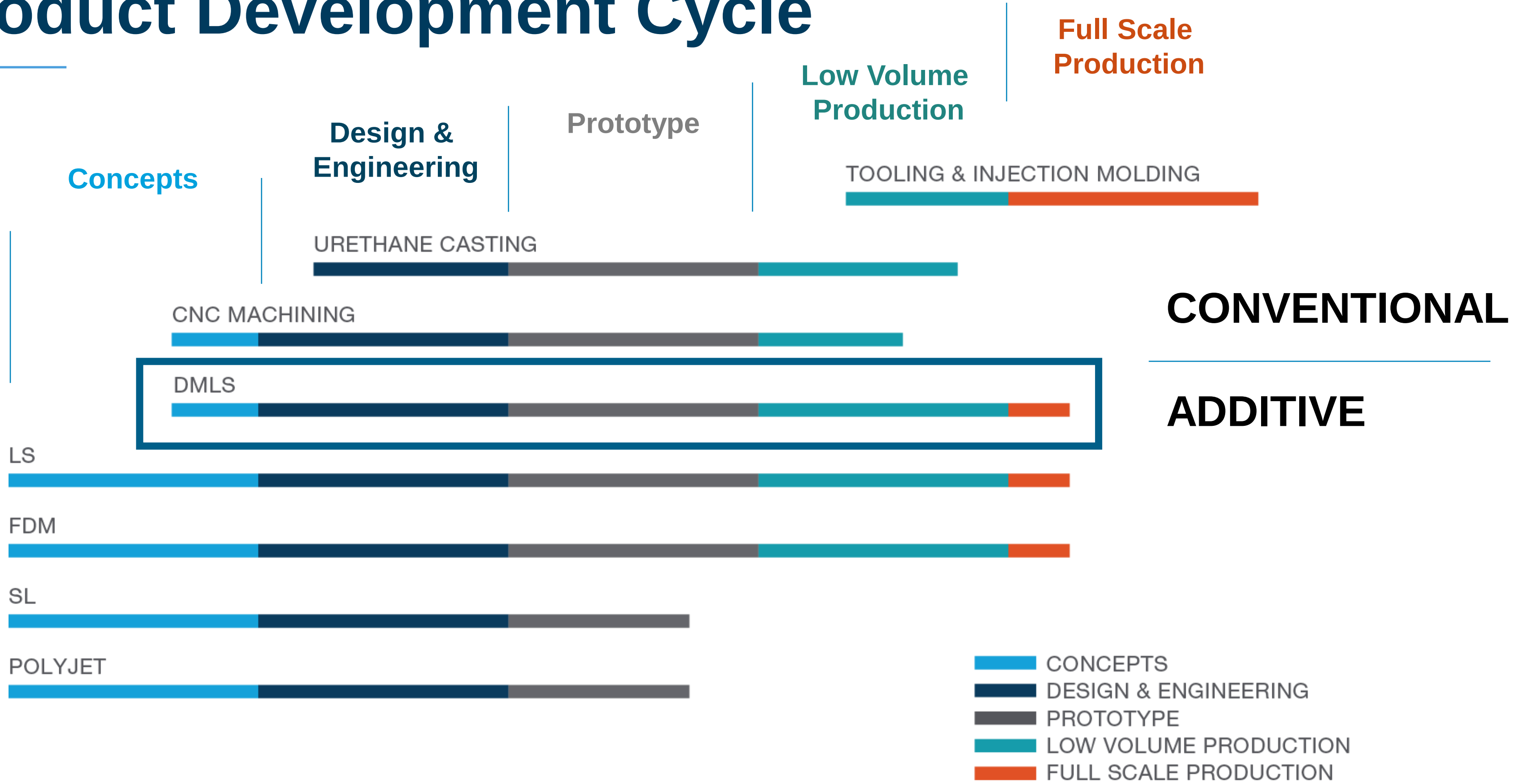
Product Development Cycle



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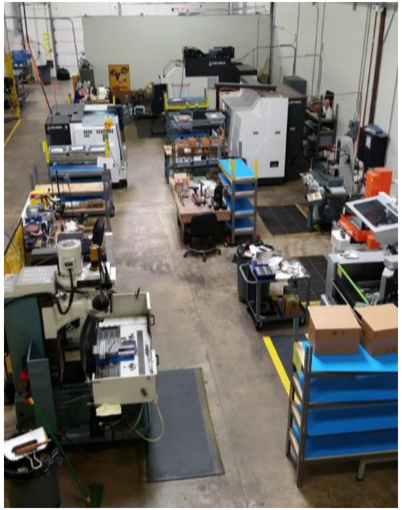
Stratasys Direct Manufacturing Additive Metals Capacity and Capabilities

Additive Metals Capacity and Capabilities



Two (2) Facilities located in: *Austin* and *Belton, TX*

Seventeen (17) Laser Powder Bed Fusion Machines

- *8 M280's, 1 M270, 1 M400 in Austin, TX*
- *4 M280's and 3 M290 in Belton, TX*

Ten (10) Metal Alloys

Staff: Programmers, Machine Technicians, Finishers, Machinists, Design Engineers, Application Engineers and Manufacturing Process Engineers

Post AMM Support

- Five (5) CNC Mills; 3, 4, and 5-axis
- Two (2) CNC Lathes
- Two (2) Wire EDM and Drill EDM
- Surface grinder, Stress-relief kiln, Down draft tables, shot peen blast cabinets, multiple tumbling machines

Outsource: Abrasive flow machining, Mechanical-Chemical Polishing

AMM Inspection

Metallographic Mount and Polisher, hardness tester, Zeiss CMM, Flow bench, High resolution scale, Profilometer

ADDITIVE METALS PRODUCTION FACILITIES

Austin and Belton, TX - Similar Capacity, Redundant Capability

Austin, TX

Belton, TX

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Additive Manufacturing Metal Alloys

Feedstock = Argon gas atomized powder.

Current Alloy Offerings

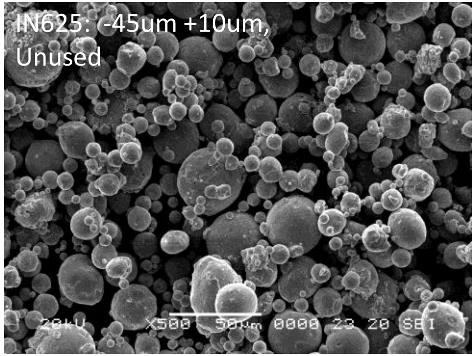
1. SS 17-4 PH*
2. **SS316L**
3. IN 625*
4. IN 718*
5. IN718 API-std
6. CoCrMo
7. Monel K-500
8. Invar-36
9. **AlSi10Mg**
10. Ti 6-4 Gd5*

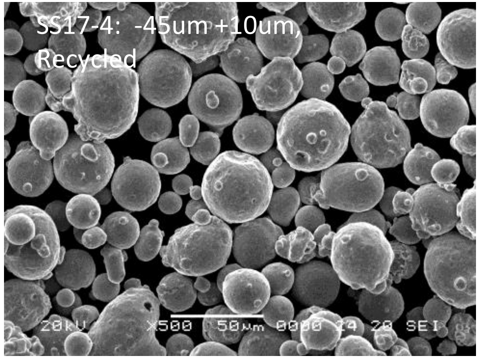
** Powder chemistry ordered to meet respective AMS standards.**

Standard Text = Performance Super Alloys

Bold Text = Quick Turn Alloys

Alloys sourced directly from multiple established atomizers.





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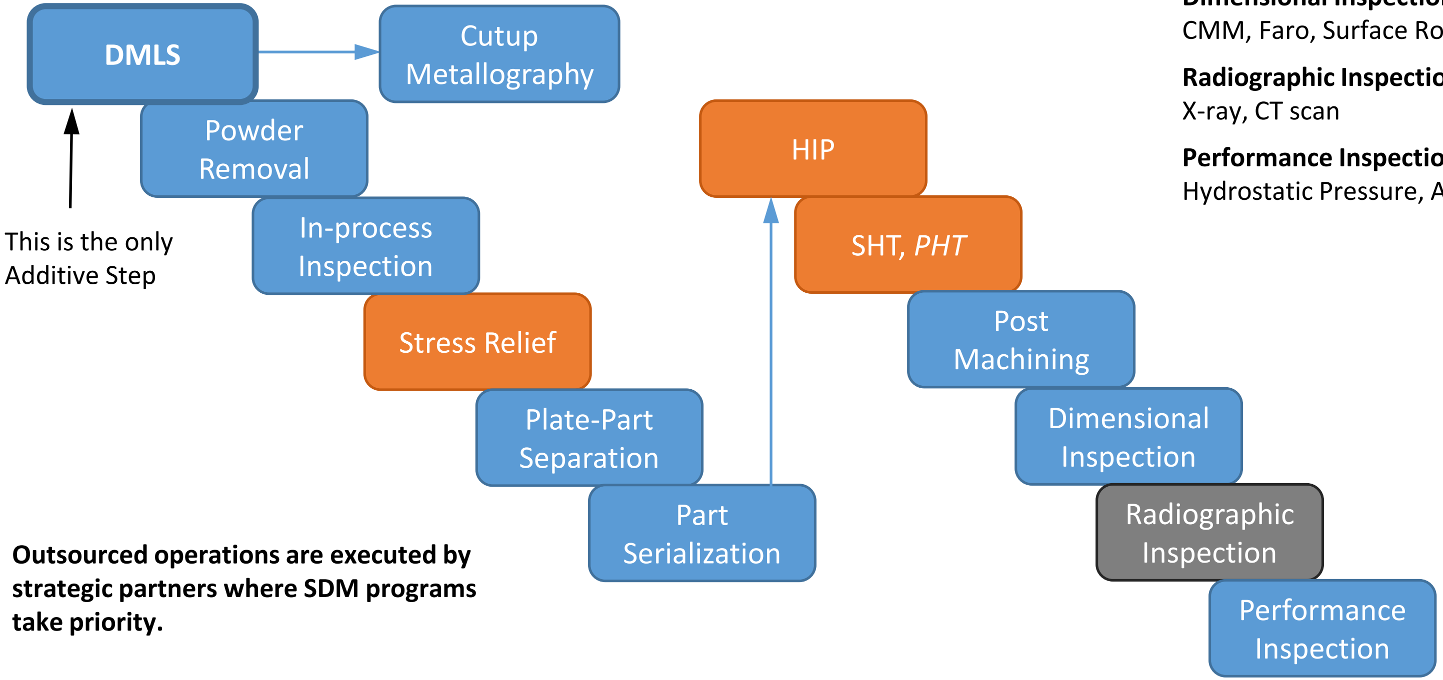
Additive Manufacturing includes the Conventional

DMLS is only an incremental step in Additive Manufacturing. SDM offers the total solution.

Stratasys Direct, In-house | Heat Treating Vendor | Radiographic Testing Vendor



Dimensional Inspection
CMM, Faro, Surface Roughness

Radiographic Inspection
X-ray, CT scan

Performance Inspection
Hydrostatic Pressure, Air Effective Area

Outsourced operations are executed by strategic partners where SDM programs take priority.

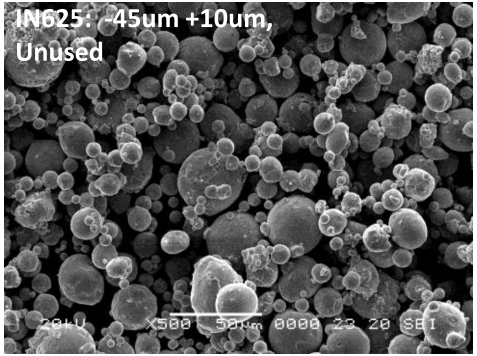
ANSWERING PROCESS QUESTIONS

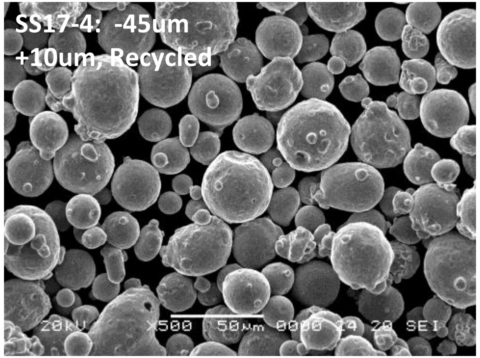
Addressing the Industry-Wide Question; Does AM Feedstock degrade with time and exposure?

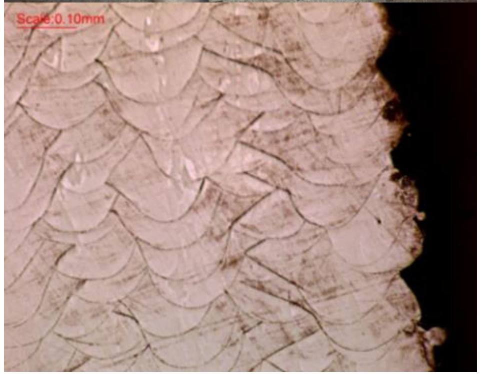
Industry claims powder degrades with time and exposure.

- Companies are forming around the fear.
- Customer's specs call for no part to be built with any powder older than 90 days.

The mechanical and material properties trended against **Blend Composition** will answer industry's question of powder degradation.







IN625 Powder Recycle and Reuse Study

* ANALYSIS ACROSS SEVEN (7) EOS M280 MACHINES OVER THE COURSE OF EIGHT MONTHS WITH MORE THAN 800 BUILDS

Powder Reuse Study

Addressing the industry wide question.

Material Property Study - Insight into Powder Life Cycle

Tensile and Microstructure

Industry claims powder degrades with time and exposure.
Companies are forming around the fear
Customer's specs call for no part to be built with any powder older than 90 days.

SDM's answer:

- 7 machines building the same material
- 2 tensile bars and 1 metallographic coupon positioned per plate
- over 60 builds/machine

Material properties trended against **Blend Composition** will answer industry's question of powder degradation.

