Metal Additive Manufacturing Myths:

The truth about powder reuse and its effect on mechanical properties

Andrew Carter | Senior Manufacturing Engineer

stratasys
DIRECT MANUFACTURING

stratasys®

30 Years of Additive Applied.

Headquarters:
Eden Prairie, MN
and Rehovot, Israel

Over **1,200**
Granted or
Pending Additive
Manufacturing
Patents Globally

$668 Million
Revenue (2017)

Publicly Traded
On **Nasdaq**
(SSYS)

Over 30
Technology and
Leadership
Awards

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The Power of Additive. Applied.

ABOUT STRATASYS DIRECT MANUFACTURING

Stratasys Direct Manufacturing is one of the largest providers of 3D printing and advanced manufacturing services.

- 7 U.S. manufacturing facilities
- 9 Manufacturing technologies
- 500+ employees
- Certifications: ISO 9001, AS9100
- ITAR registered





MANUFACTURING FACILITIES

- Valencia, CA
- Poway, CA
- Tucson, AZ
- Phoenix, AZ
- Eden Prairie, MN
- Austin, TX
- Belton, TX

OUR TEAM

Our experienced team of project and applications engineers are committed to your success with:

- Design support for advanced manufacturing
- Technical direction and recommendations
- Material, technology and build optimization for quality, speed and affordability

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TECHNOLOGIES

ADDITIVE

SL

POLYJET

LS

DMLS

FDM

MJF

CONVENTIONAL

CNC

URETHANE CASTING

INJECTION MOLDING

SECTION TWO

Additive Metal Production

ADDITIVE METAL CAPACITY

- 2 Facilities (Austin, TX & Belton, TX)
- 17 DMLS MACHINES
    - 11 EOS M280'S
    - 4 EOS M290's
    - 1 EOS M400
    - *1 EOS M400-4*
- 2 Fully supported Machine Shops
- Dedicated Quality Lab
    - Cutup Metallography
    - Flow Bench, Hydrostatic Tester
    - CMM

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ADDITIVE ALLOYS

Current Offering

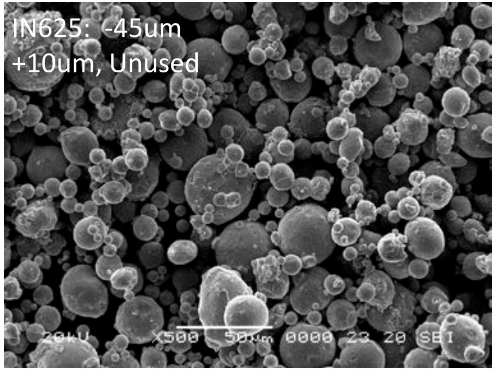
SS 17-4 PH*
SS316L
AlSi10Mg
Ti 6-4 Gd5*
CoCr
INCONEL™ 625*
INCONEL™ 718* (API-Std avail.)
MONEL™ K500

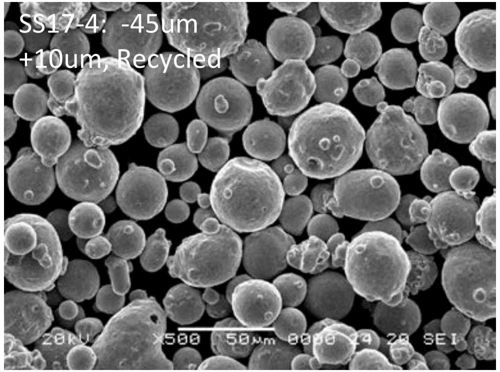
Powder chemistry ordered to meet respective AMS standards.

Standard Text = Performance Super Alloys

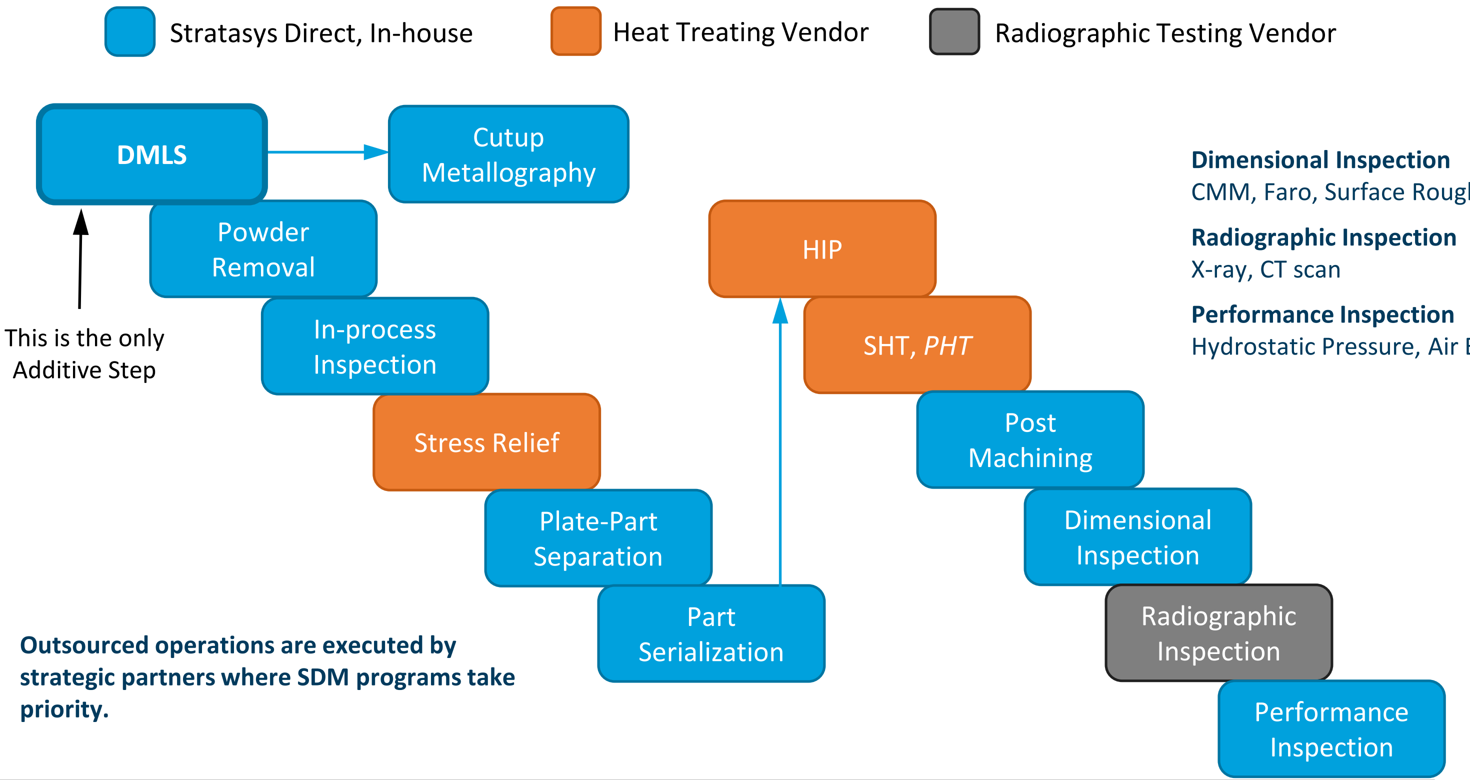
Bold Text = Quick Turn Alloys

Sourced directly from multiple established atomizers.





ADDITIVE MANUFACTURING IS MOSTLY CONVENTIONAL



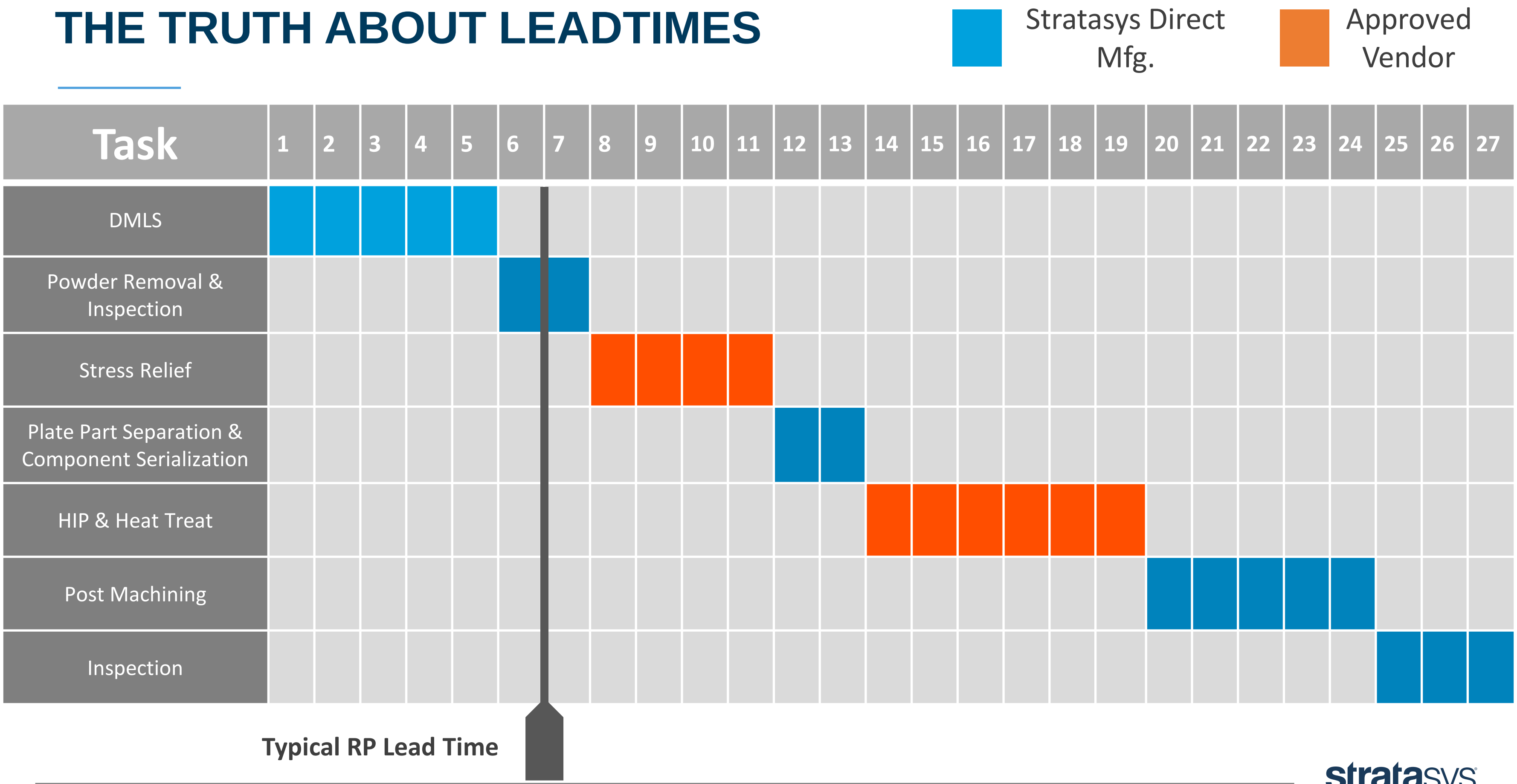
Dimensional Inspection
CMM, Faro, Surface Roughness

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.

THE TRUTH ABOUT LEADTIMES



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SECTION TWO

The truth of powder recycling - “its happening”

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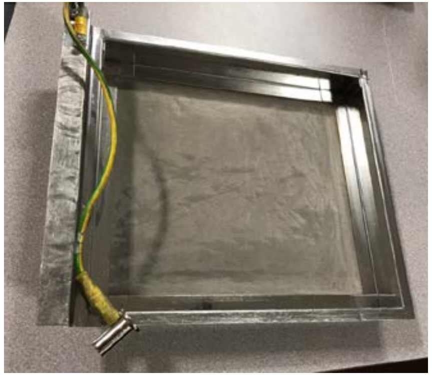
Powder handling is an after thought… (by the machine manufacturers')

Here is how its being done by the OEM's …

EOS Recommended method M280-M290

+



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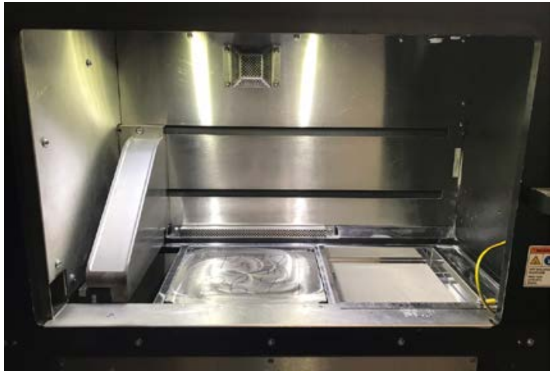

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Powder handling is an after thought… (by the OEM's)

Here is how its being done by the OEM's …

EOS Recommended method M400's

Powder handling is … EM’s)