IN625 – As Built Microstructure

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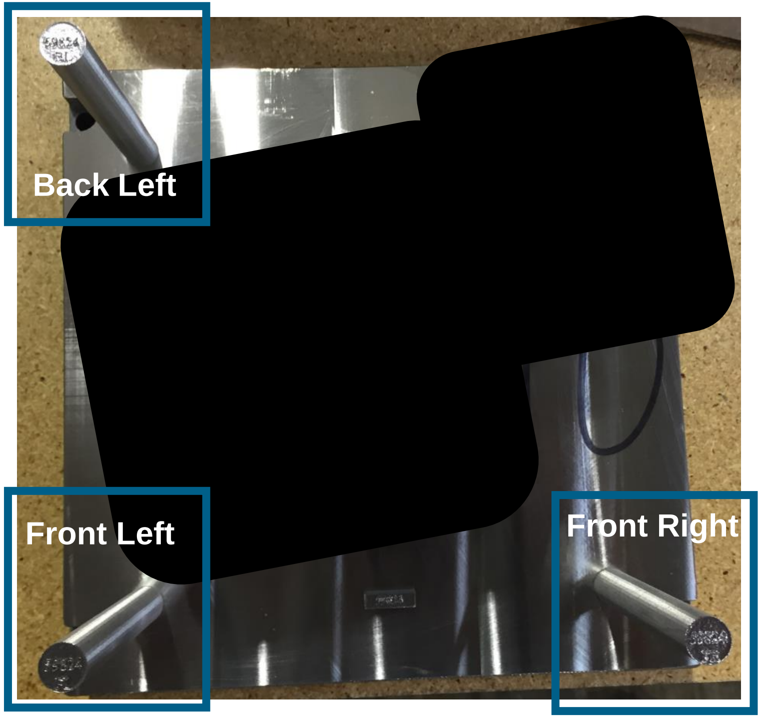
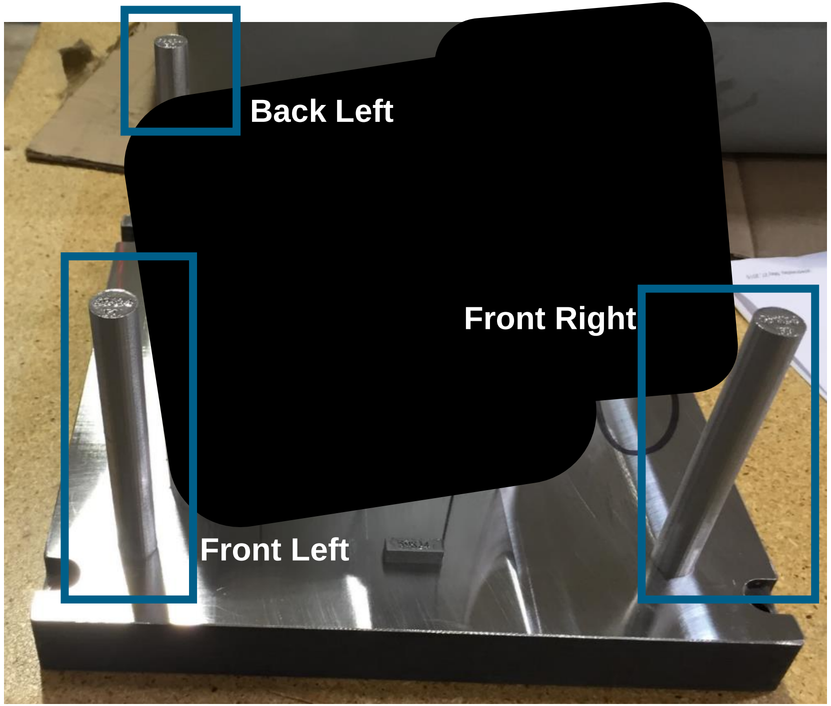
Build Configuration

3 Sacrificial Cylindrical Blanks, >800 Builds





Processing

- Tensile Blanks were process alongside component
- Coupons represent relieved component.

Additive Manufacturing
(94hour build, >2800 Layers)

Stress Relief
(1925F for 120min)

Plate Part Separation
(Saw)

HIP
(1950F @ 14.5ksi for 4hrs)

Solution Heat Treatment
(2175F for 60min)

Machining
(Per ASTM E8 cylindrical bars)

Testing
(Per ASTM E8 cylindrical bars)

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What was Involved

7 Machines, 2 Material Providers, 8 Material Lots, >55 Builds per Machine

210 tensile bars, 14 Chemical, 20 Metallography

Comparisons:

- ✓ Material Provider
- ✓ Build Location
- ✓ Machine to Machine Consistency
- ✓ Powder Composition

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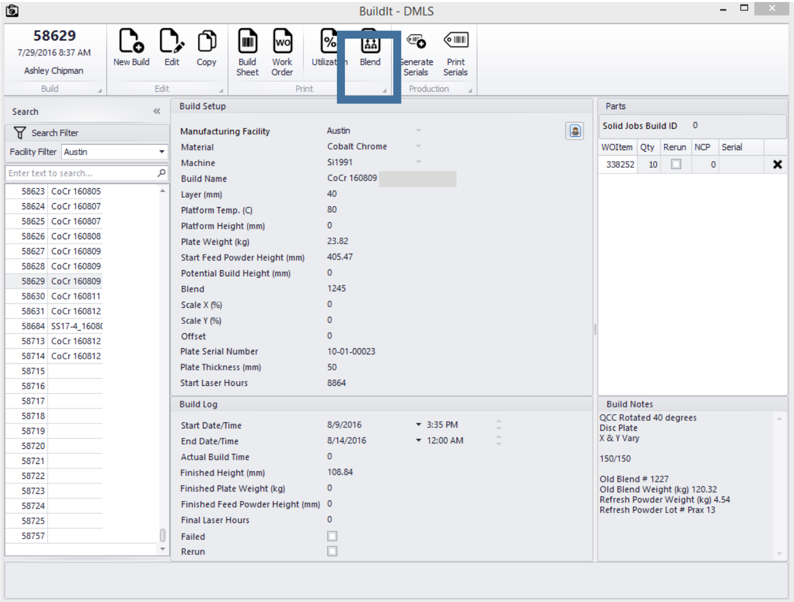
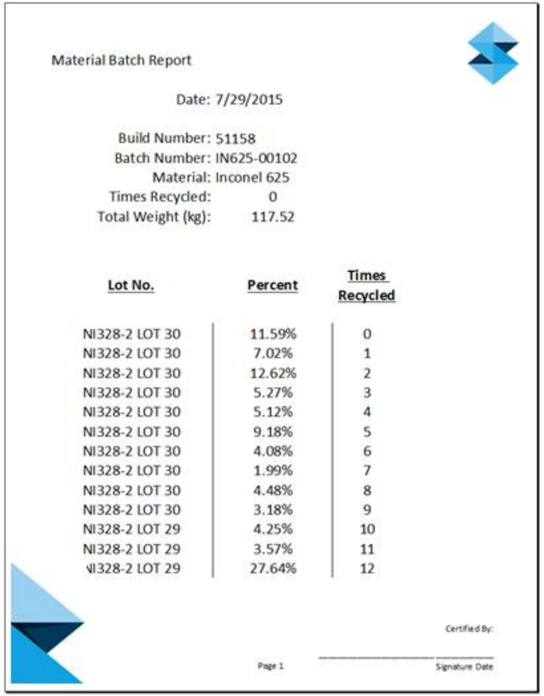
Fundamentals

Implemented a digital system providing a resolution in powder composition unmatched by industry. Logging and minding powder composition over time.





Material Batch Report

Date: 7/29/2015

Build Number: 51158
Batch Number: IN625-00102
Material: Inconel 625
Times Recycled: 0
Total Weight (kg): 117.52

Lot No.	Percent	Times Recycled
NI328-2 LOT 30	11.59%	0
NI328-2 LOT 30	7.02%	1
NI328-2 LOT 30	12.62%	2
NI328-2 LOT 30	5.27%	3
NI328-2 LOT 30	5.12%	4
NI328-2 LOT 30	9.18%	5
NI328-2 LOT 30	4.08%	6
NI328-2 LOT 30	1.99%	7
NI328-2 LOT 30	4.48%	8
NI328-2 LOT 30	3.18%	9
NI328-2 LOT 29	4.25%	10
NI328-2 LOT 29	3.57%	11
NI328-2 LOT 29	27.64%	12

Certified By:

Page 1

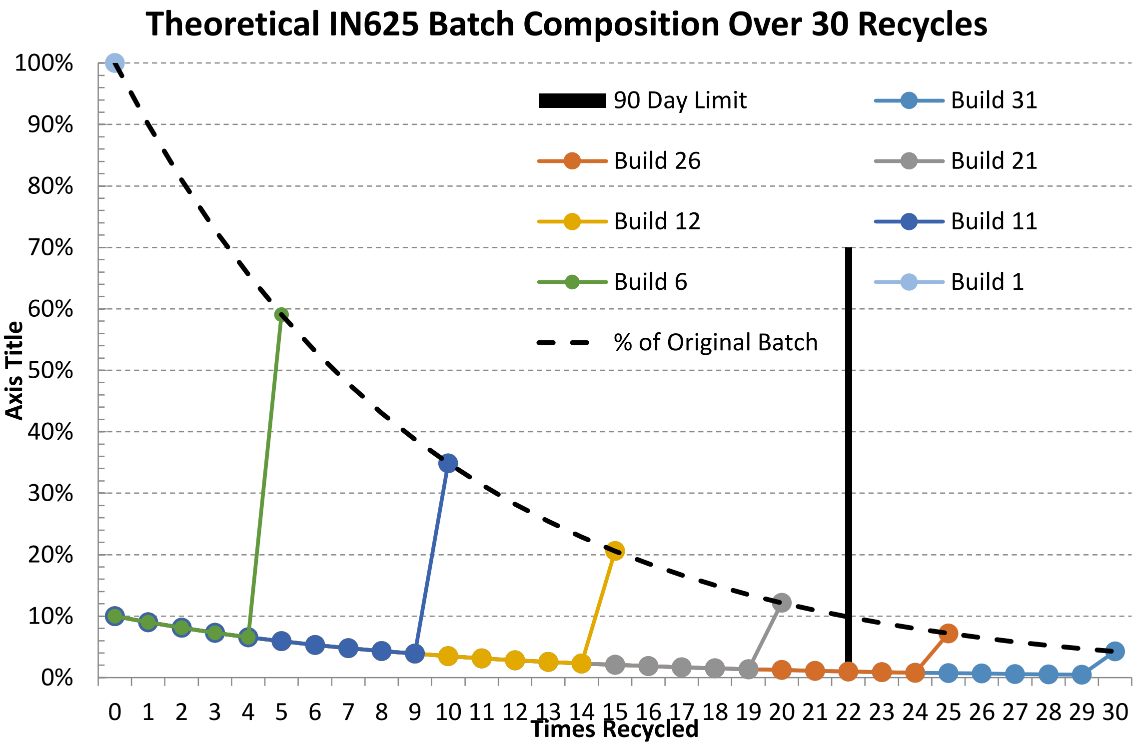
Signature Date

Workbench - BuildIt / Powder Report

Digital means to log and mine powder composition

Material Recycle and Reuse

Powder Composition is in a constant state of flux.



- SDM Recycles 100% material
- The majority of powder has been recycled.
- No test method is identified to *qualify* recycled powder

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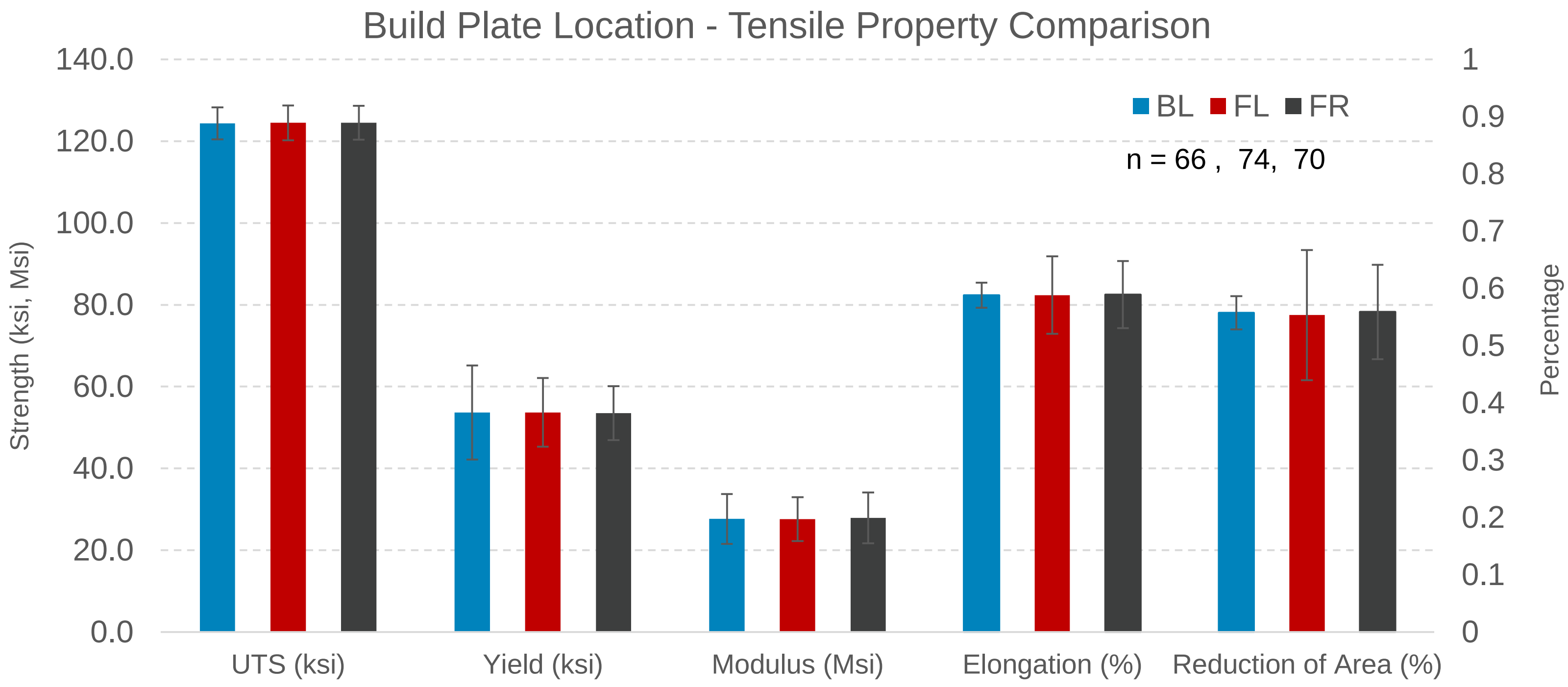
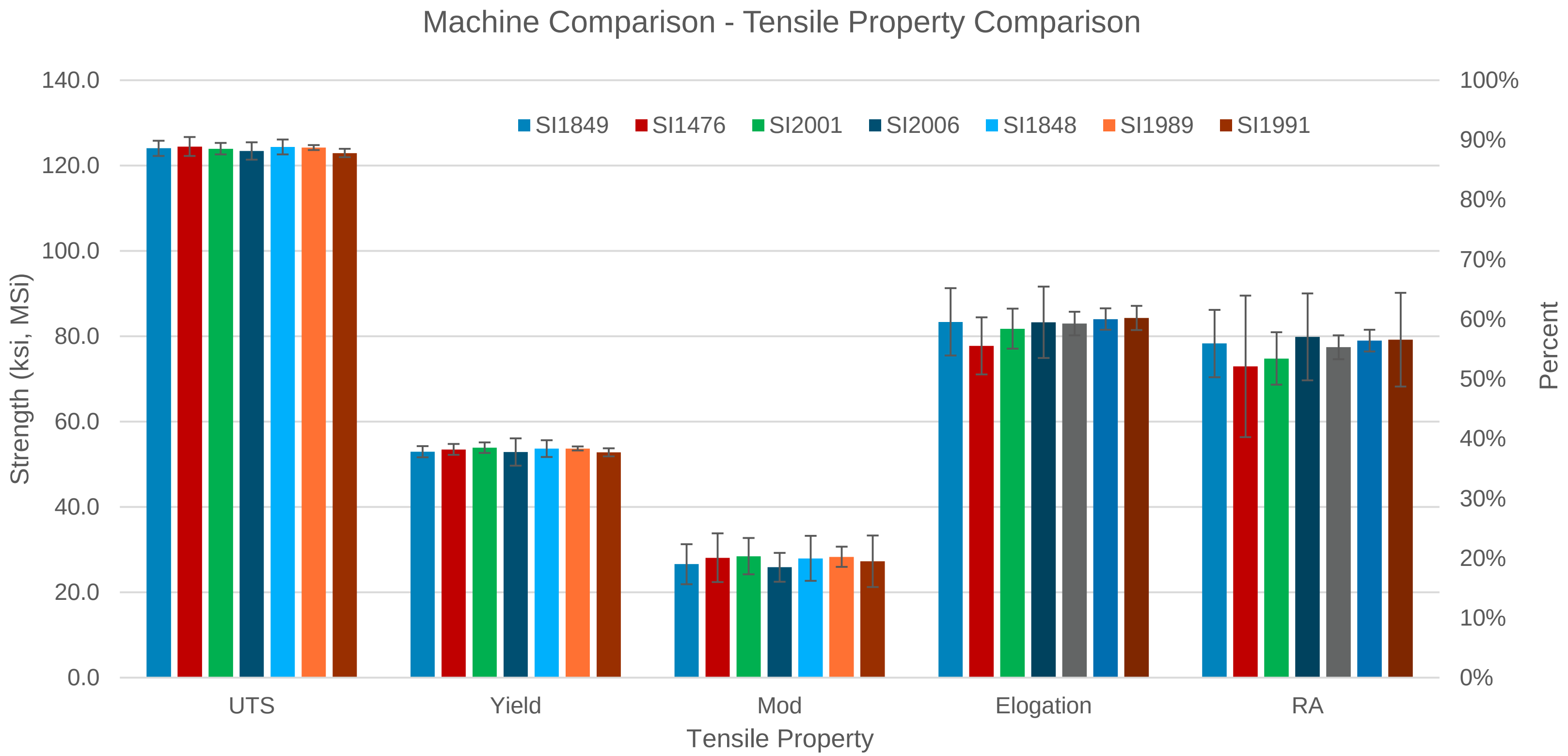
Build Location Comparison