Here is how its being don…

EOS Recommended meth…

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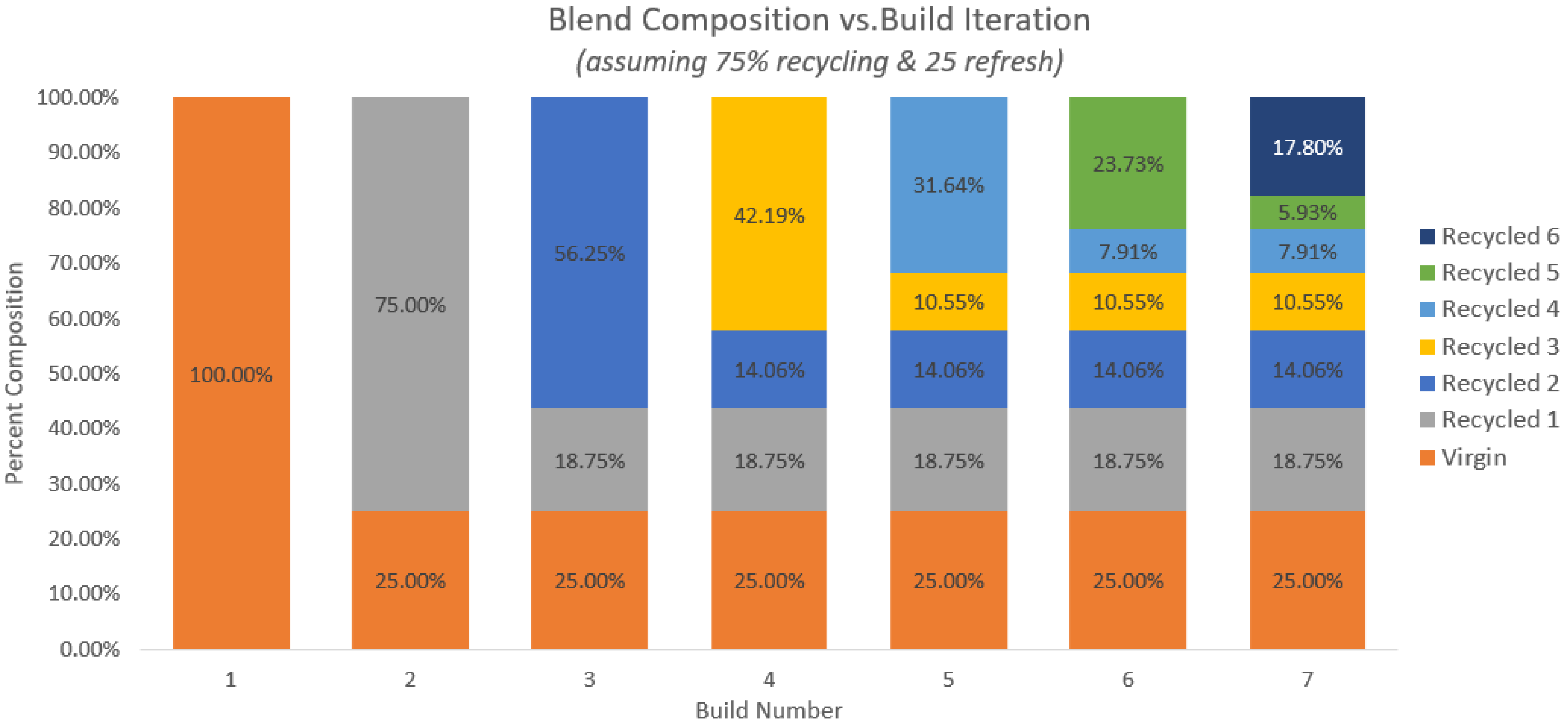
Powder handling is an after thought… (by the OEM's)

Machine Manufacturer	Powder Handling
Additive Industries	Internal
AddUp	Mixed
GE (Concept Laser)	External
3D Systems	Internal & External
EOS	External
Rennishaw	Internal
SLM Solutions	Mixed
Trumphf	External
Velo3D	Internal

No equipment manufacturer is concerned with **material traceability**.

MANUFACTURING SCENARIO



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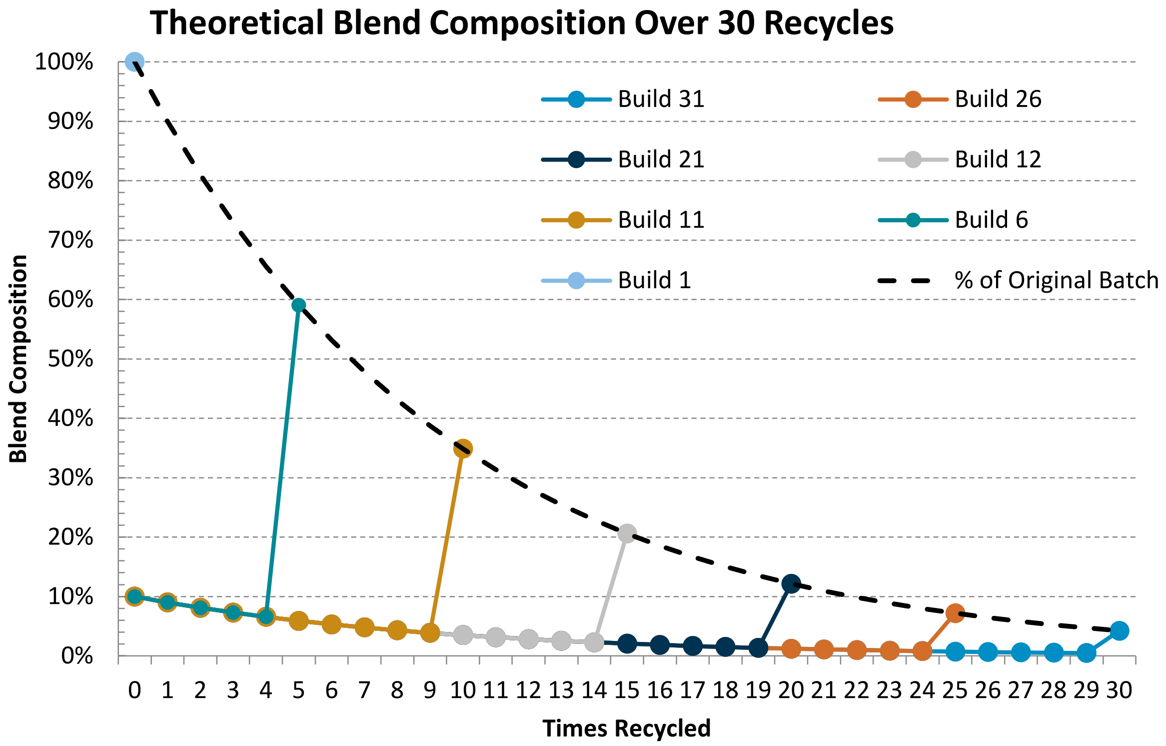
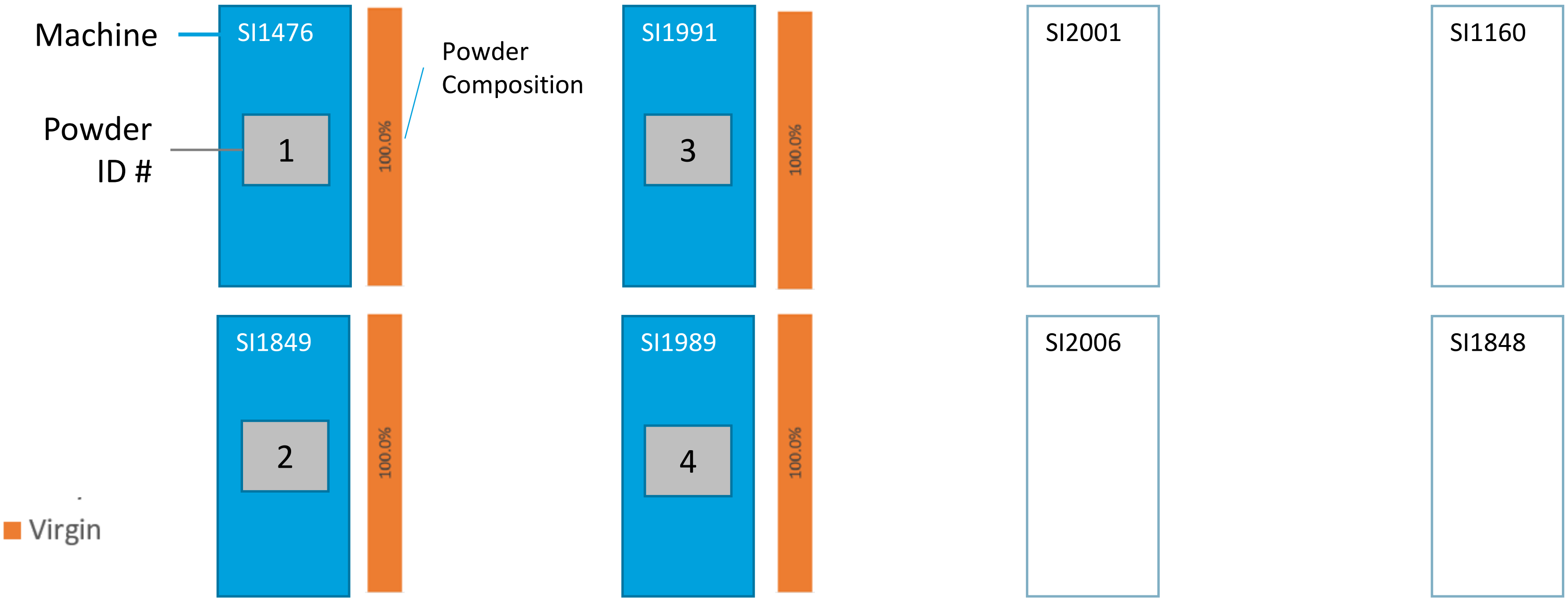
MANUFACTURING SCENARIO



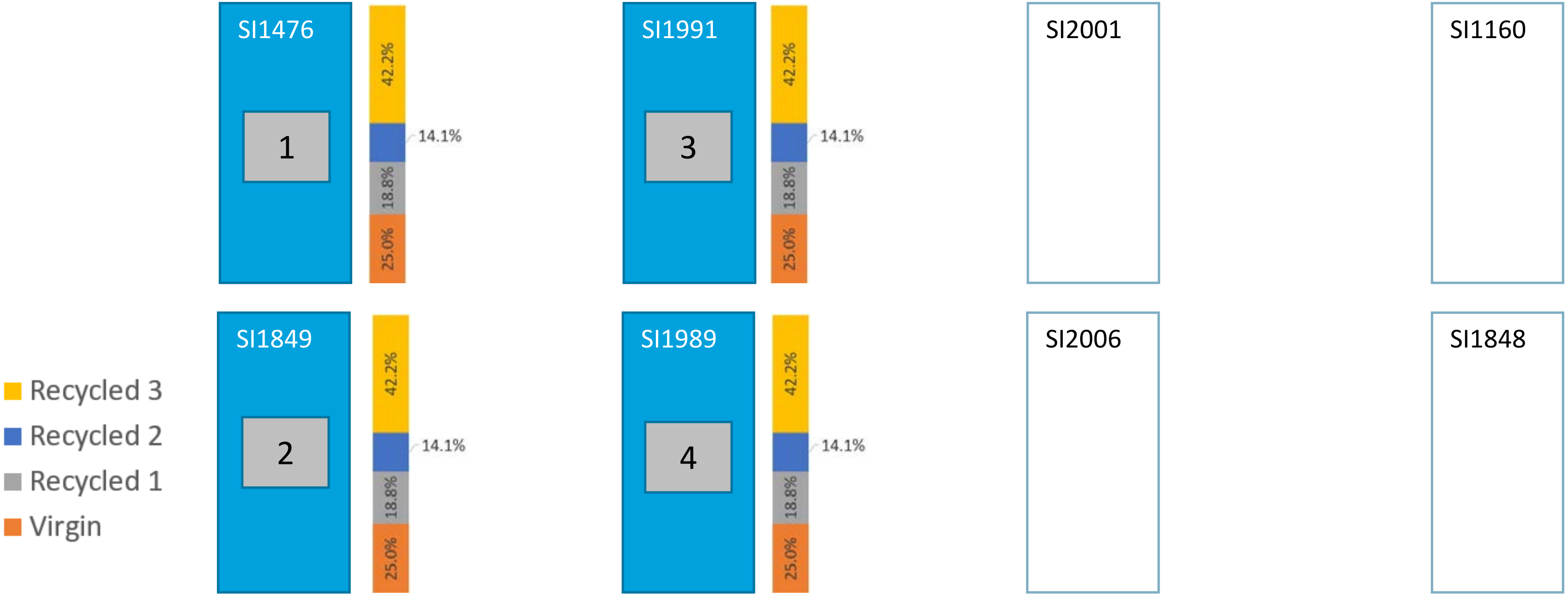
- SDM Recycles 100% material
- The majority of powder has been recycled.
- No test method is identified to *qualify* recycled powder

POWDER DOES NOT ALWAYS STAY IN THE SAME MACHINE



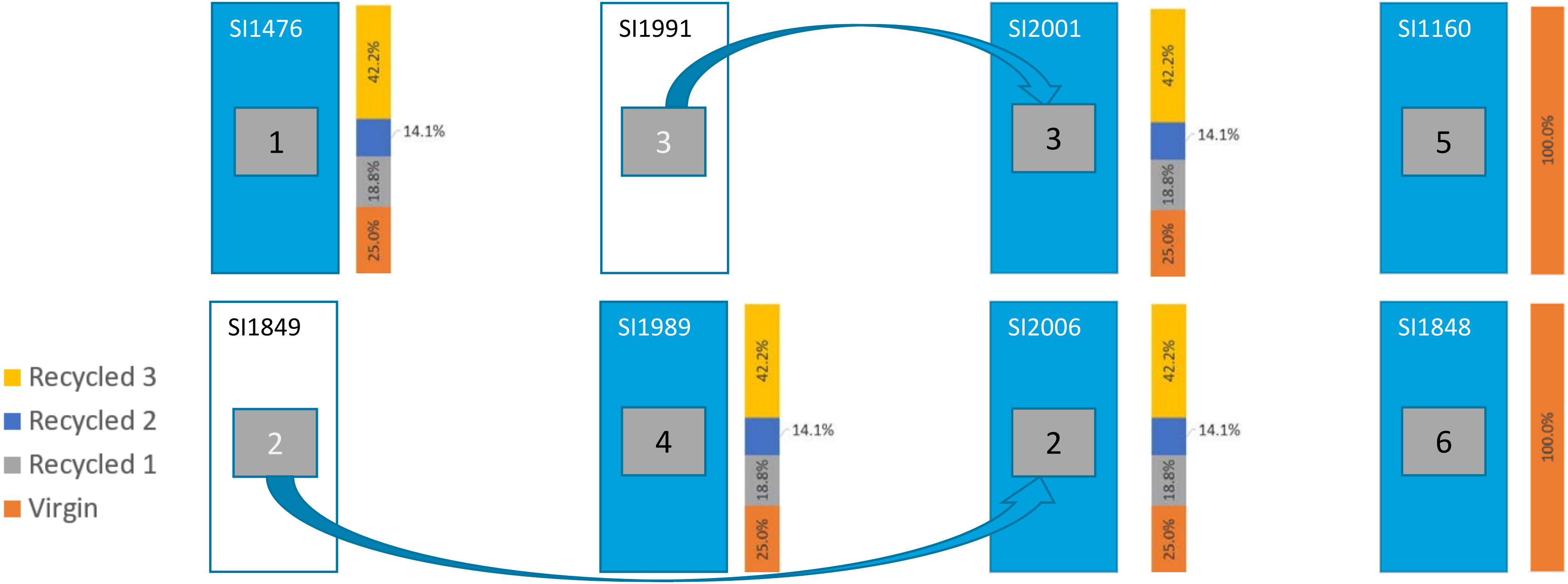
Start Production – 4 machines producing product, 4 powder evolution ID #’s

POWDER DOES NOT ALWAYS STAY IN THE SAME MACHINE



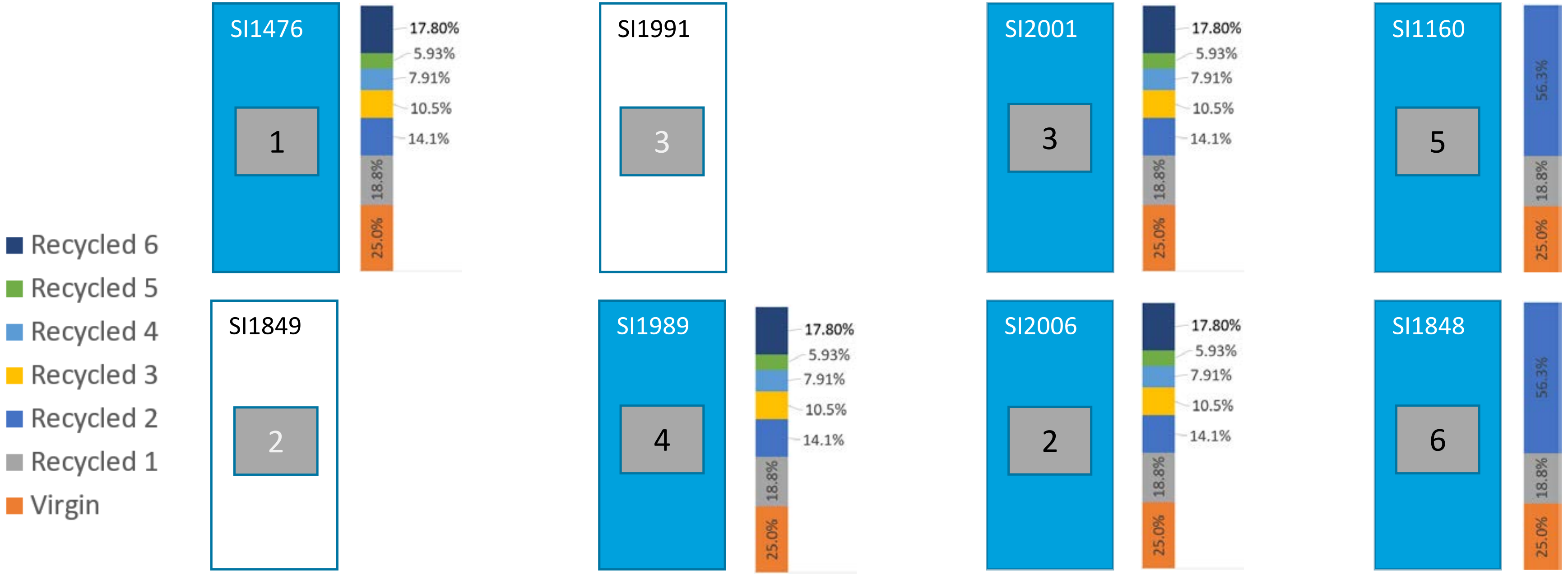
Start Production – execute 4 builds and refresh with virgin each time

POWDER DOES NOT ALWAYS STAY IN THE SAME MACHINE



Unplanned Maintenance & Increase customer demand – 6 machines producing product, swapped material between two machines, 6 powder evolution ID numbers.

POWDER DOES NOT ALWAYS STAY IN THE SAME MACHINE

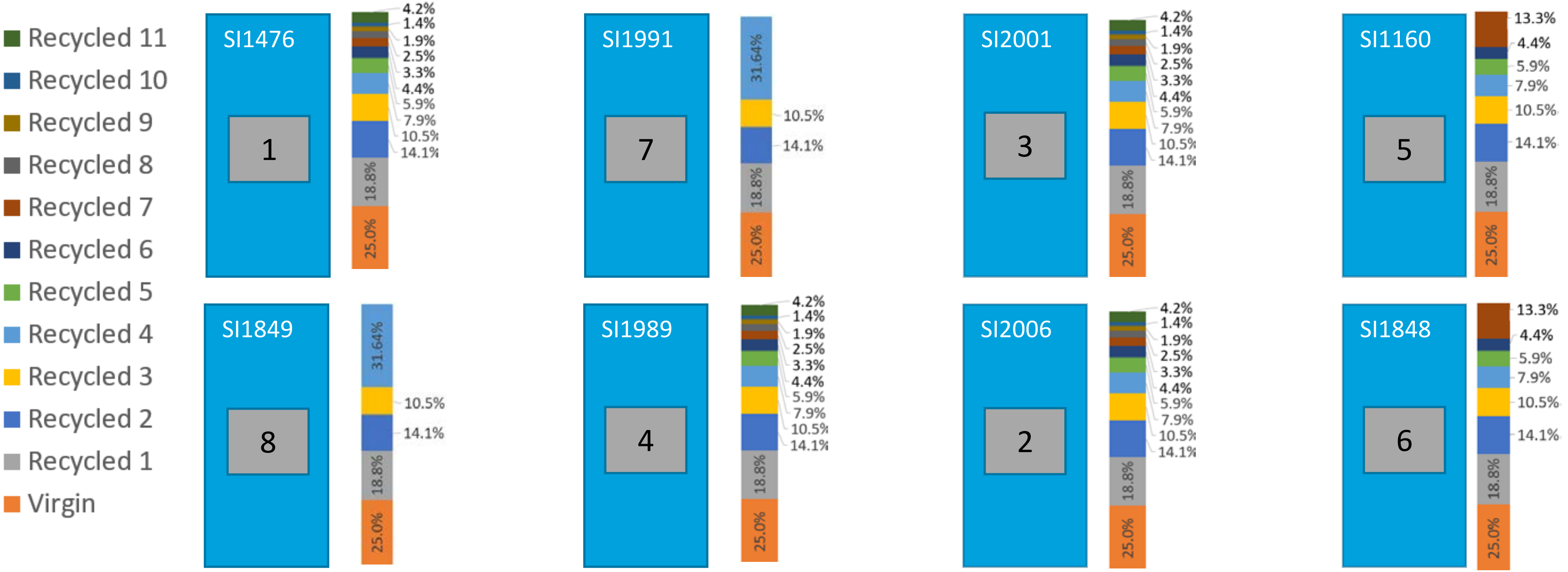


Unplanned Maintenance & Increase customer demand – execute 3 builds on all machines

POWDER DOES NOT ALWAYS STAY IN THE SAME MACHINE

Full Production – All machine capacity dedicated to producing product, 8 powder evolution ID numbers

POWDER DOES NOT ALWAYS STAY IN THE SAME MACHINE

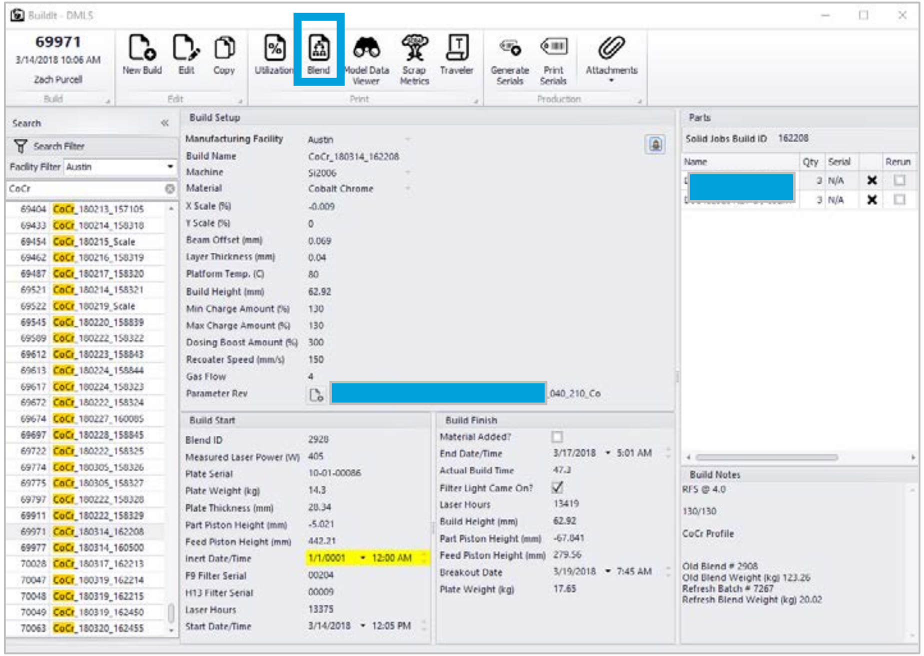


Full Production – execute 5 more builds across all machines

MATERIAL RECYCLING STATION

Sometimes simplicity is best.

MATERIAL TRACEABLITY



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MATERIAL BLEND REPORT

Build Date: 3/14/2018
Build Number: 69971
Blend Number: 2928
Material: Cobalt Chrome
Total Weight (kg): 143.28

PO Number	Virgin Lot Number	Percent	Used Count
29500	Prax CoCr Lot 21	13.97%	1
29500	Prax CoCr Lot 21	12.33%	2
29500	Prax CoCr Lot 21	10.26%	4
29500	Prax CoCr Lot 21	14.09%	5
29500	Prax CoCr Lot 19	47.00%	5
29500	Prax CoCr Lot 20	2.34%	5

MECHANICAL DATA – STRATASYS DIRECT MFG HAS IT

IN625

Blends were kept to a single system.

CoCr

Blends were transferred between systems to meet production demands.

IN718

Virgin material compared material from different lots and different machines.

Elevated Temperature Tensile Results IN718 & IN625

Sampled from multiple machines at varying levels of reuse.

Additive IN625 Property Study

Study: 7 EOS M280 Machines, 2 Material Providers, 8 Material Lots, >55 Builds per Data represents 385 production builds over an 8 month period.