Build Location – Machine to Machine – Powder Composition – Material Provider



Machine To Machine Comparison

Build Location – **Machine to Machine** – Powder Composition - Material Provider



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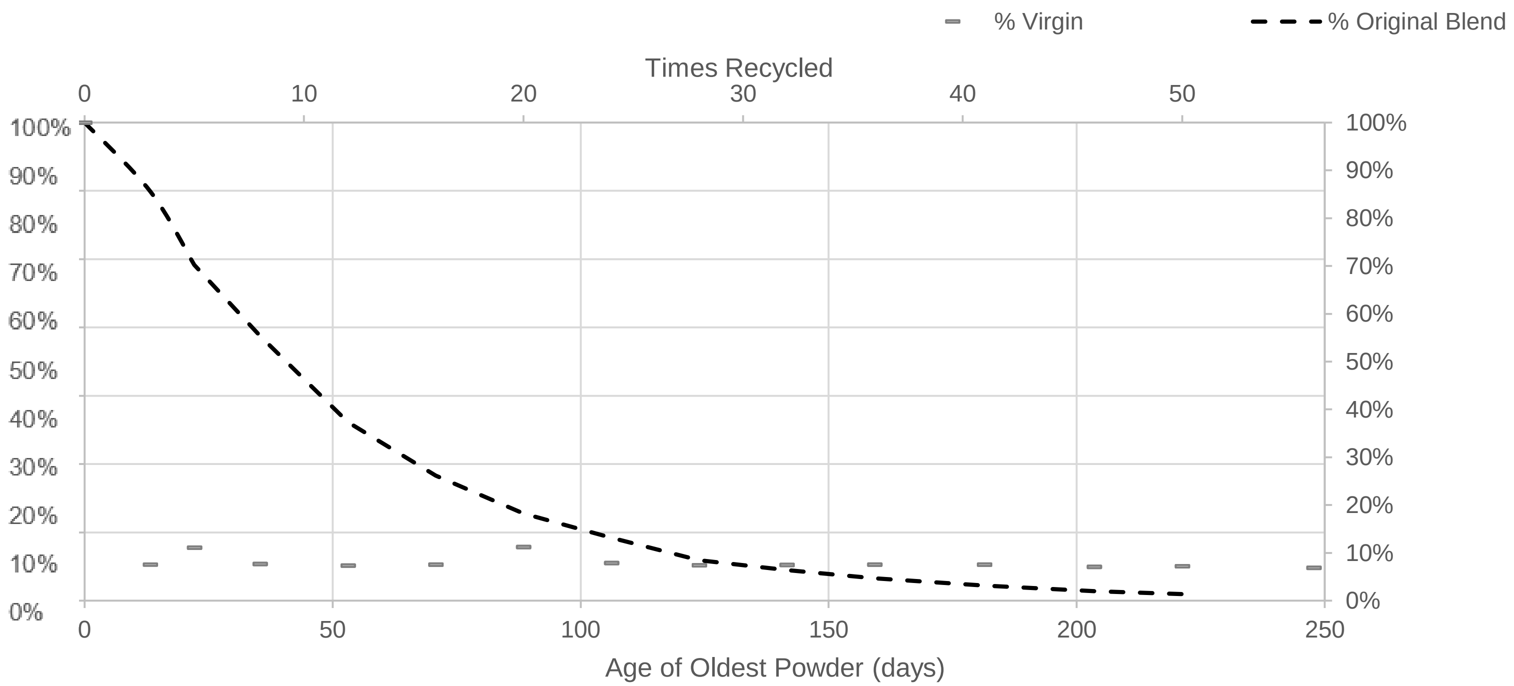
Powder Evolution / Life Cycle

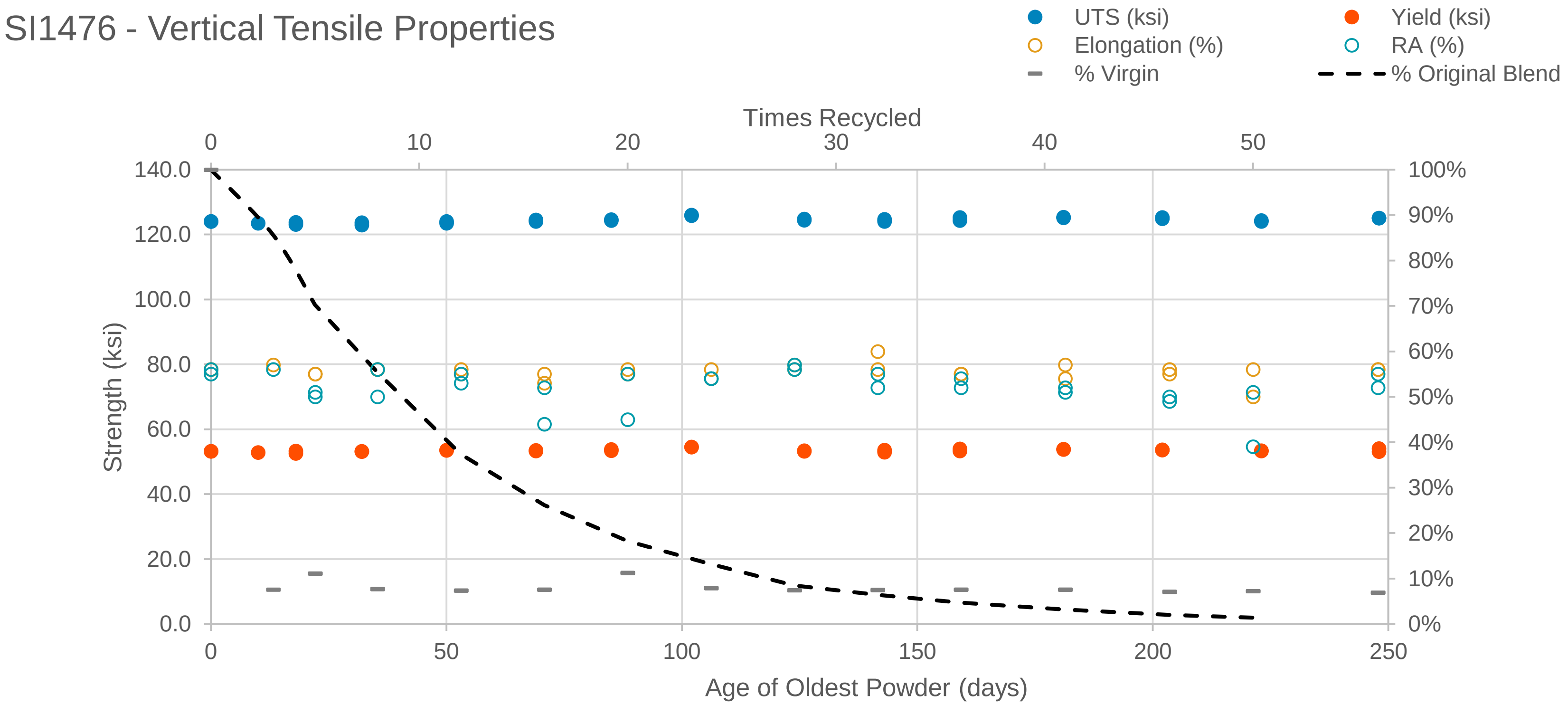
Build Location – Machine to Machine – **Powder Composition** – Material Provider

SI1476 - Vertical Tensile Properties



Tensile Properties Overlaid Onto Powder Composition

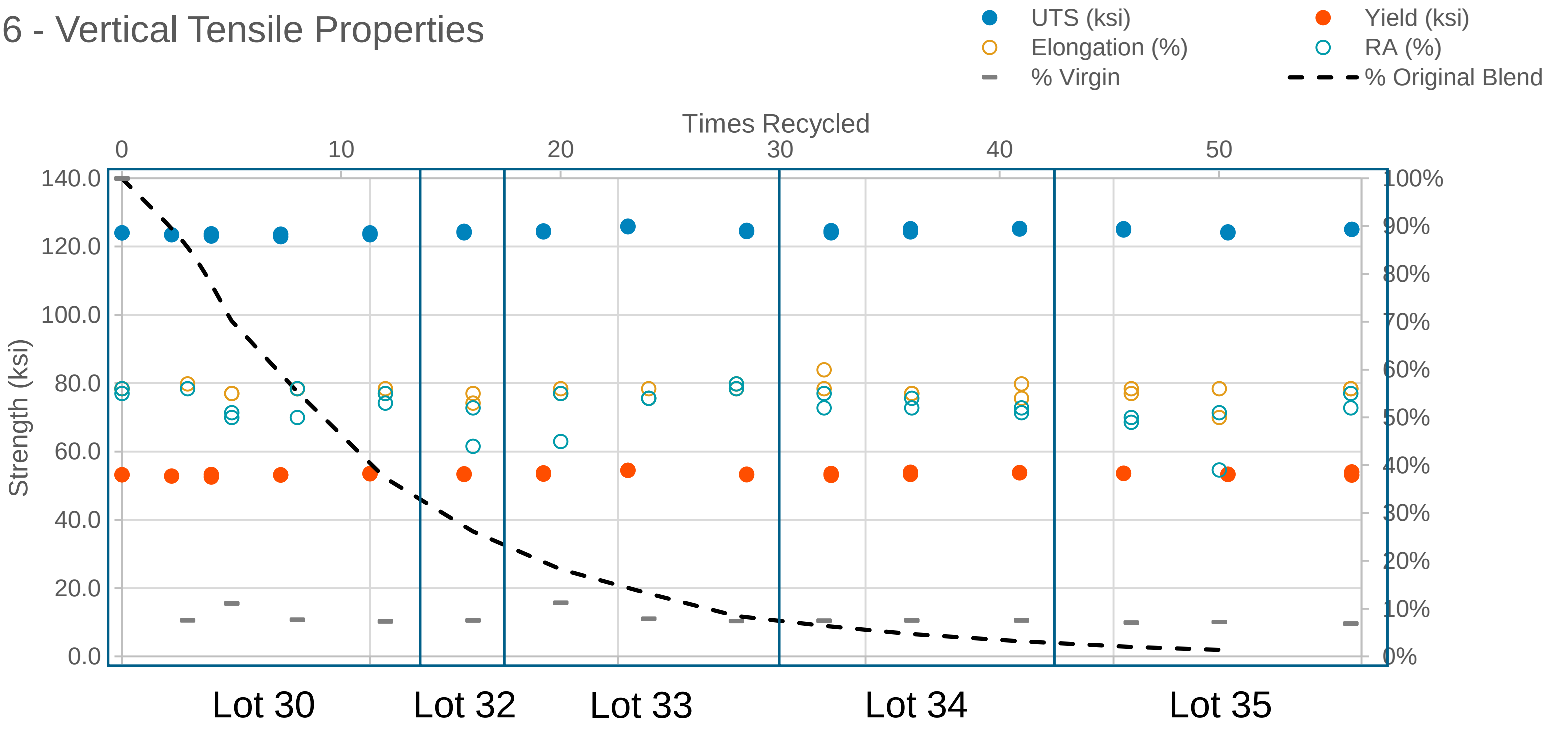
Build Location – Machine to Machine – **Powder Composition** – Material Provider