Testing Included: 210 tensile bars (tests performed approx. every 4 builds), 14 Chemical, 20 Metallography

Data Analysis: All data submitted to Battelle

Comparisons:

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

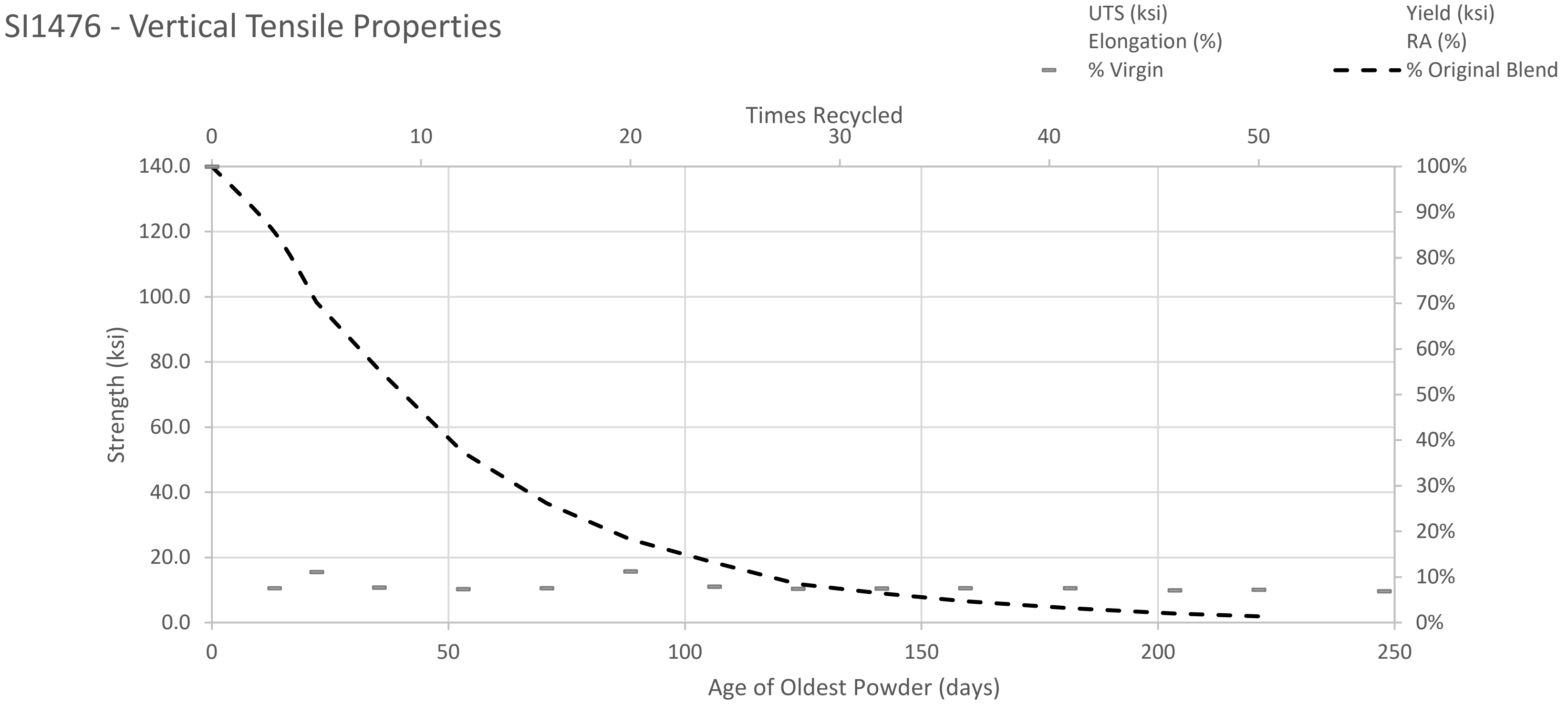
AMS 7000:

- ✓ Process Control Document (PCD)
- ✓ Class B - Material Chemistry and PSD

Mechanical Testing:

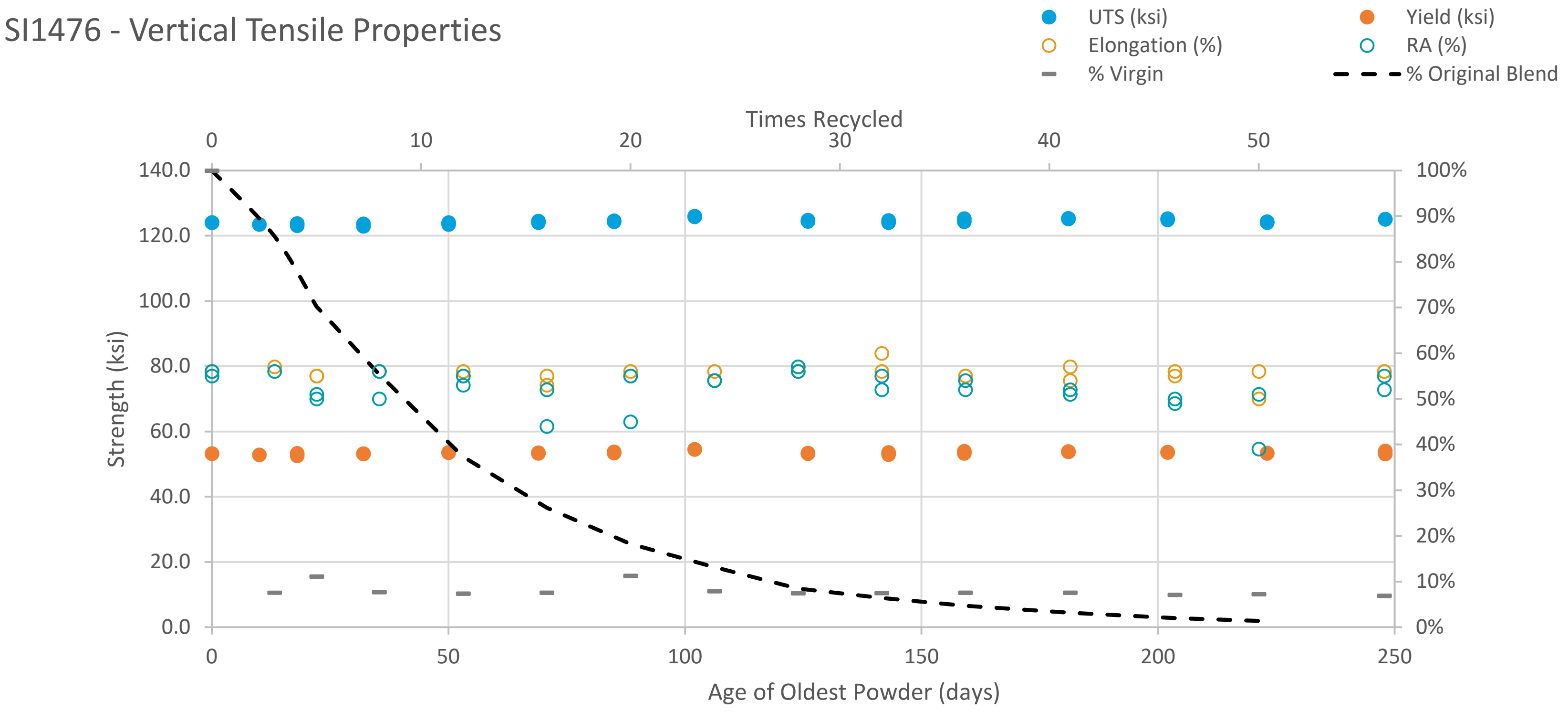
- ✓ Nadcap & A2LA Accredited Test House

POWDER EVOLUTION / LIFE CYCLE



IN625 | CoCr | IN718 | High Temp

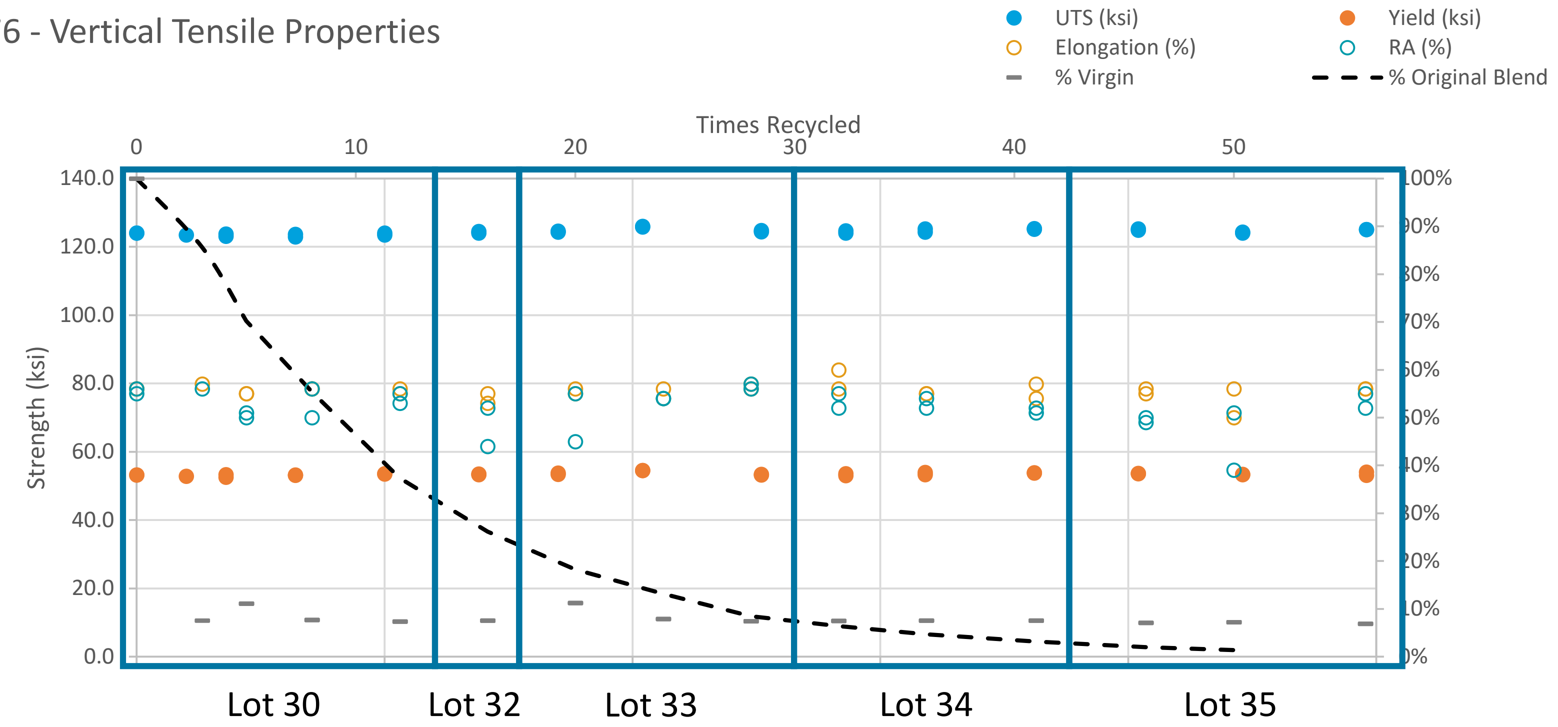
TENSILE PROPERTIES OVERLAID ONTO POWDER COMPOSITION



IN625 CoCr IN718 High Temp

INTRODUCTION OF SEPARATE POWDER LOTS

SI1476 - Vertical Tensile Properties



IN625 CoCr IN718 High Temp

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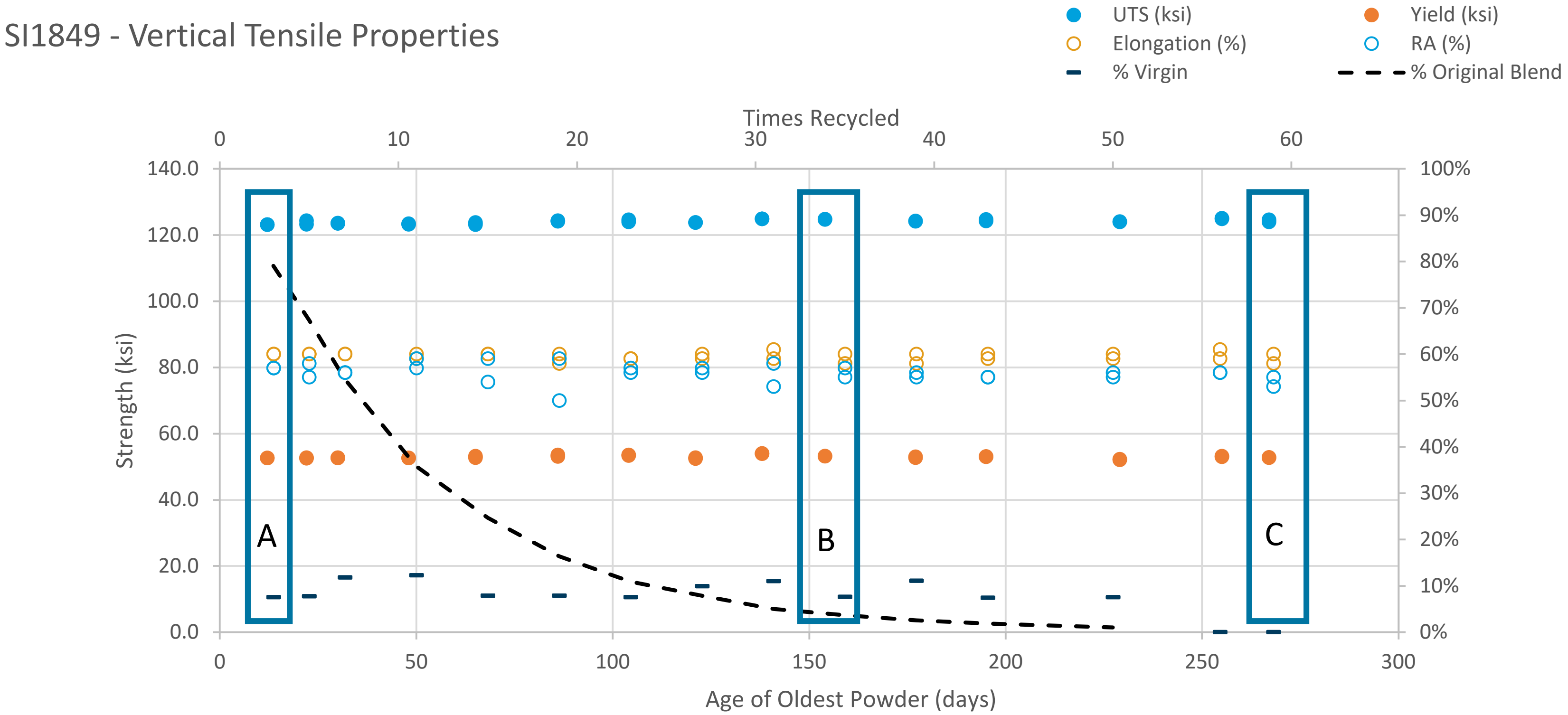
MICROSTRUCTURE OVER TIME