Introduction of Separate Powder Lots

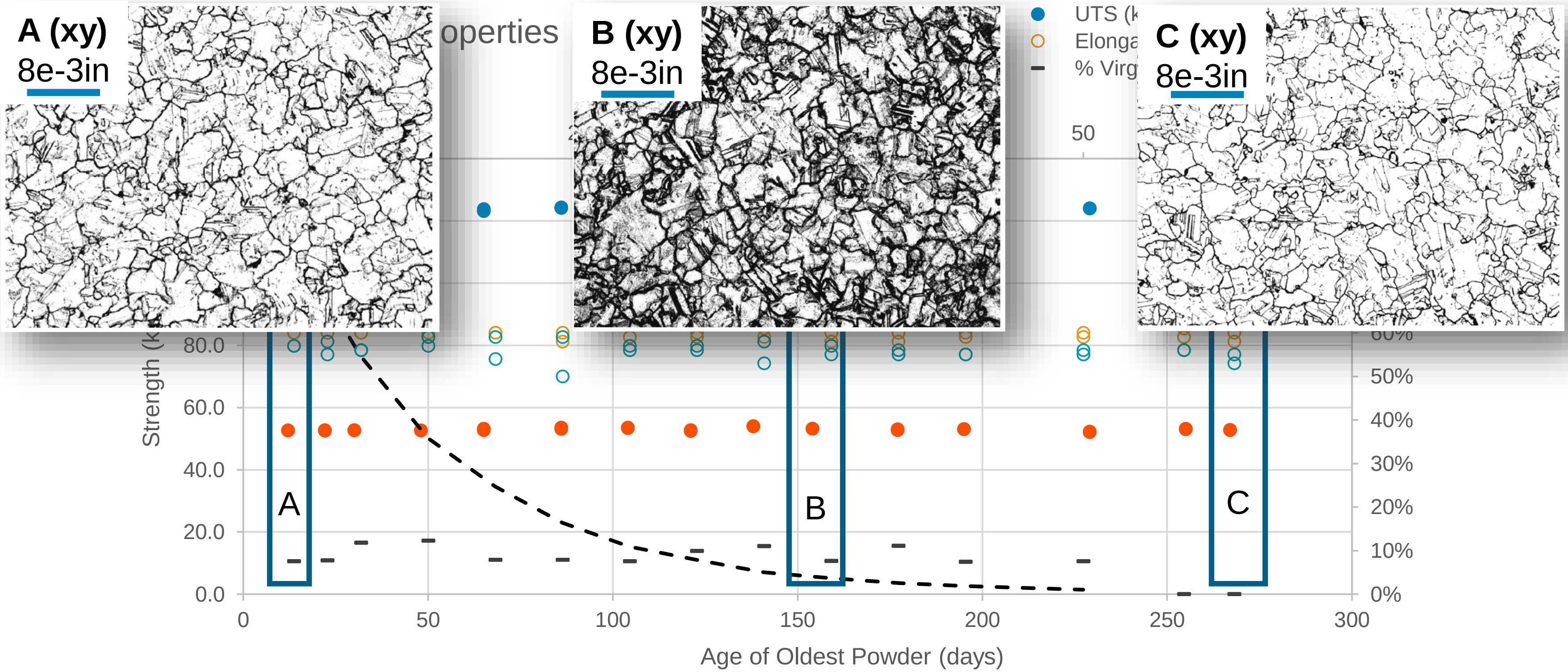
Build Location – Machine to Machine – **Powder Composition** – Material Provider

SI1476 - Vertical Tensile Properties



Microstructure Over Time

Build Location – Machine to Machine – **Powder Composition** – Material Provider



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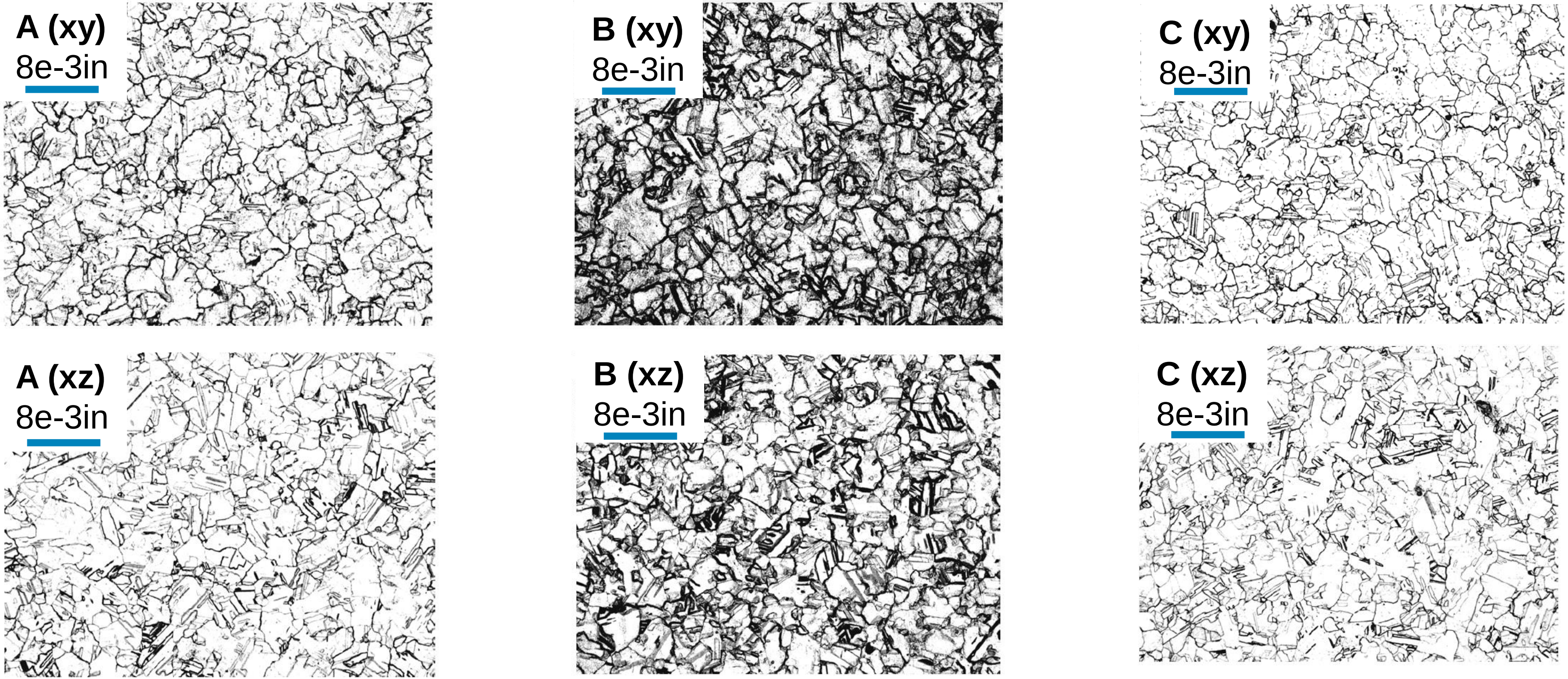
Microstructure Different Orientations

Build Location – Machine to Machine – **Powder Composition** – Material Provider



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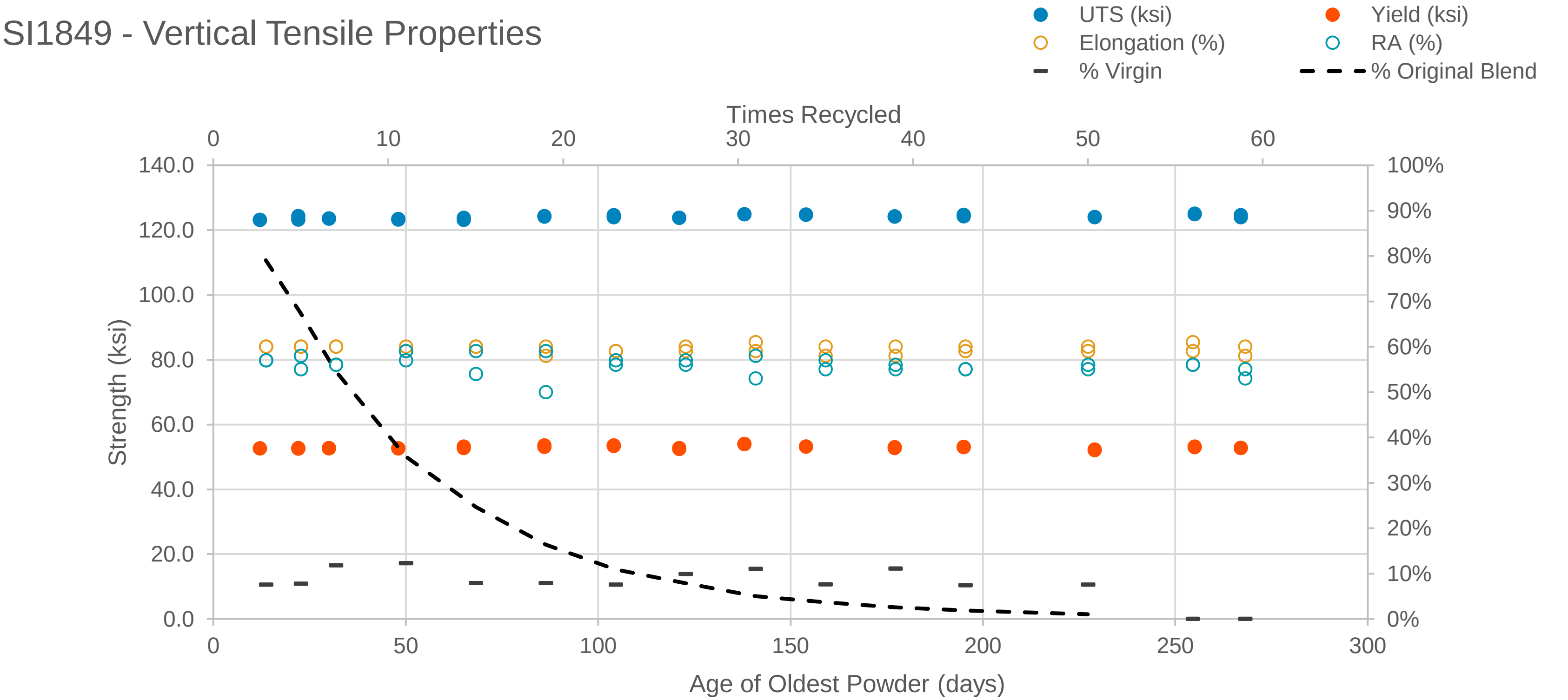
Material Chemistry Over Time

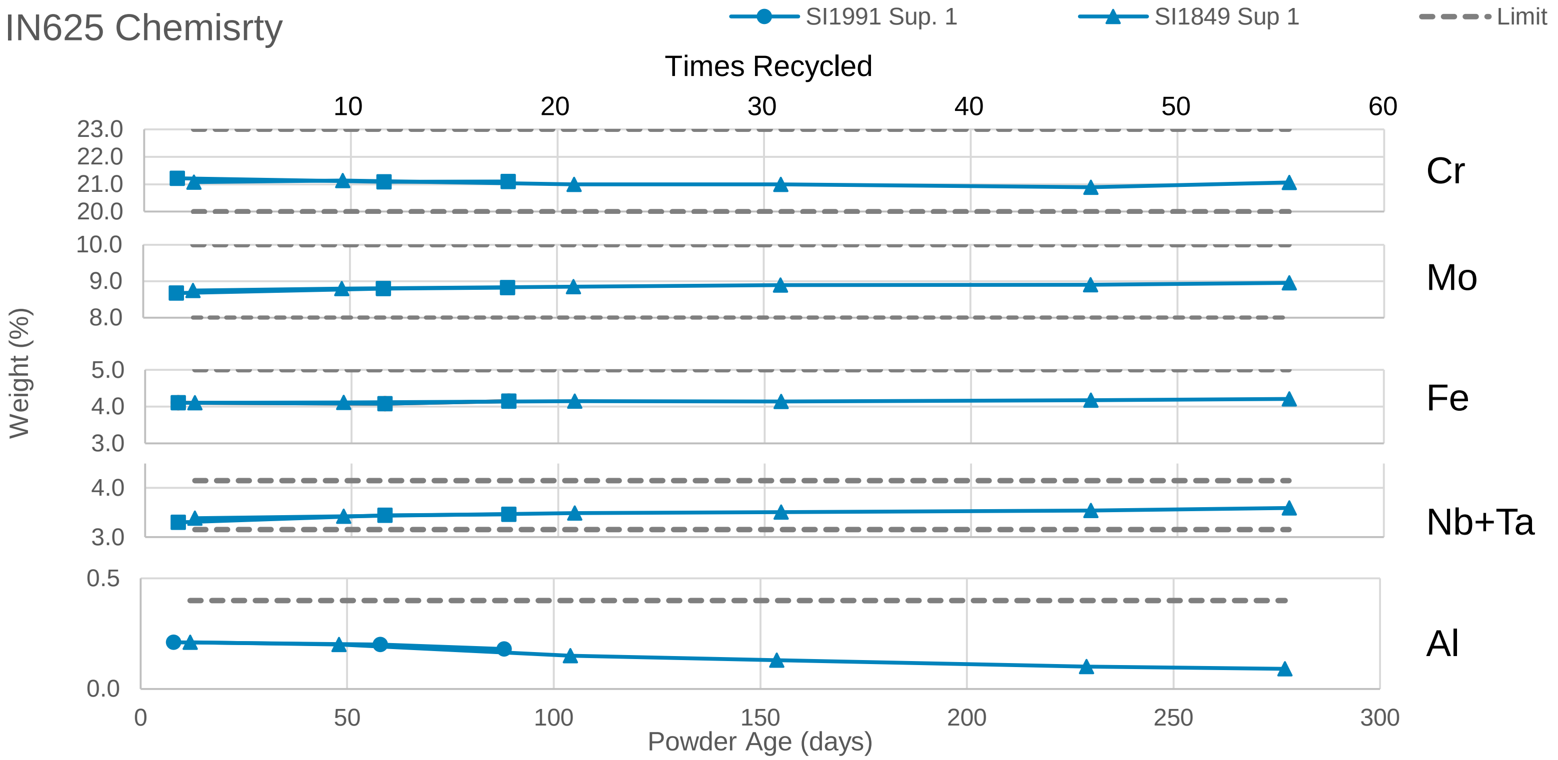
Build Location – Machine to Machine – **Powder Composition** – Material Provider



Material Chemistry Over Time

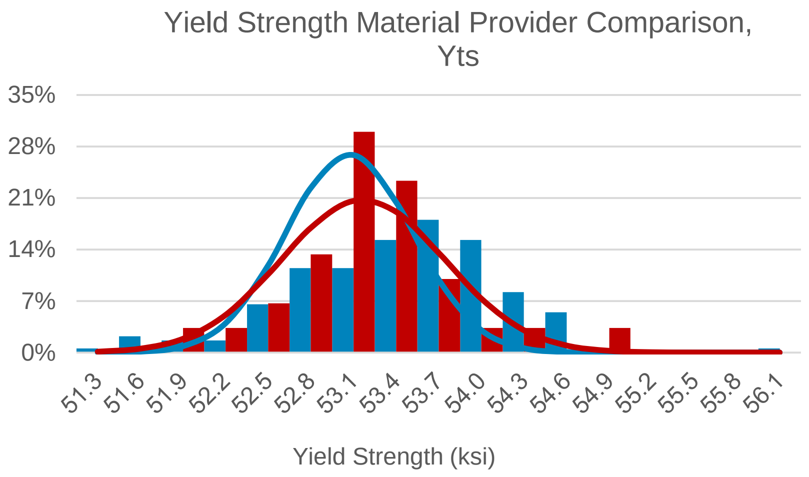
Build Location – **Machine to Machine** – **Powder Composition** – Material Provider