IN625 | CoCr | IN718 | High Temp

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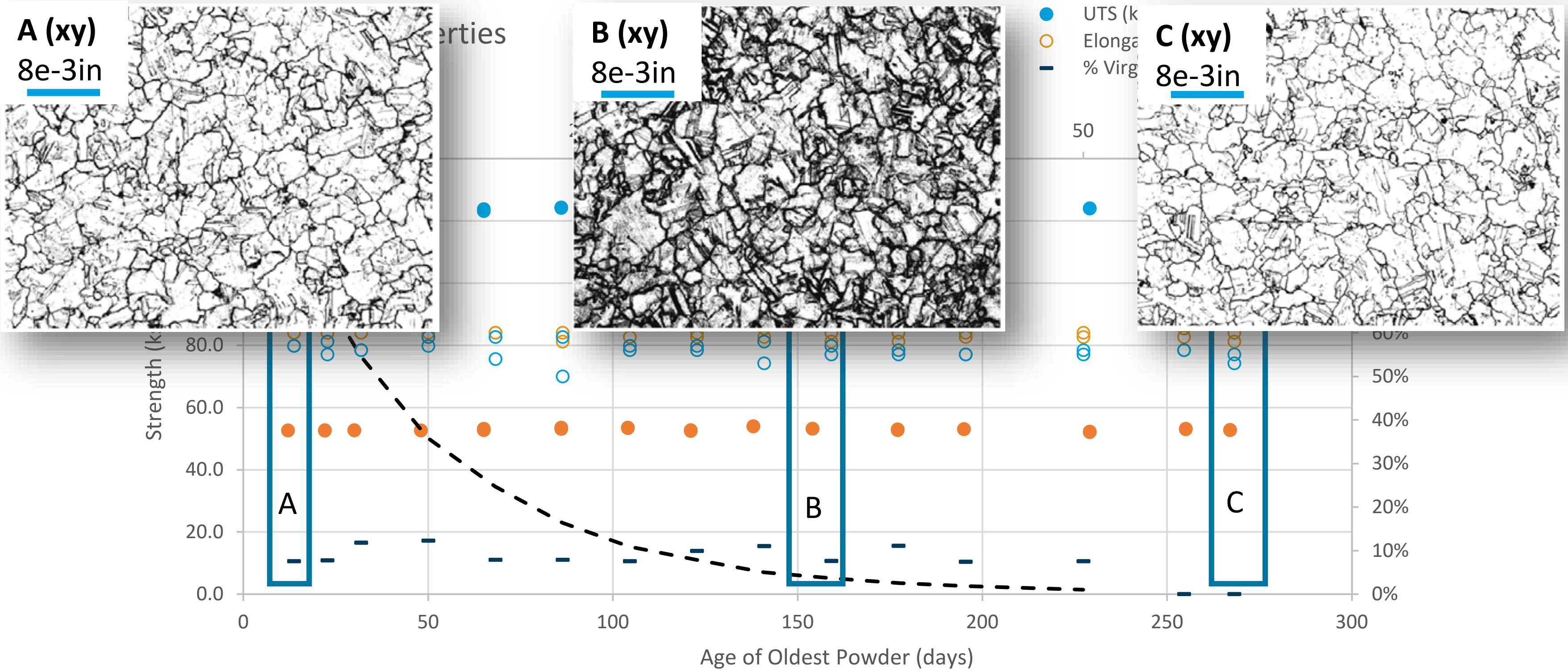

IN625 | CoCr | IN718 | High Temp

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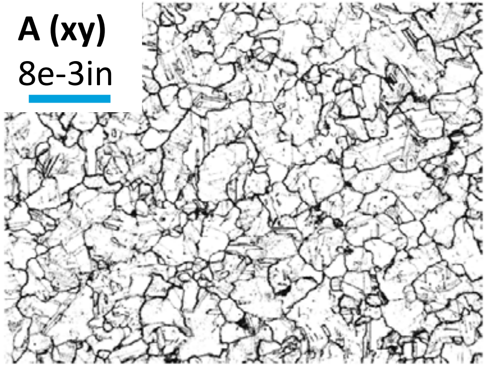
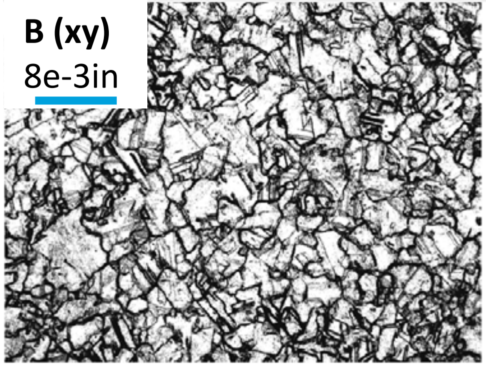
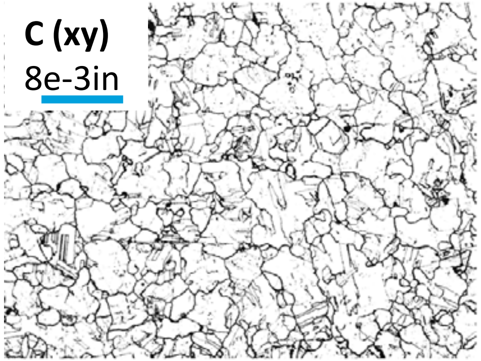
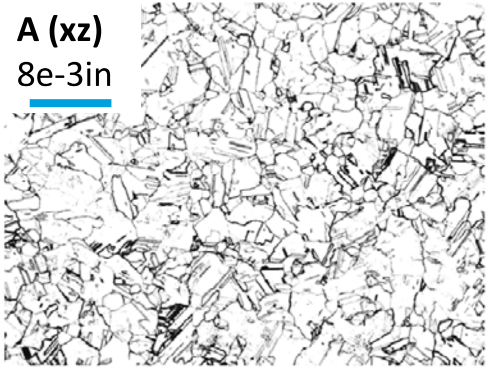
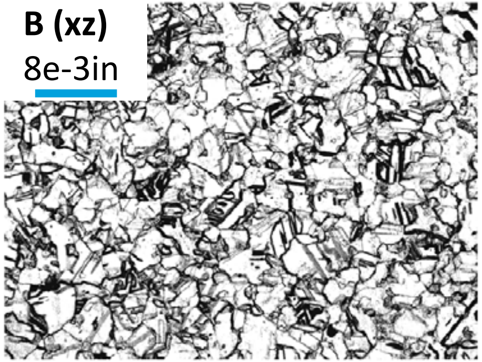
MICROSTRUCTURE – DIFFERENT ORIENTATIONS

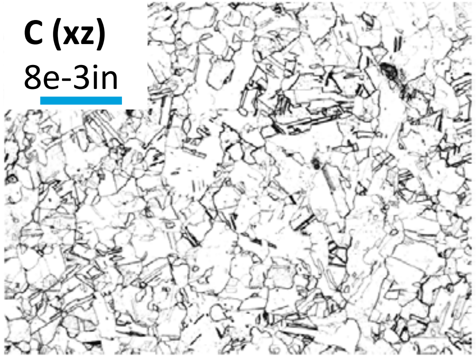




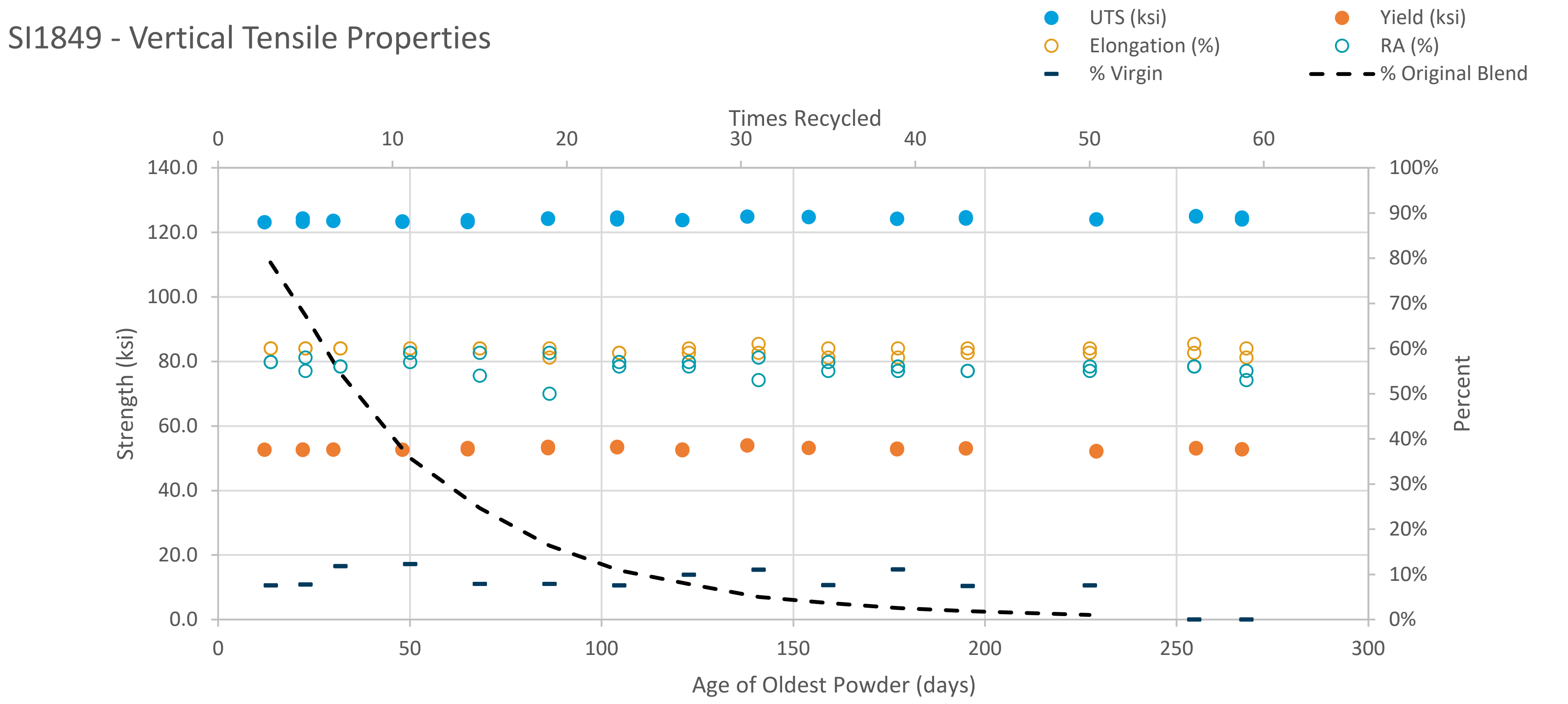








MATERIAL CHEMISTRY OVER TIME



IN625 | CoCr | IN718 | High Temp

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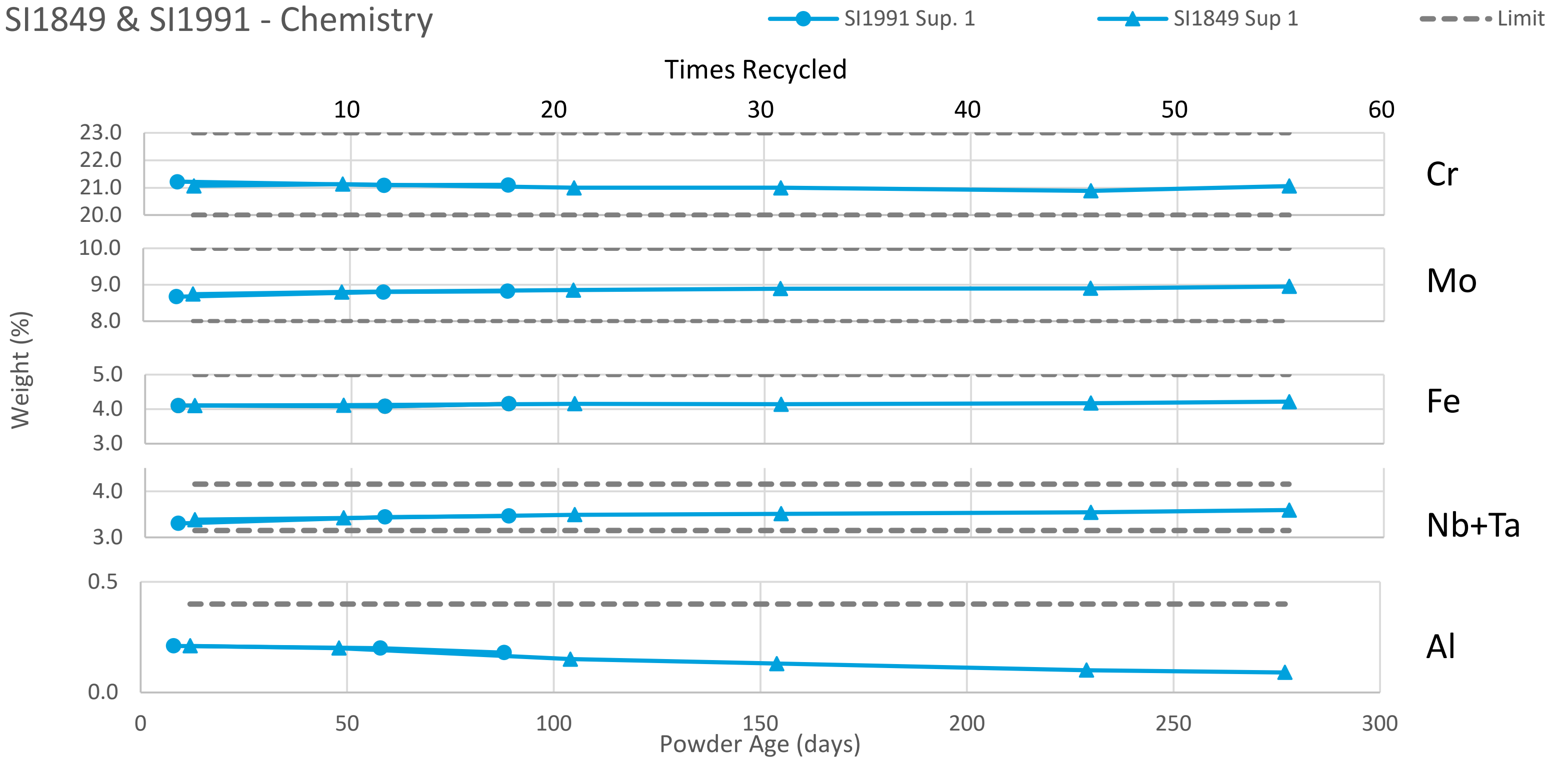
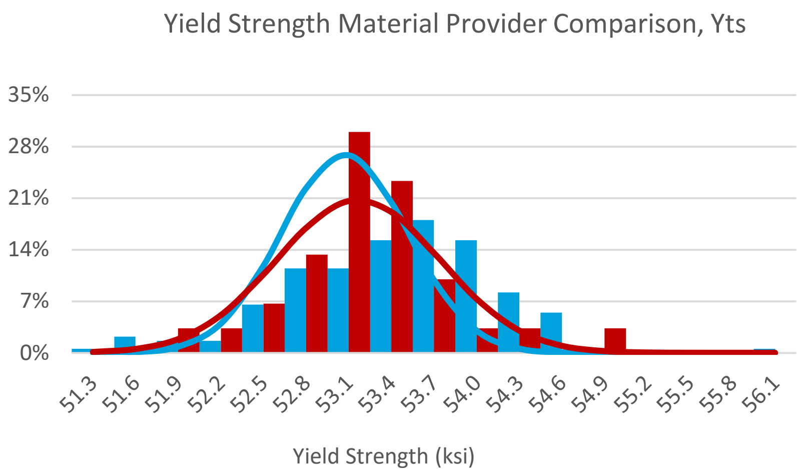
MATERIAL CHEMISTRY OVER TIME