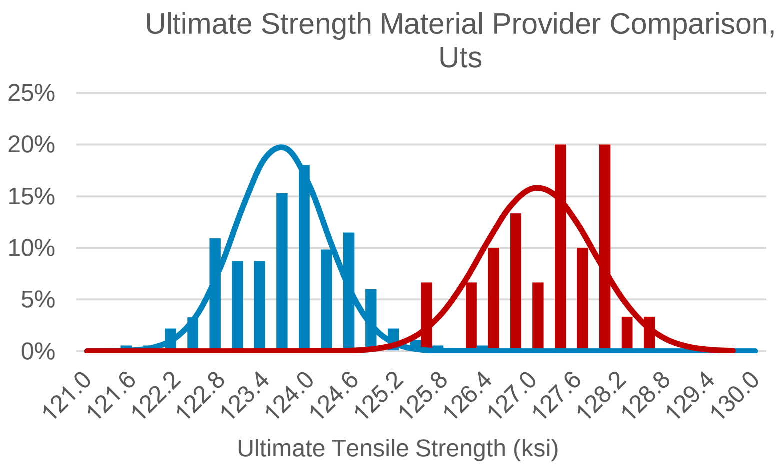
IN625 Chemisrty



Material Provider Comparison

Build Location – Machine to Machine – Powder Composition – **Material Provider**

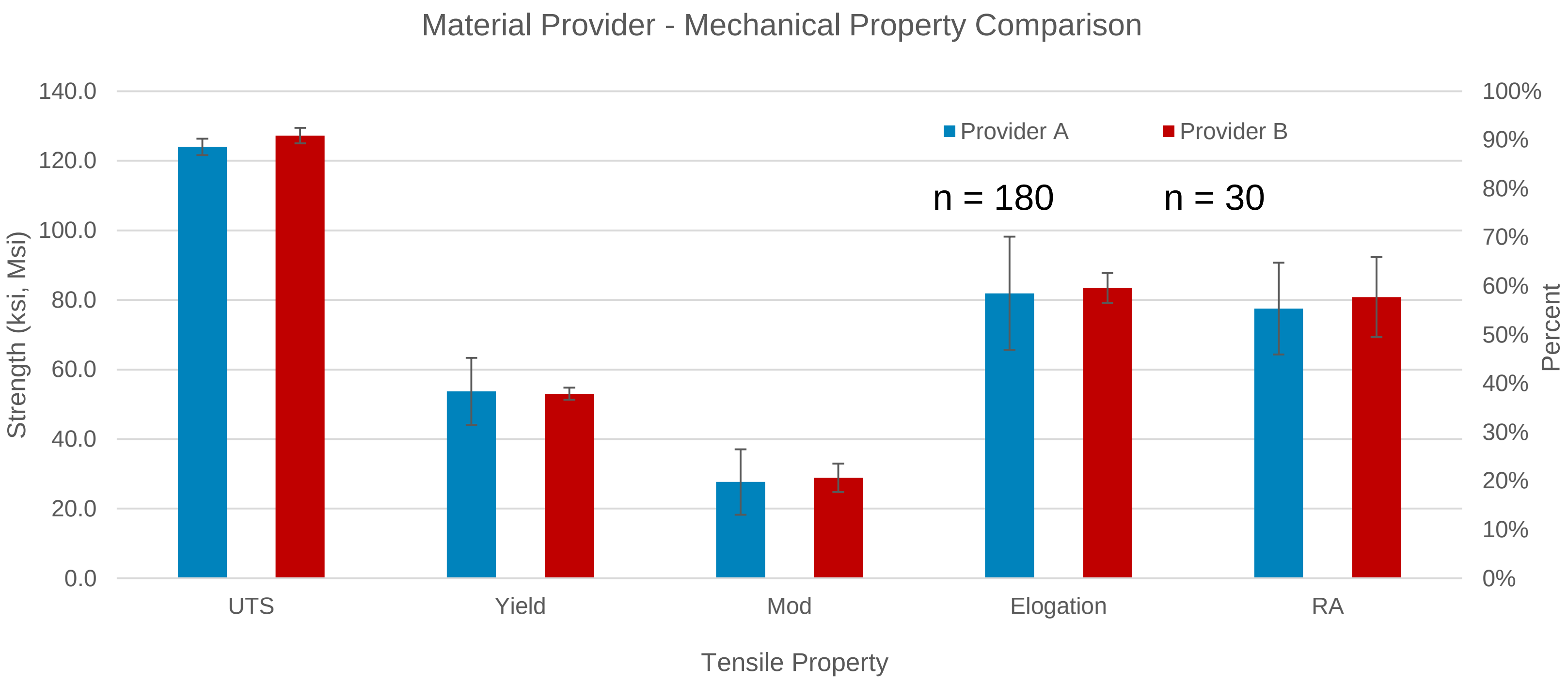




Material Provider 1, n = 180
Material Provider 2, n = 30

Material Provider Comparison

Build Location – Machine to Machine – Powder Composition – **Material Provider**



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Material Provider Comparison

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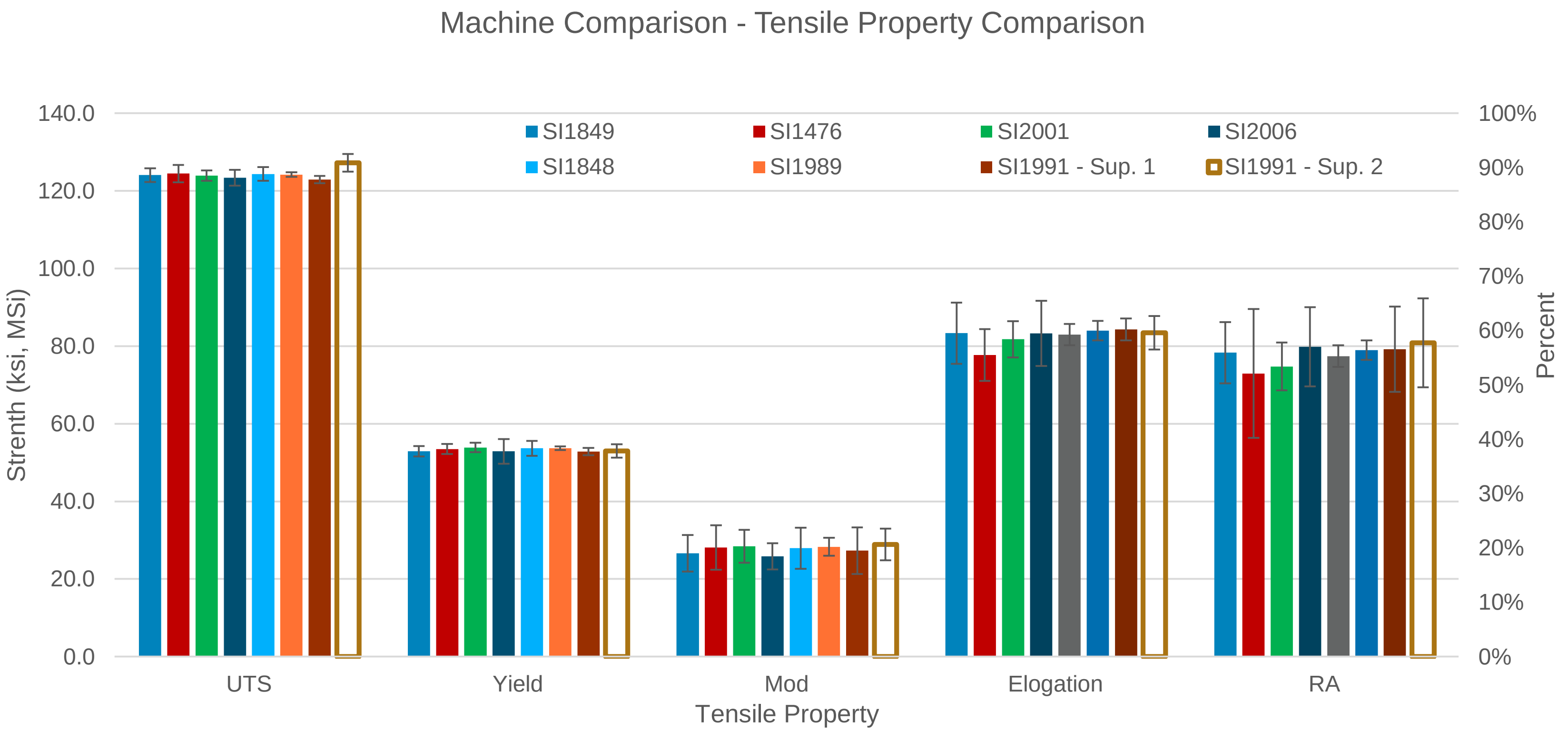

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Material Provider Comparison

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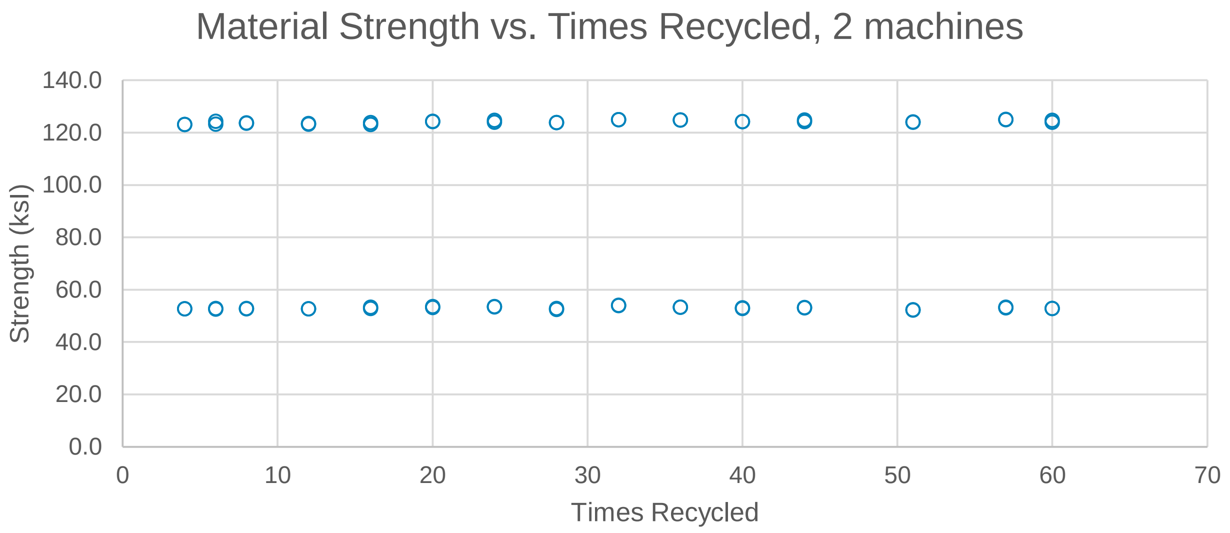

Material Provider Comparison

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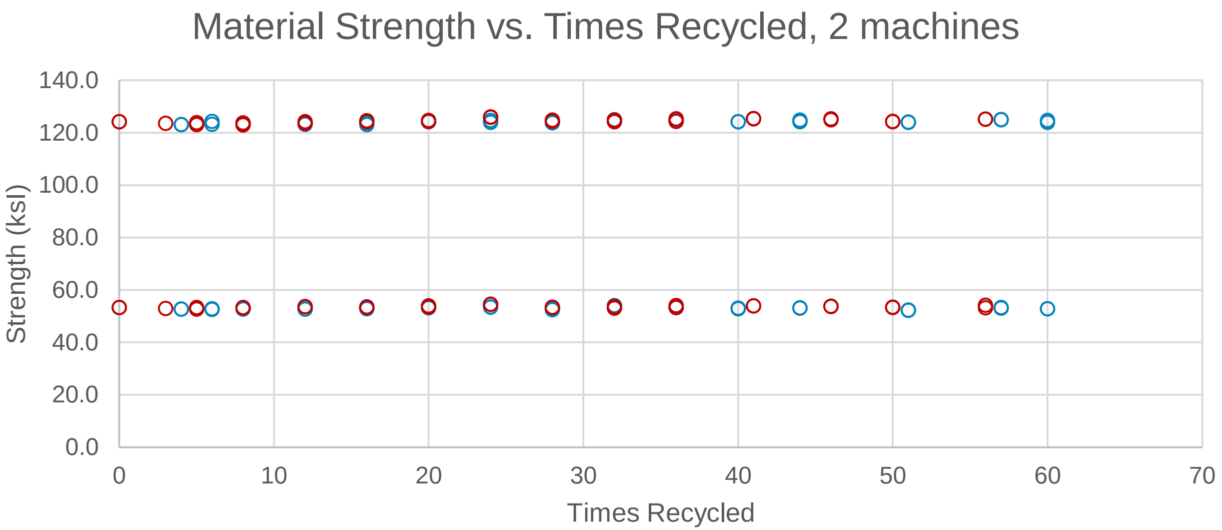

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Material Provider Comparison

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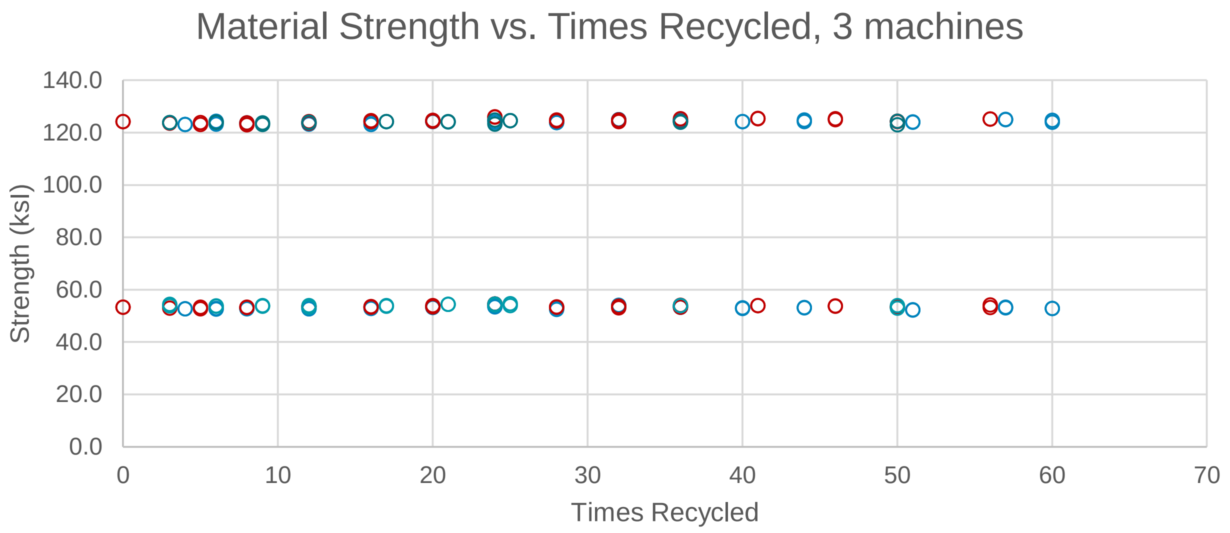

Material Provider Comparison

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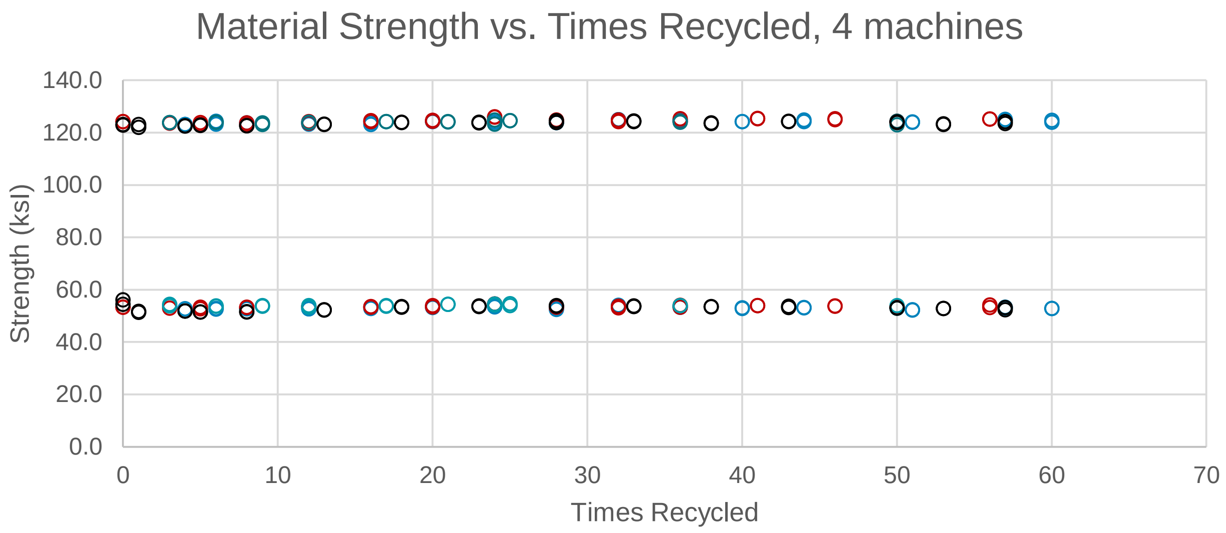

Material Provider Comparison

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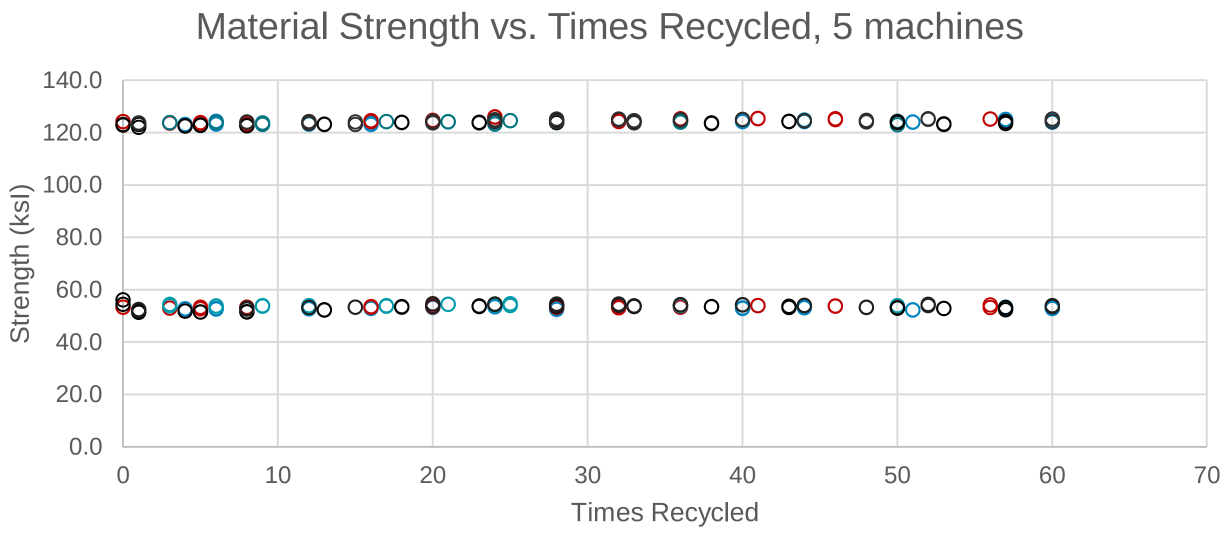

Material Provider Comparison

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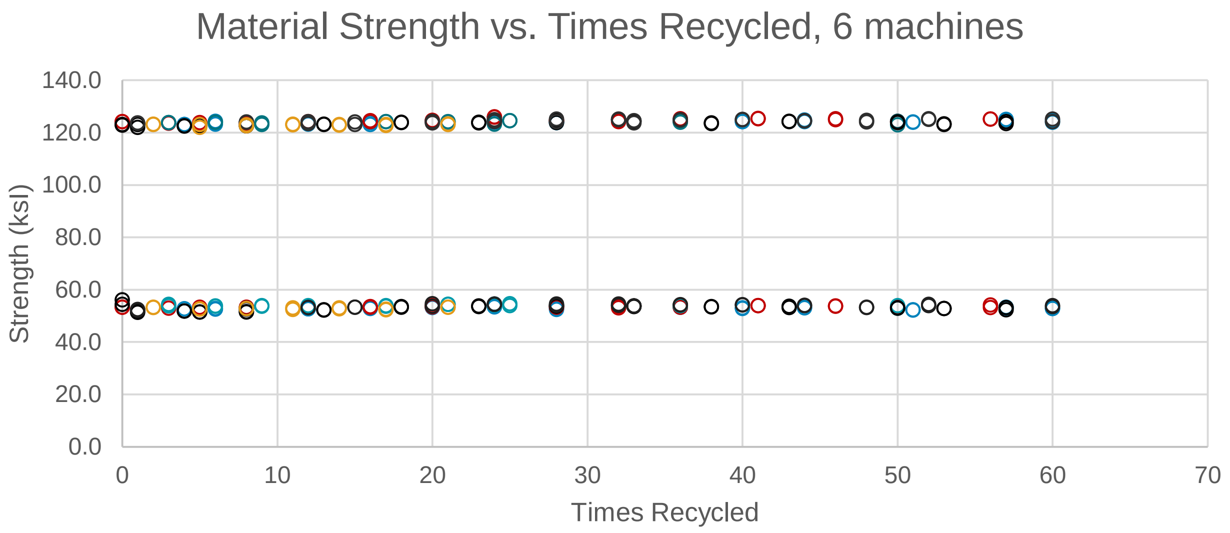

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Material Provider Comparison

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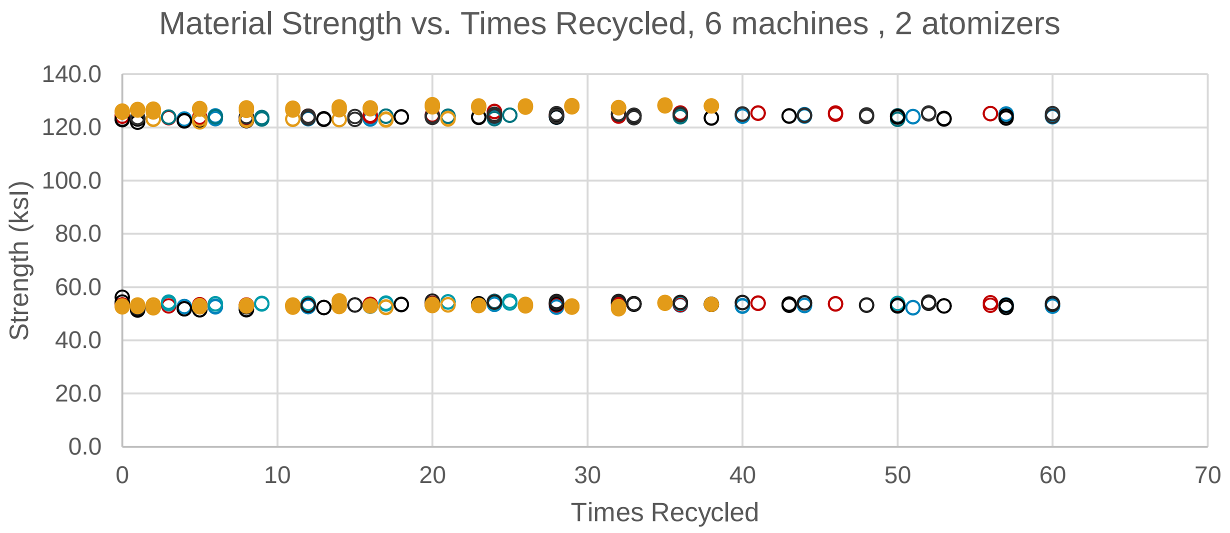

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Material Provider Comparison

Build Location – Machine to Machine – Powder Composition – **Material Provider**

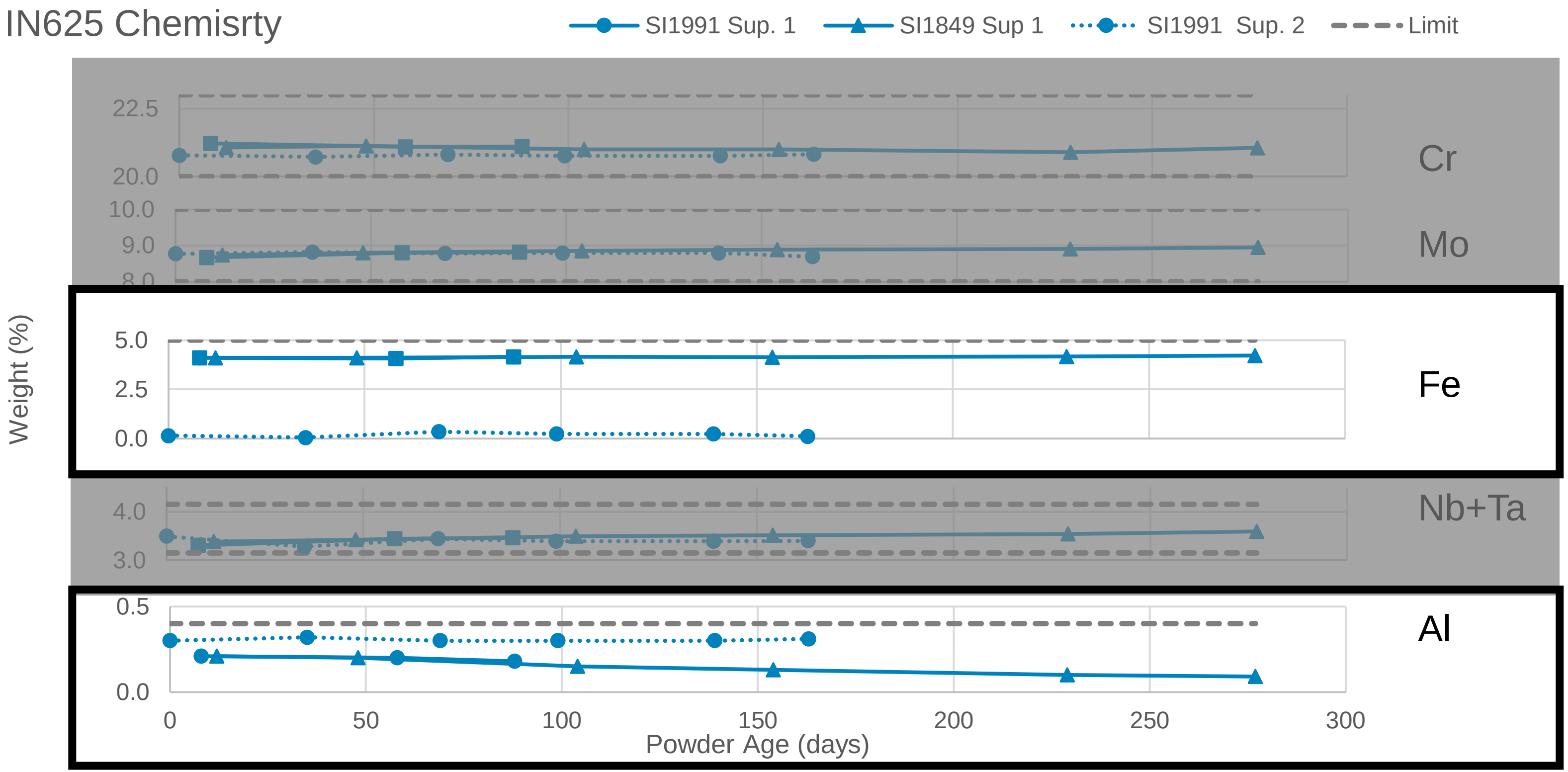
The **different chemistries** produced by different suppliers produced statistically different ultimate tensile strength.