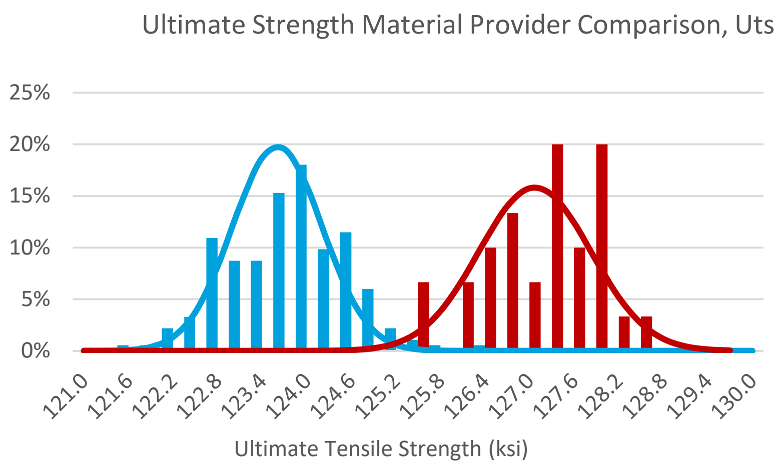


IN625 | CoCr | IN718 | High Temp

MATERIAL PROVIDER COMPARISON



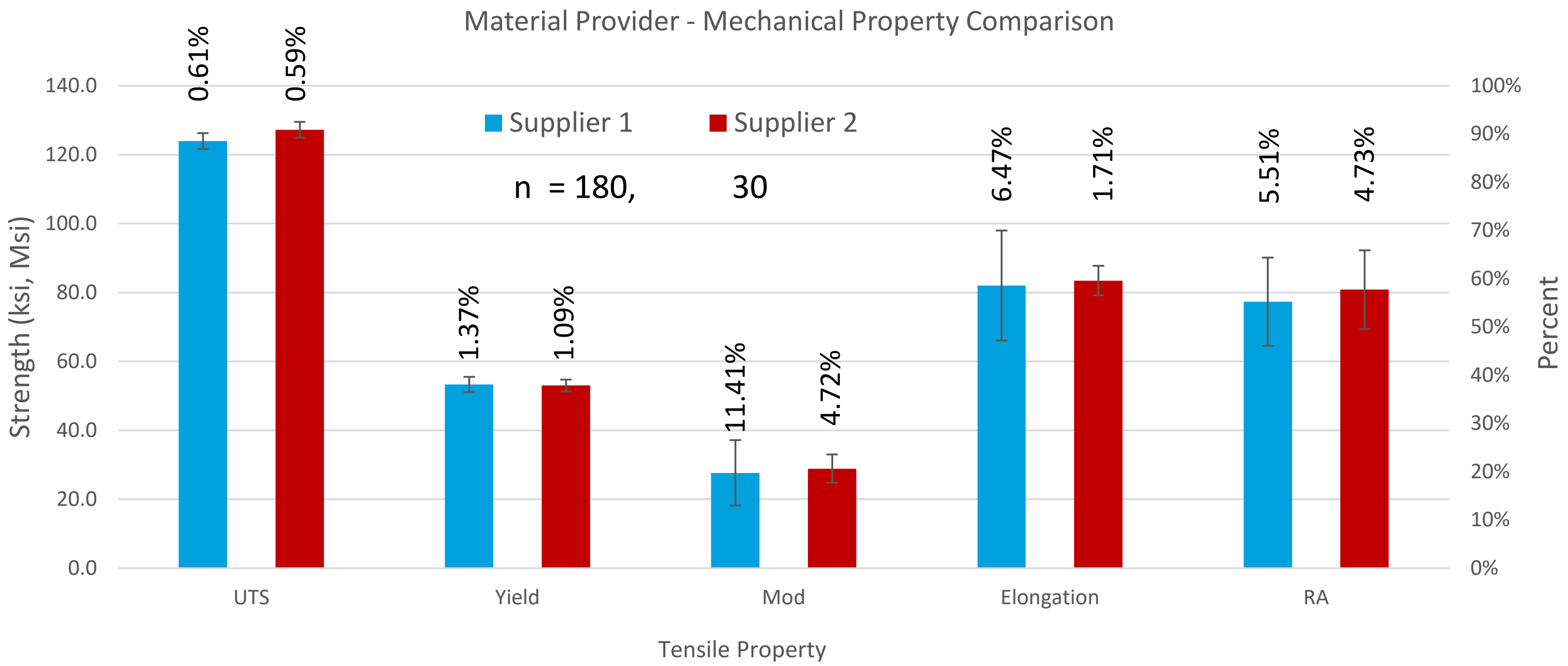
Provider 1 YTS, *Avg* = 53.3ksi σ = 0.769ksi
Provider 2 YTS, *Avg* = 53.0ksi σ = 0.756ksi



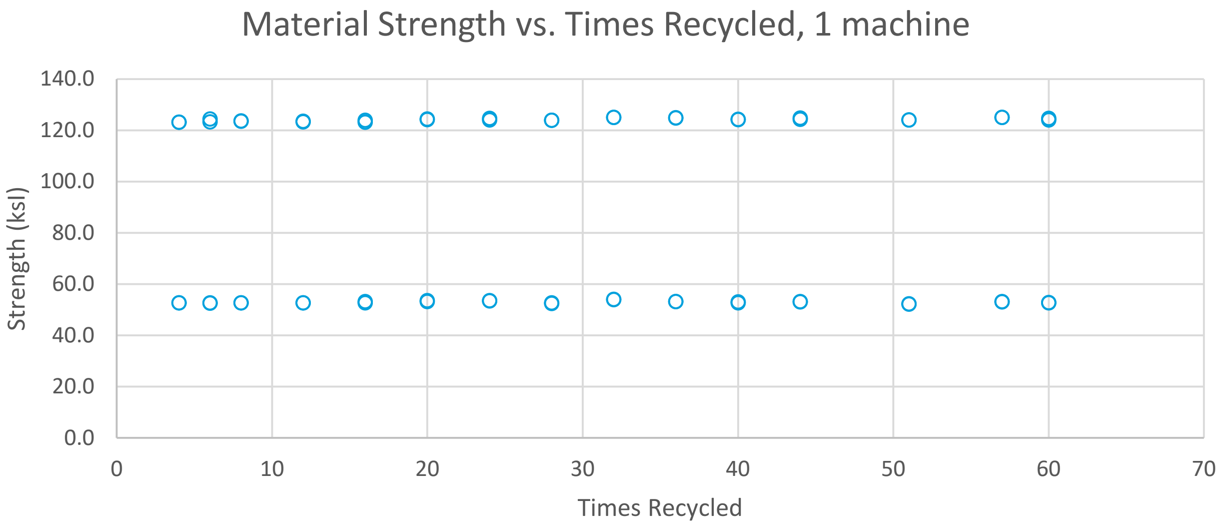
Provider 1 UTS, Avg = 124.0ksi σ = 0.731ksi
Provider 2 UTS, Avg = 127.2ksi σ = 0.577ksi

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

MATERIAL PROVIDER COMPARISON



Machine to Machine Consistency



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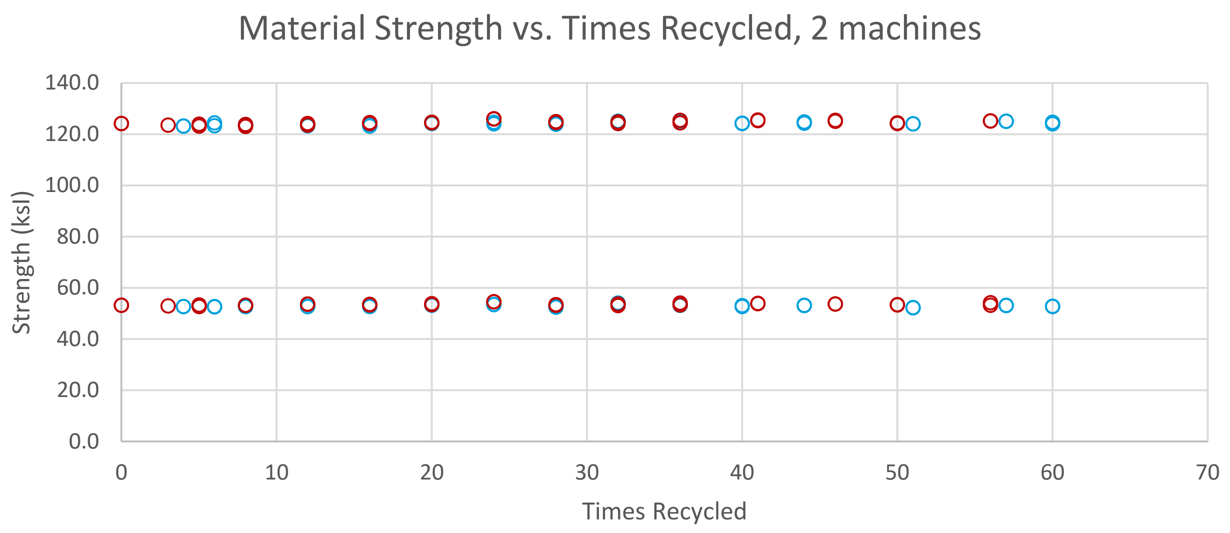
Machine to Machine Consistency



IN625 CoCr IN718 High Temp

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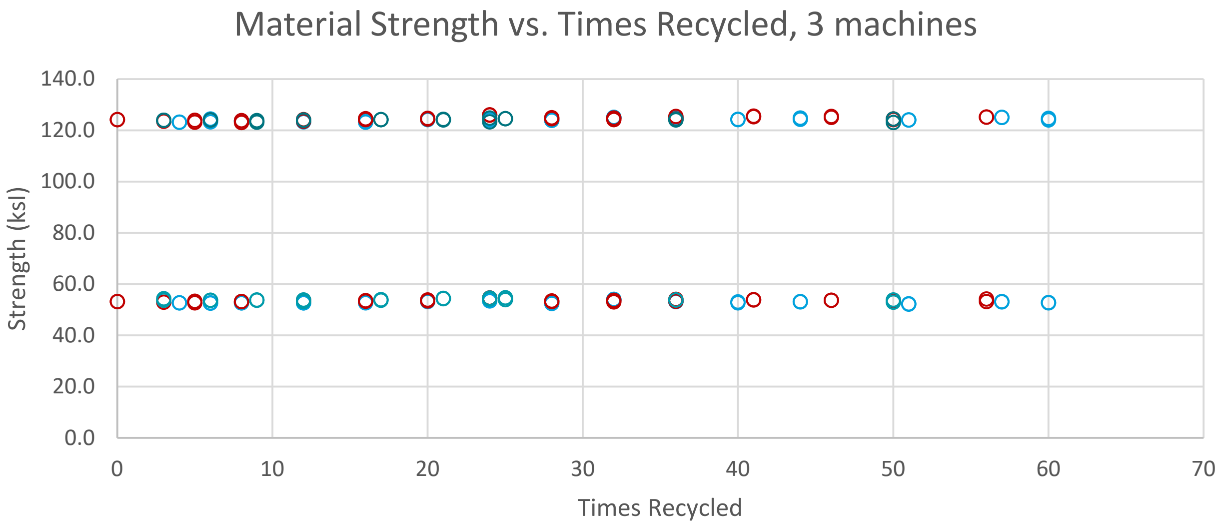