Material Chemistry

Supplier	Supplier 1 *(% by Weight)*	Supplier 2 *(% by Weight)*
Al	**0.32**	**0.14**
Cr	21.02	21.54
Mo	9.2	9.1
Nb+Ta	3.66	3.73
Fe	**0.04**	**3.90**

Material Provider Comparison

Build Location – Machine to Machine – Powder Composition – **Material Provider**



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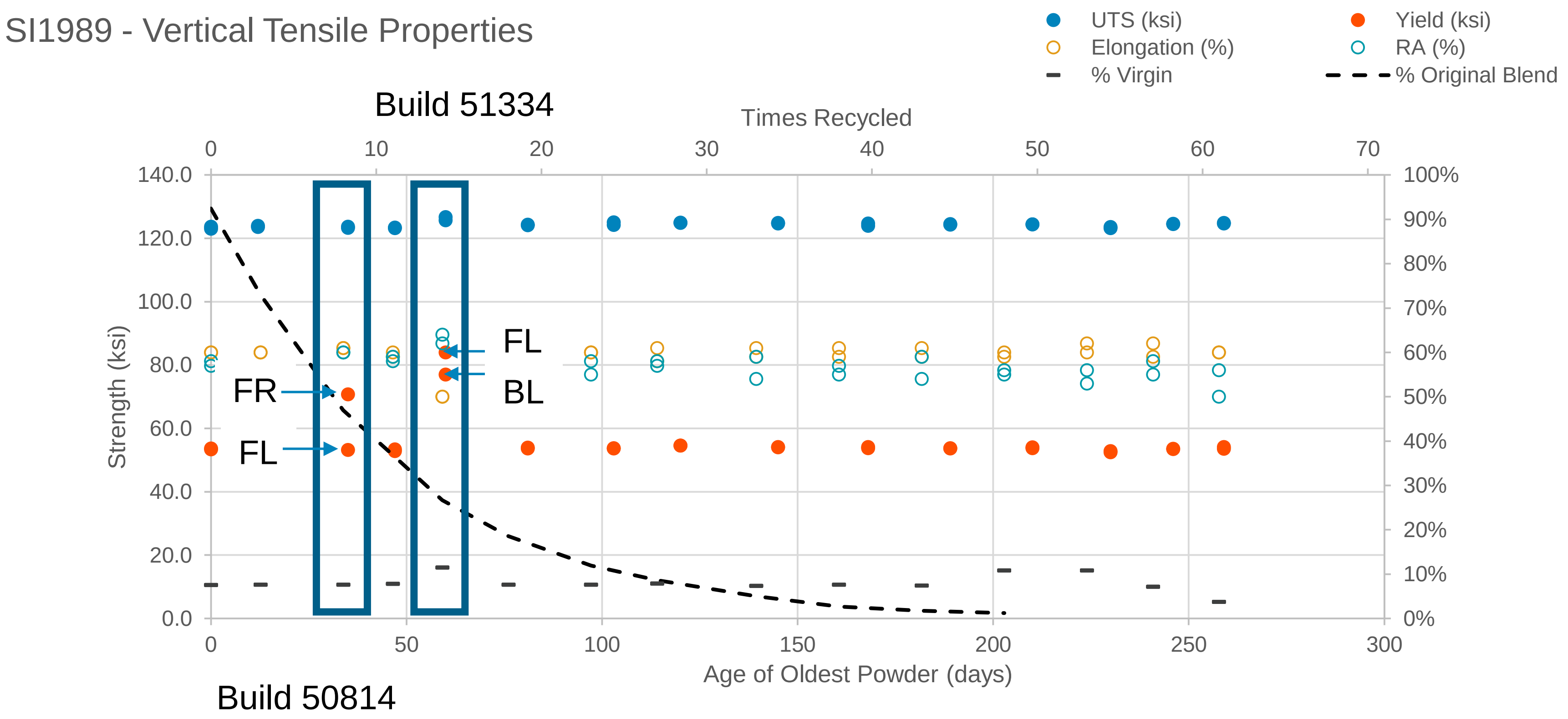
Out of the 220 Bars, 2 Appeared *"Different"*



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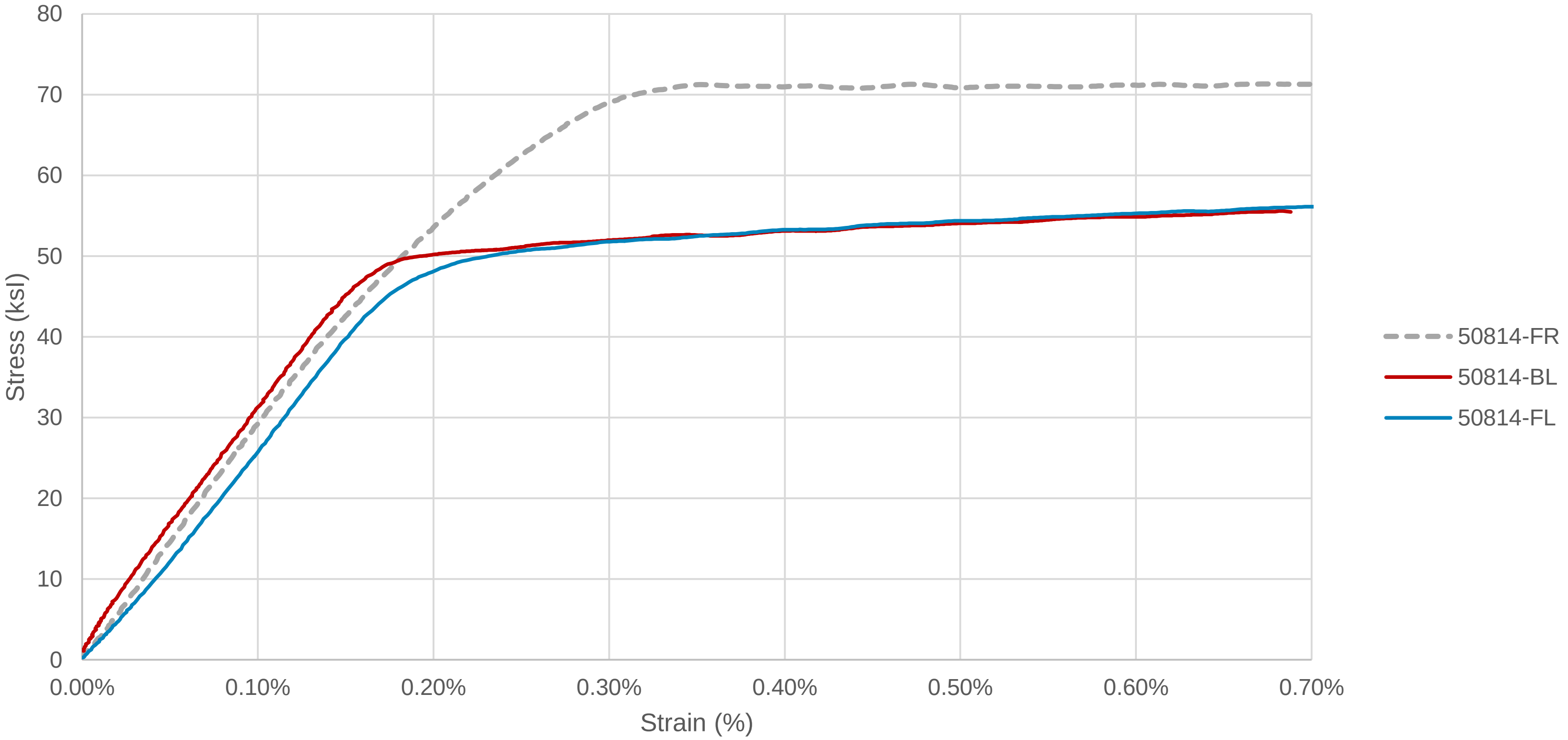
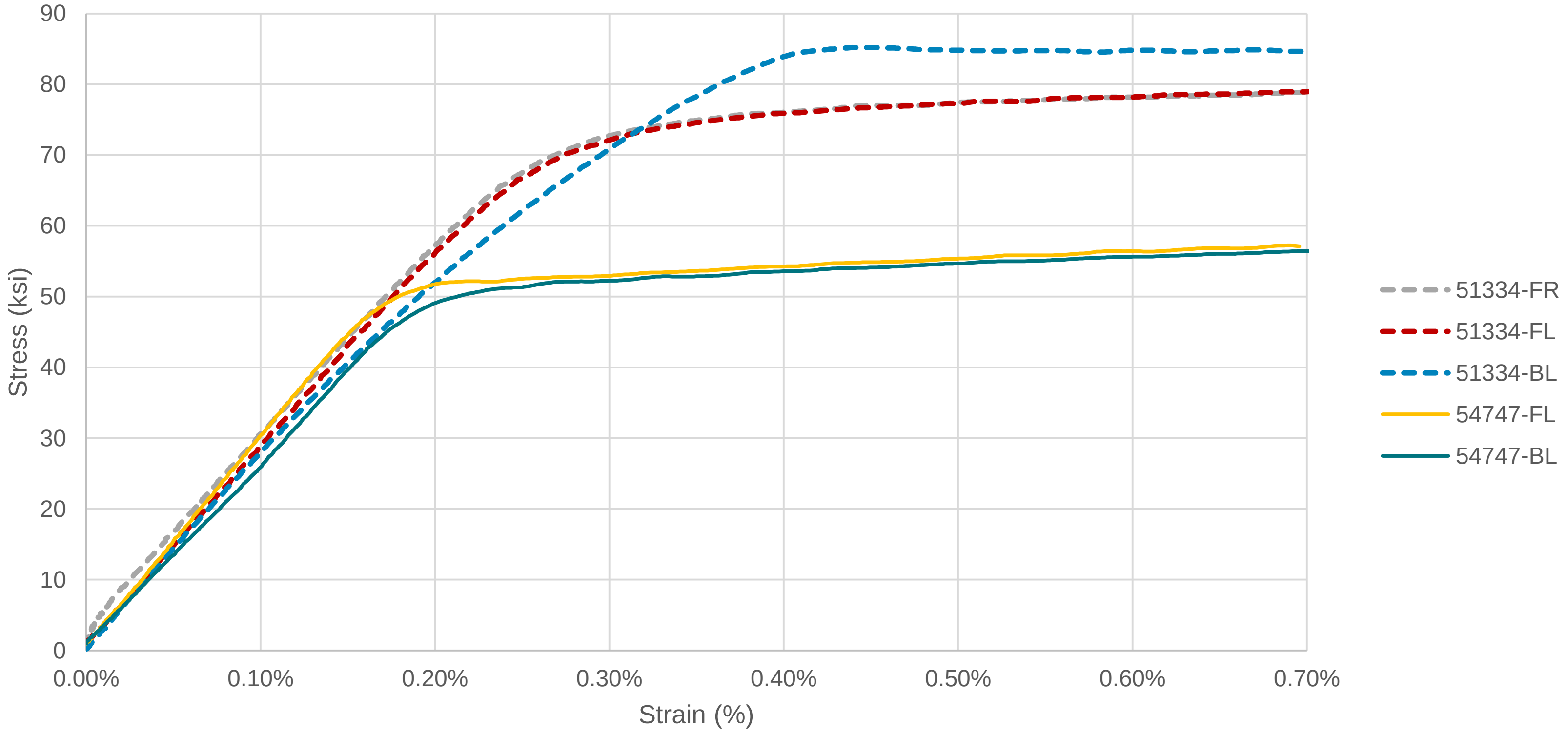
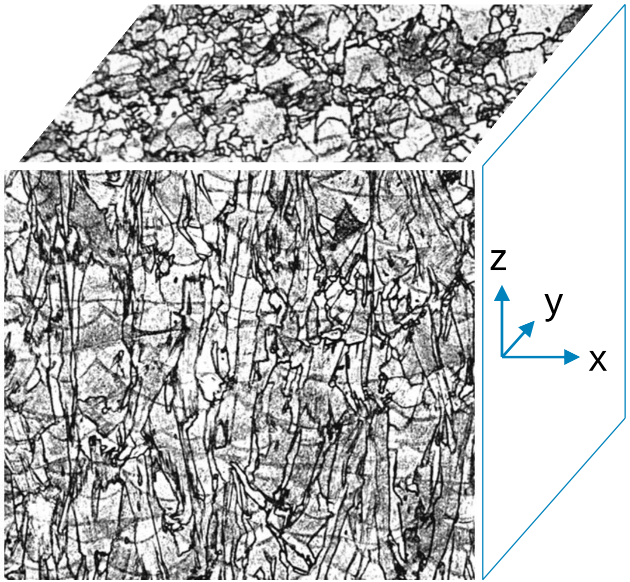
Tensile Results Build 50814



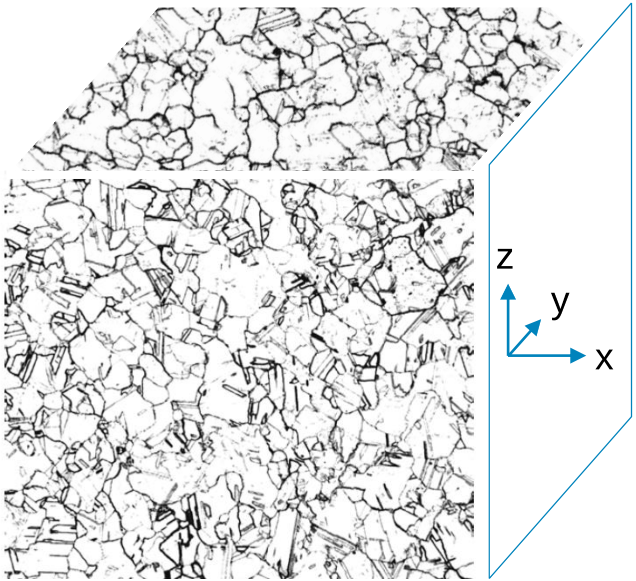
Tensile Comparison, Build 51334 & 54747



Metallographic Comparison, Build 51334 & 54747



Stress Relieved, Additive IN625 (100x)



Solution Heat Treated, HIP’ed, Stress Relieved, Additive IN625 (100x)

Conclusion

SDM's mission to control, track, and develop the AM production process has lead to **vertical integration of multiple post process operations and inspection techniques** providing the industry with

- The most efficient and economic powder management process.
- Decreased response time to process drift and potential defect parts.
- Increased confidence in DMLS material/part quality
- Separation from SDM's competition.
- Increased customer confidence.
- Insight into powder lifecycle

AM Capabilities for Thermal Management

WHY CHOOSE AM FOR THERMAL MANAGEMENT?

Next-generation thermal management demands:

- Increased performance with minimum pressure loss
- Reduced size and weight
- Affordable, modular, scalable

Part Consolidation

- Eliminate thermal resistance between components
- Reduce assembly time and weight

Tool-less, Digital Inventory

- Easily iterate through the design/build/test cycle
- Reduced lead times
- Simplified supply chain

WHY CHOOSE AM FOR THERMAL MANAGEMENT?