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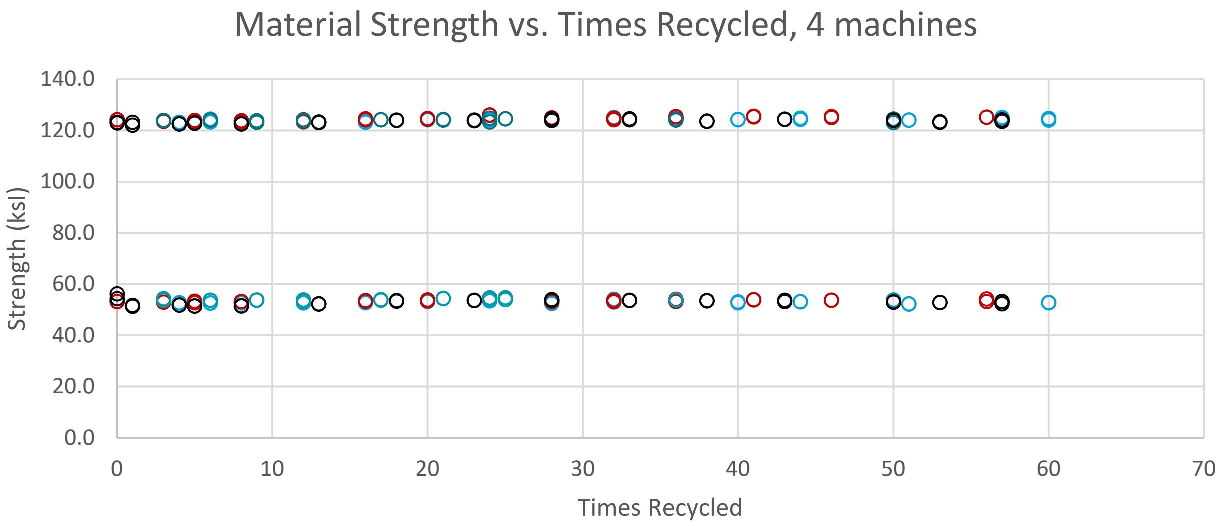

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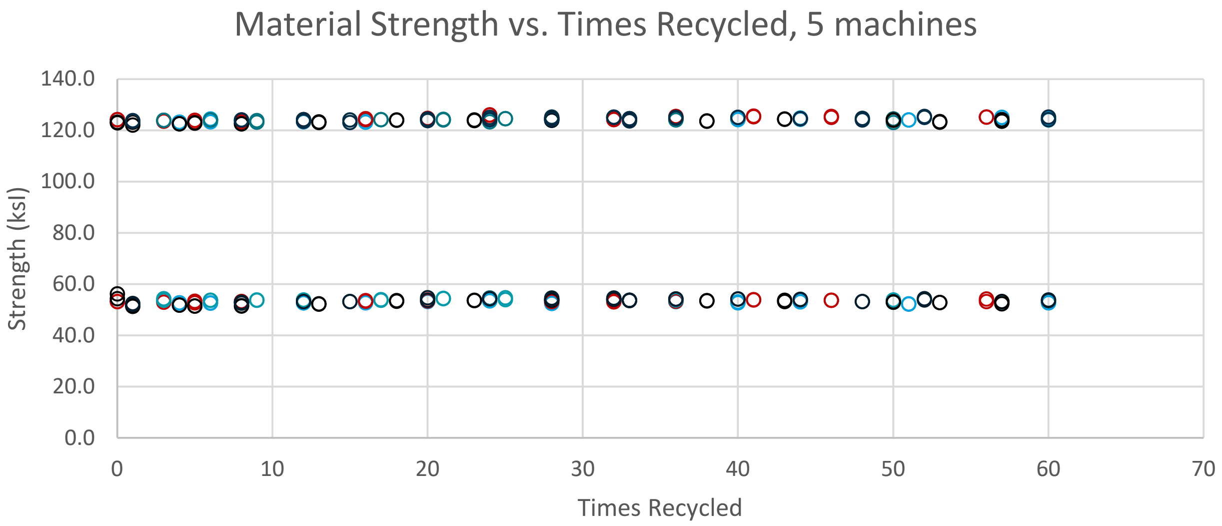

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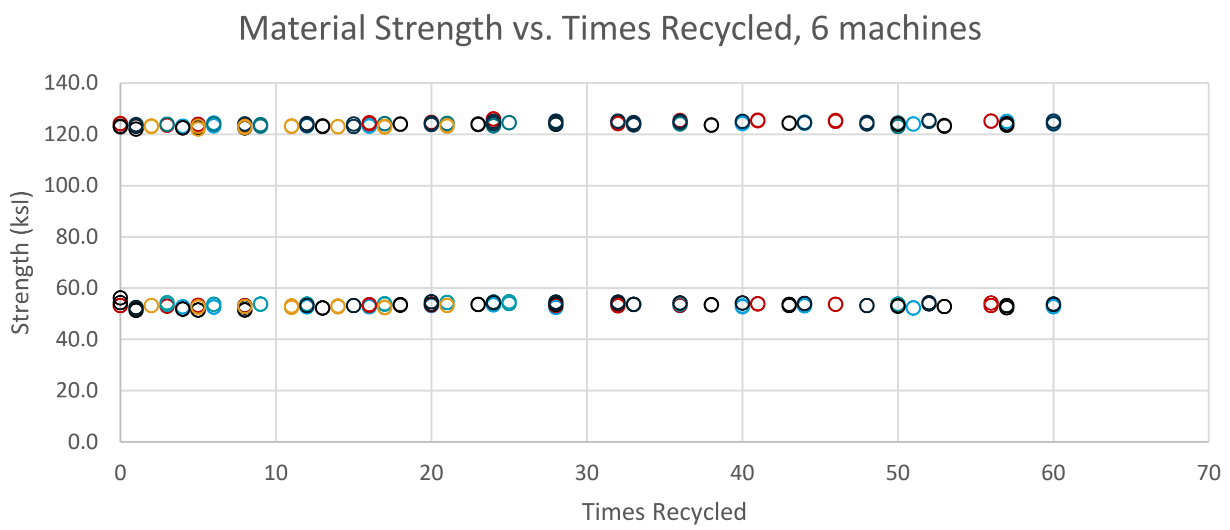

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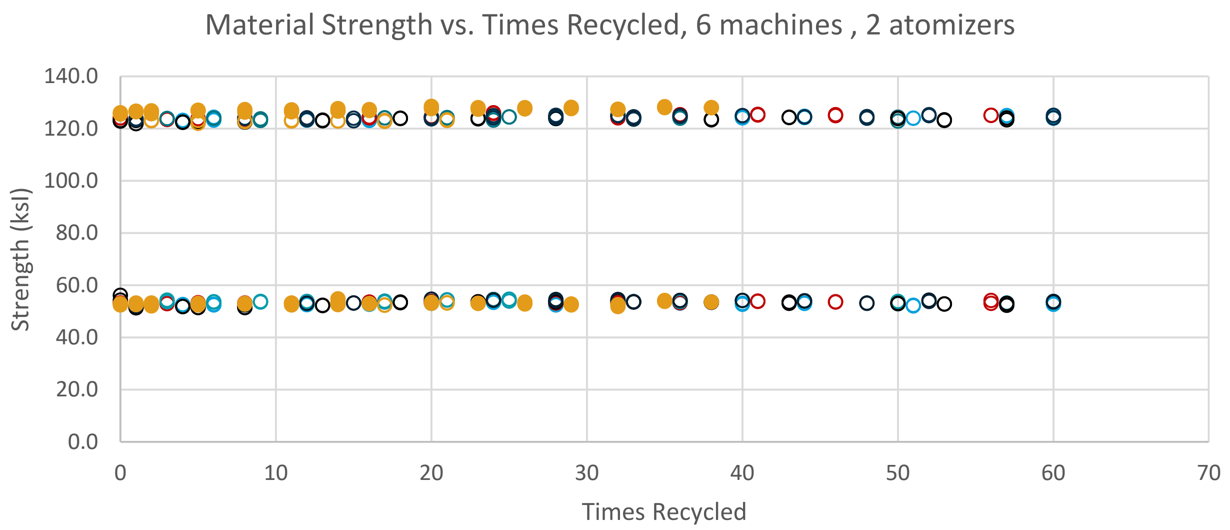


IN625 | CoCr | IN718 | High Temp

MATERIAL PROVIDER COMPARISON

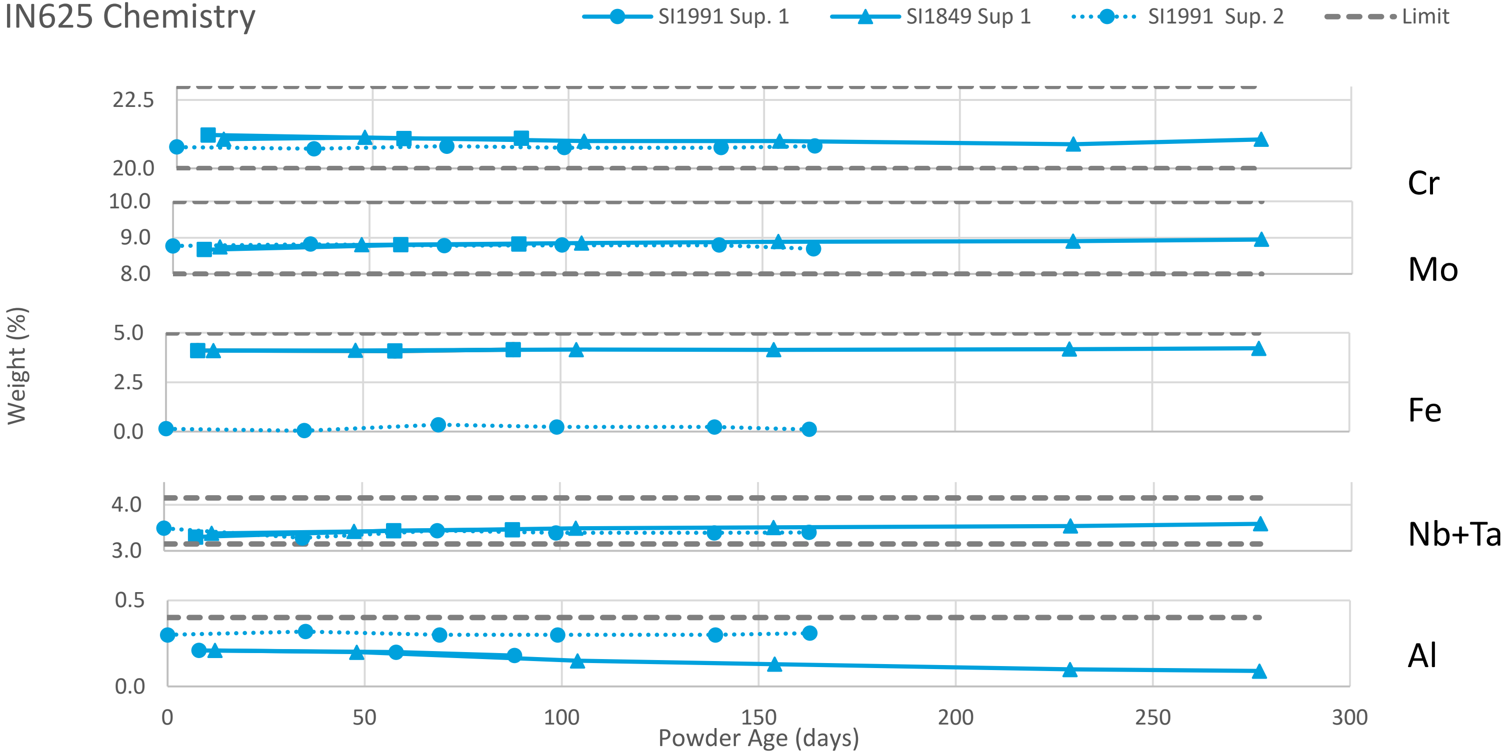
The **different chemistries** produced by different suppliers produced statistically different ultimate tensile strength.