Design freedom enables increased performance

- Few tooling constraints
    - Cost does not scale with complexity
- Nonlinear, tapered, optimized variable geometries
    - Extended surfaces: fins, vanes, blades
    - Heat pipe capillary wicking structures
    - Conformal internal passages
- Thermal topology optimization

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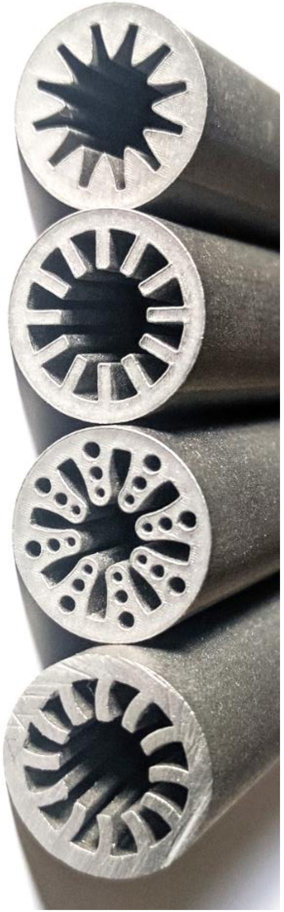
Additive Applications

ADDITIVE THERMAL MANAGEMENT APPLICATIONS

Known thermal management applications include:

- 3D modeling for concept validation
- Integral regenerative cooling of rocket engines
- Optimized wicking structures for passive heat pipes
- Microchannel and jet impingement strategies for microelectronic device cooling
- Lattice structures for integral thermal shielding
- Conformal cooling for injection molds
- Thin-film cooling
- Pin-fin heat exchangers



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PROOF OF CONCEPT MODELS

3D printing provides vibrant, informative models to:

- Serve as a “proof of concept”
- Conduct flow analysis
- Communicate business value
- Illustrate product enhancements

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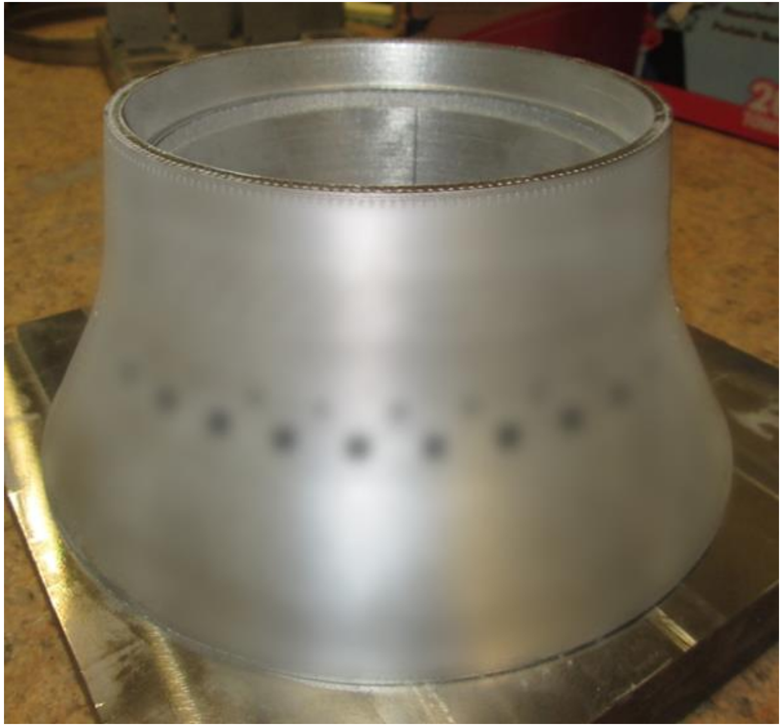
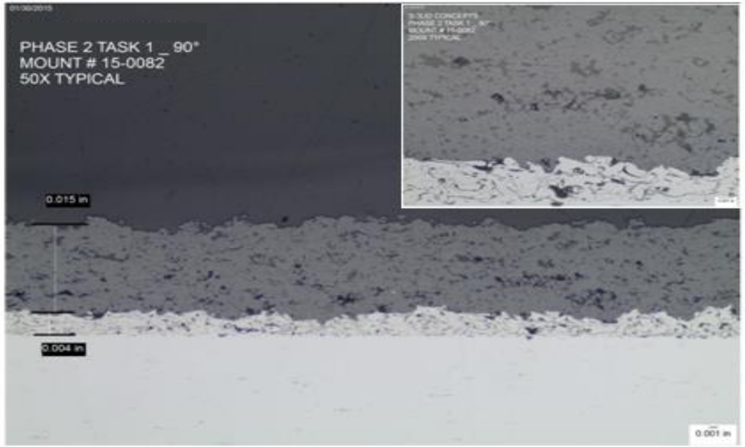
THIN-FILM COOLING

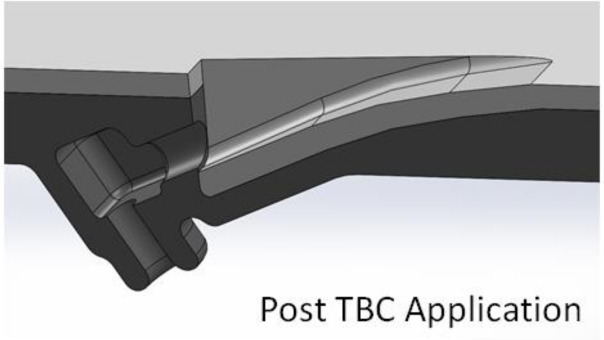
- Phase II SBIR
- Manufacture advanced combustion liners with shaped film cooling holes for gas turbine engines
- Take advantage of complex internal passages and inlet/outlet geometry without post-machining

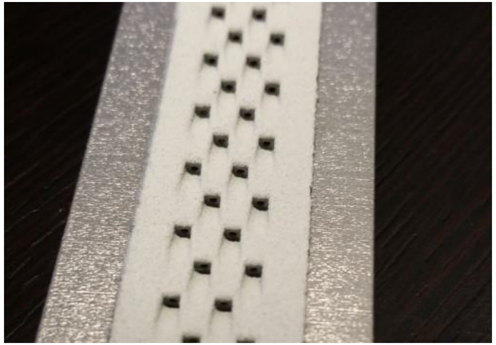


THERMAL BARRIER COATING

- An optimal process was developed with CTS to apply TBC to the effusion hole surfaces
- Successful adhesion and acceptable porosity in TBC layer
- Experimental testing at research institution







CHALLENGES AND FUTURE WORK

LIMITATIONS OF AM FOR HEAT EXCHANGERS

- Process capabilities
  - Wall thickness and feature detail
  - Surface finish
  - Support design and removal
  - Powder removal

- Limited material selection
  - Metals: Various copper and aluminum alloys
  - Plastics: Still under development

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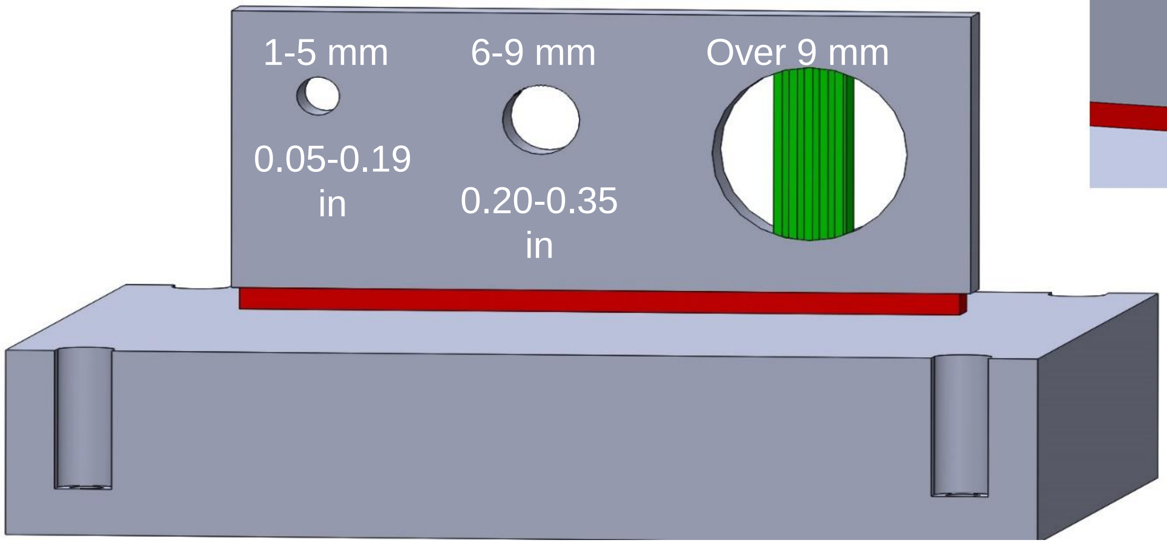
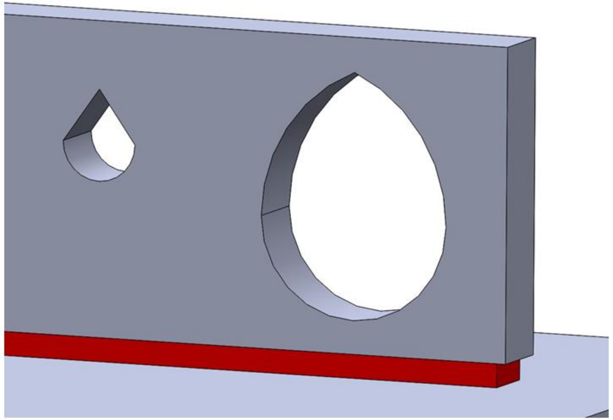
DESIGN CONSIDERATIONS: HORIZONTAL HOLES





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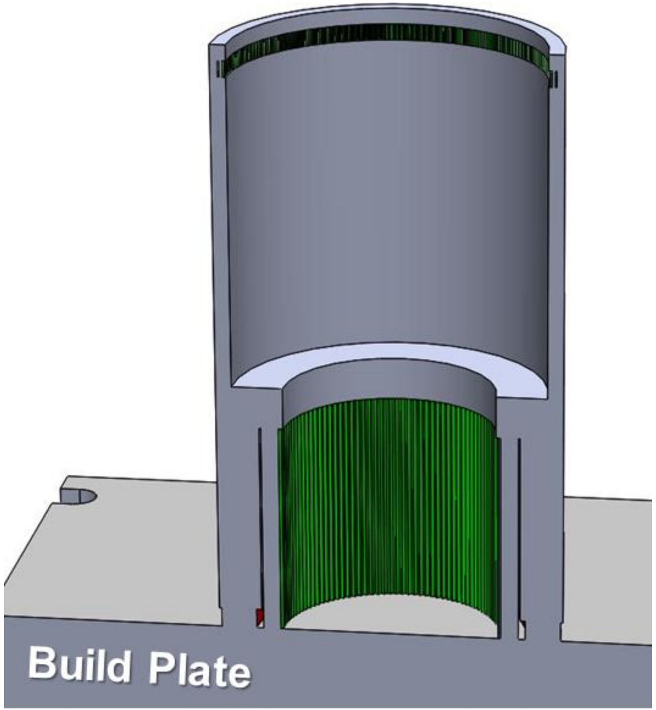
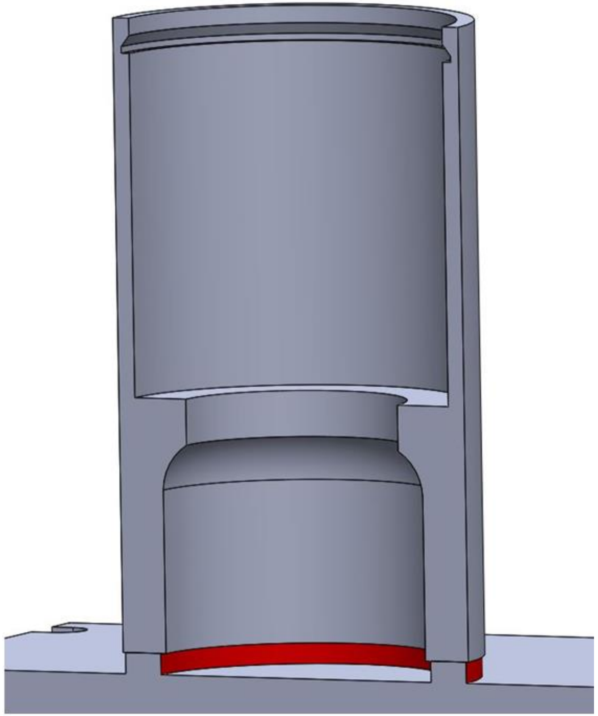
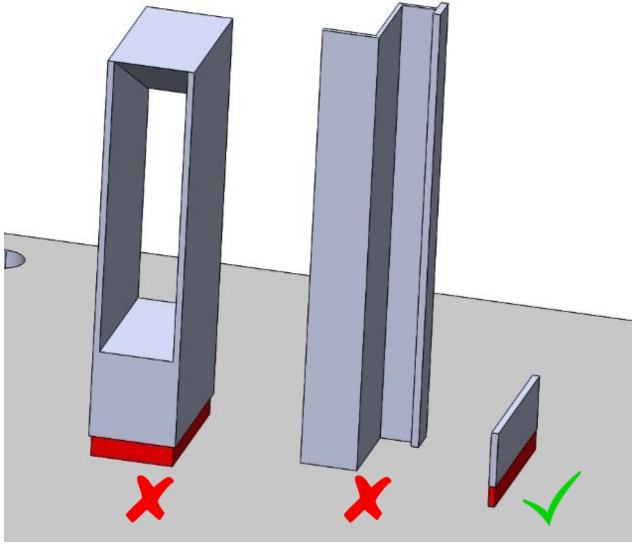
DESIGN CONSIDERATIONS: TRAPPED SUPPORTS





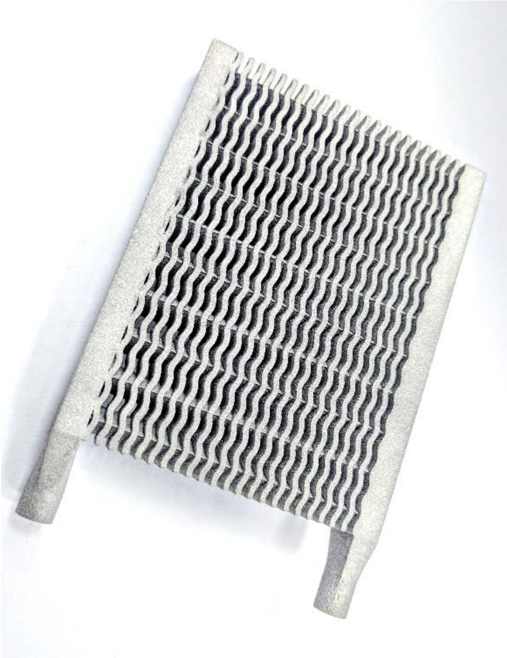
WALL THICKNESS

- Lower limit bounded by laser spot size, ~100 µm or 0.004”
- Practical lower limits are defined by thermal stress
- Geometry and material dependent
- Warpage mitigated by support structure design



MATERIALS

- Current materials: $AlSi_{10}Mg$ and C18150
- Thermal conductivity, specific heat, and mechanical properties similar to wrought
- Material availability driven by industry demand, gas atomizer capacity
- We are actively evaluating further Al and Cu alloy blend
- Further characterization of geometry capabilities on a per-material basis



SUMMARY

- Additive metal manufacturing empowers designers to create the next generation of thermal management systems for improved functionality
- Unparalleled geometric freedom without traditional tooling constraints
- Reduce cost, lead-time, and assembly time
    - Integration of multiple components into efficient, modular, scalable systems
- Maintain digital inventories and iterate quickly

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THANK YOU

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