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**

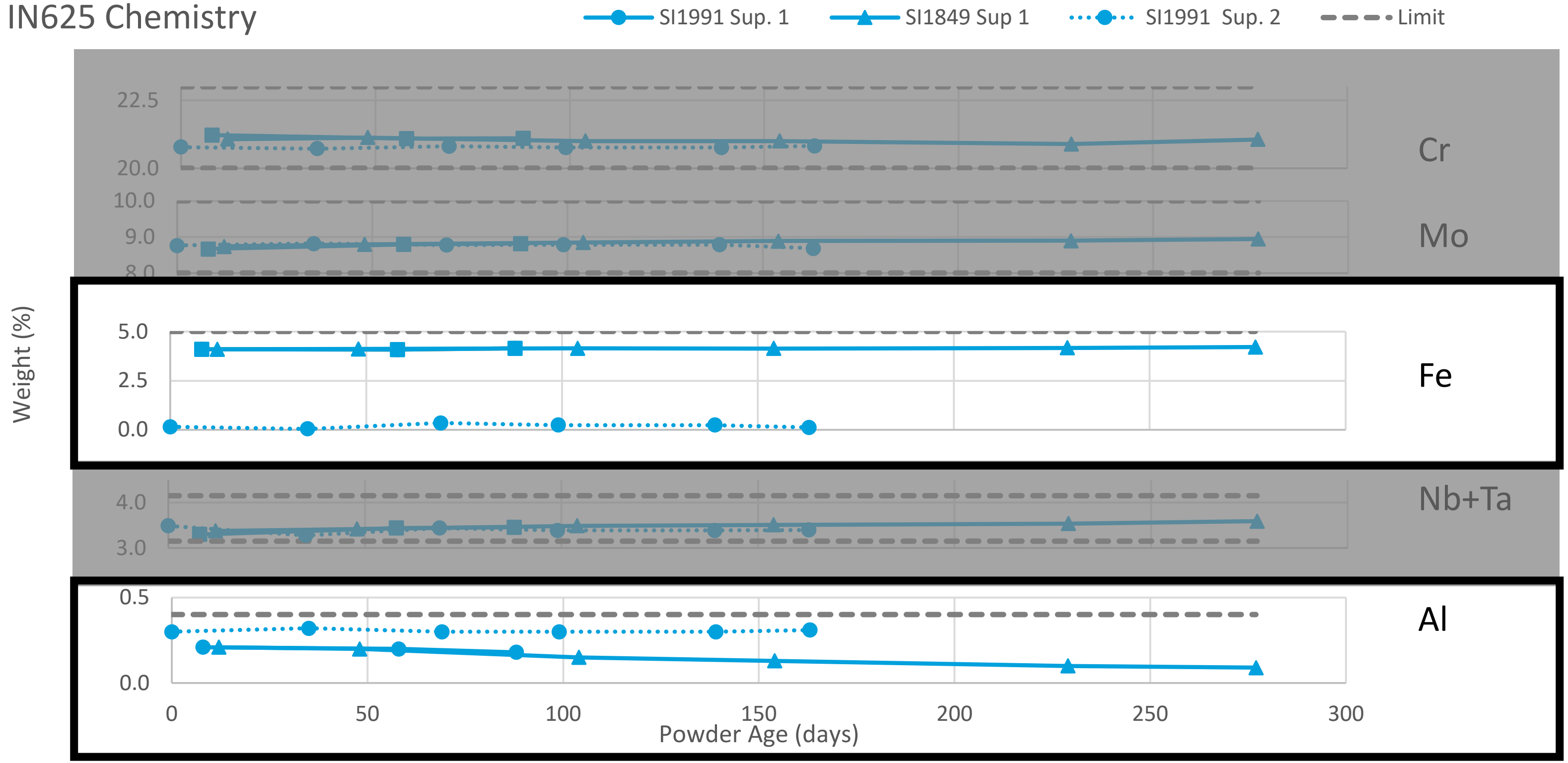
MATERIAL PROVIDER COMPARISON

IN625 Chemistry



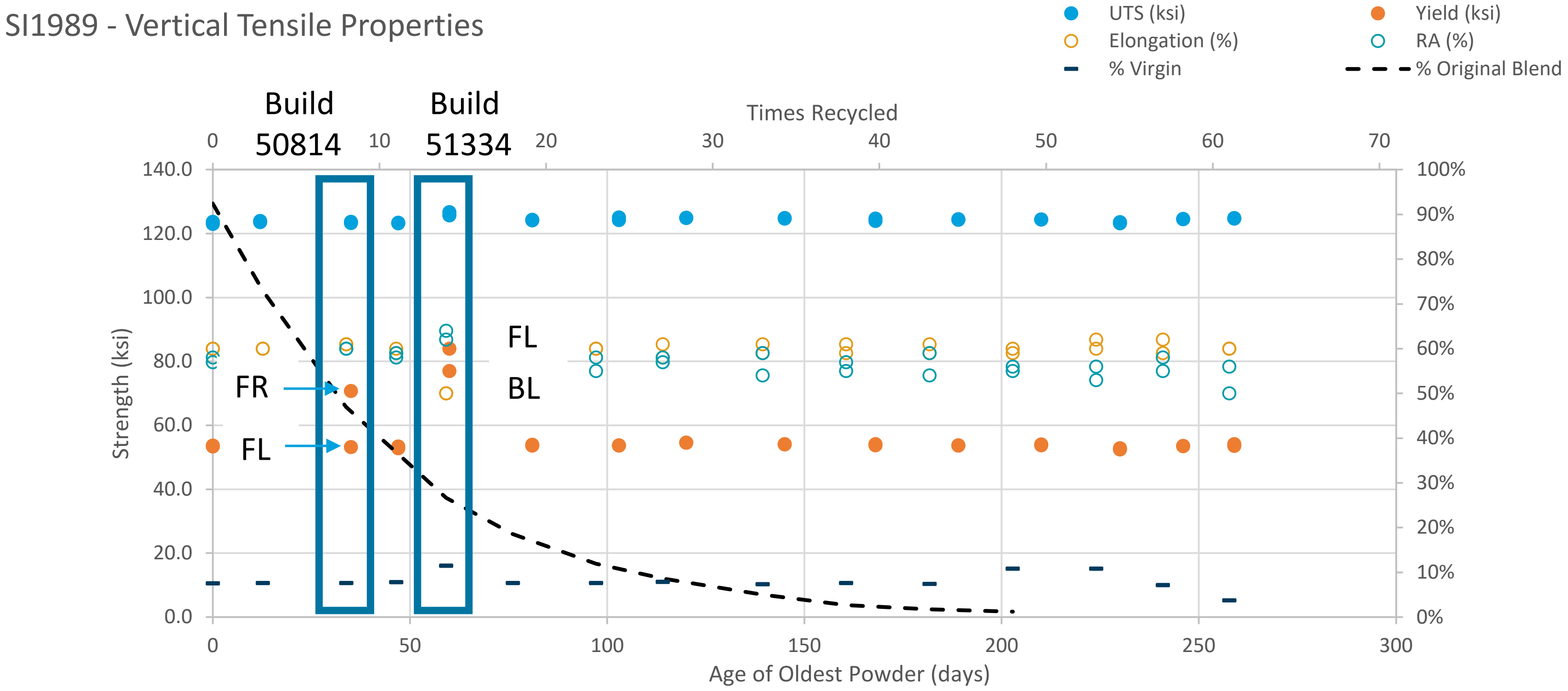
MATERIAL PROVIDER COMPARISON

IN625 Chemistry



IN625 | CoCr | IN718 | High Temp

OUT OF THE 220 BARS, 2 APPEARED “DIFFERENT”



IN625 | CoCr | IN718 | High Temp

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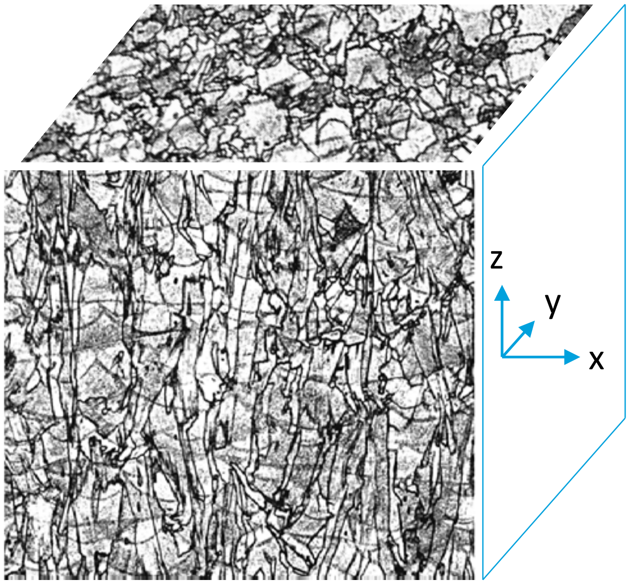
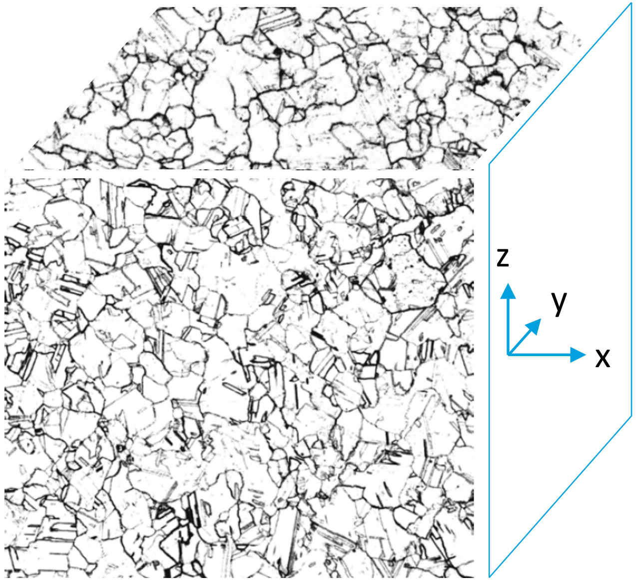
METALLOGRAPIC COMPARISON, BUILDS 51334 & 54747



Stress Relieved, Additive IN625 (100x)



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

CONCLUSION – ADDITIVE IN625

Stratasys Direct Manufacturing'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:

- An efficient and economic powder management process
- Increased confidence in DMLS material/part quality
- Increased customer confidence
- Insight into powder lifecycle
- Evidence process variation at the additive system level is reduced via certified heat treatments

Additive CoCr Property Study

90 room temperature tensile blanks from:

- 2 material provides
- 6 different machines
- 51 bars sampled before corrective action (17 builds)
- 39 bars sampled after the corrective action (39 builds)
- >50 times recycled

MANUFACTURING STUDY SAMPLING

90 room temperature tensile blanks from:

- 2 material provides
- 6 different machines
- 51 bars sampled before corrective action *(17 builds)*
- 39 bars sampled after the corrective action *(39 builds)*
- 6 different powder evolutions

Powder Evolution Num.	Machine	Before or After Corrective Action
8	SI1476	Before
9	SI1991	Before
10	SI1849	Before
	SI1476	After
12	SI1849	Before
	SI2006	After
14	SI1848	After
15	SI1991	After

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STUDY OUTCOMES

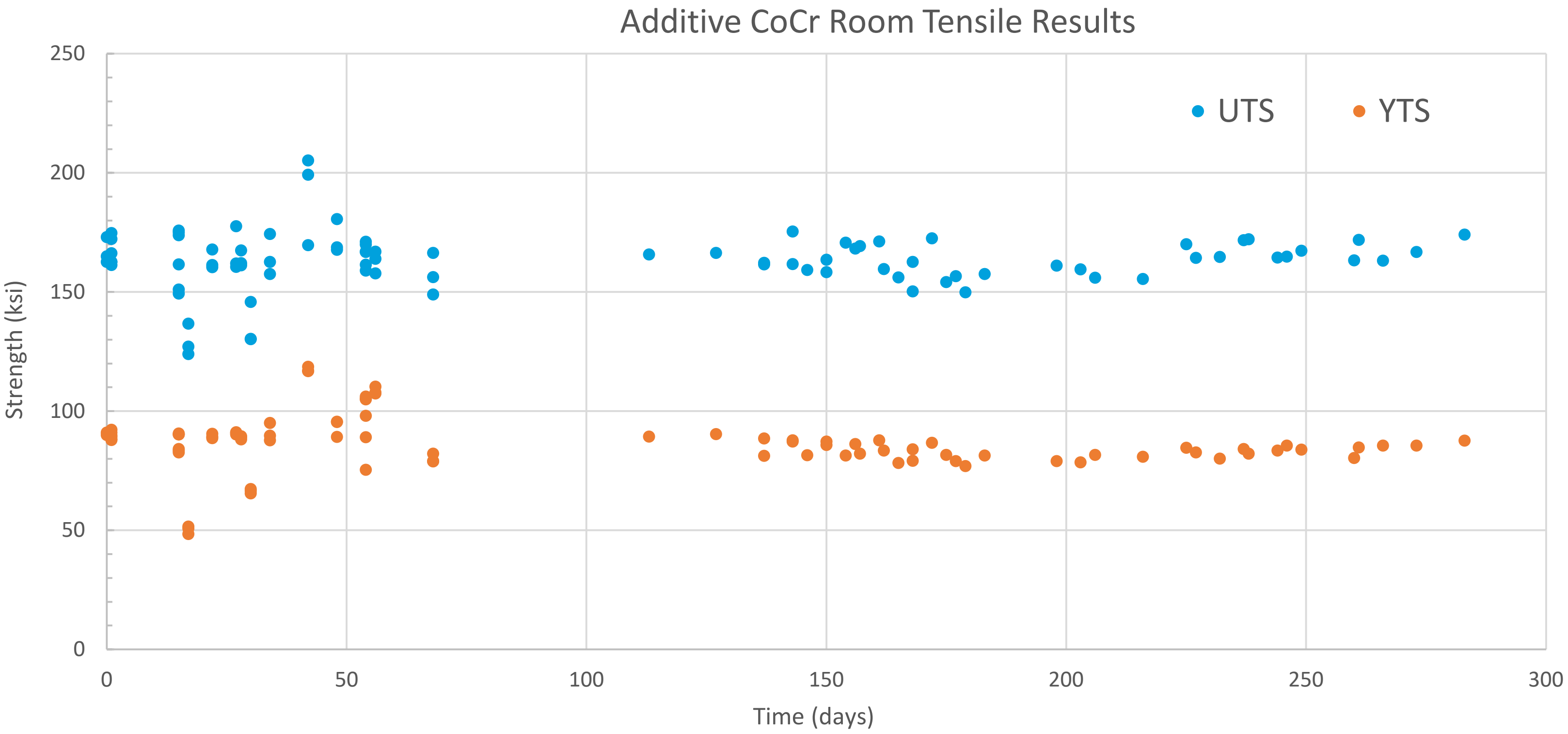
COMPARISONS:

- Before and after the corrective action
- Machine to Machine
- Material Provider
- Material Blend Composition (times recycled)

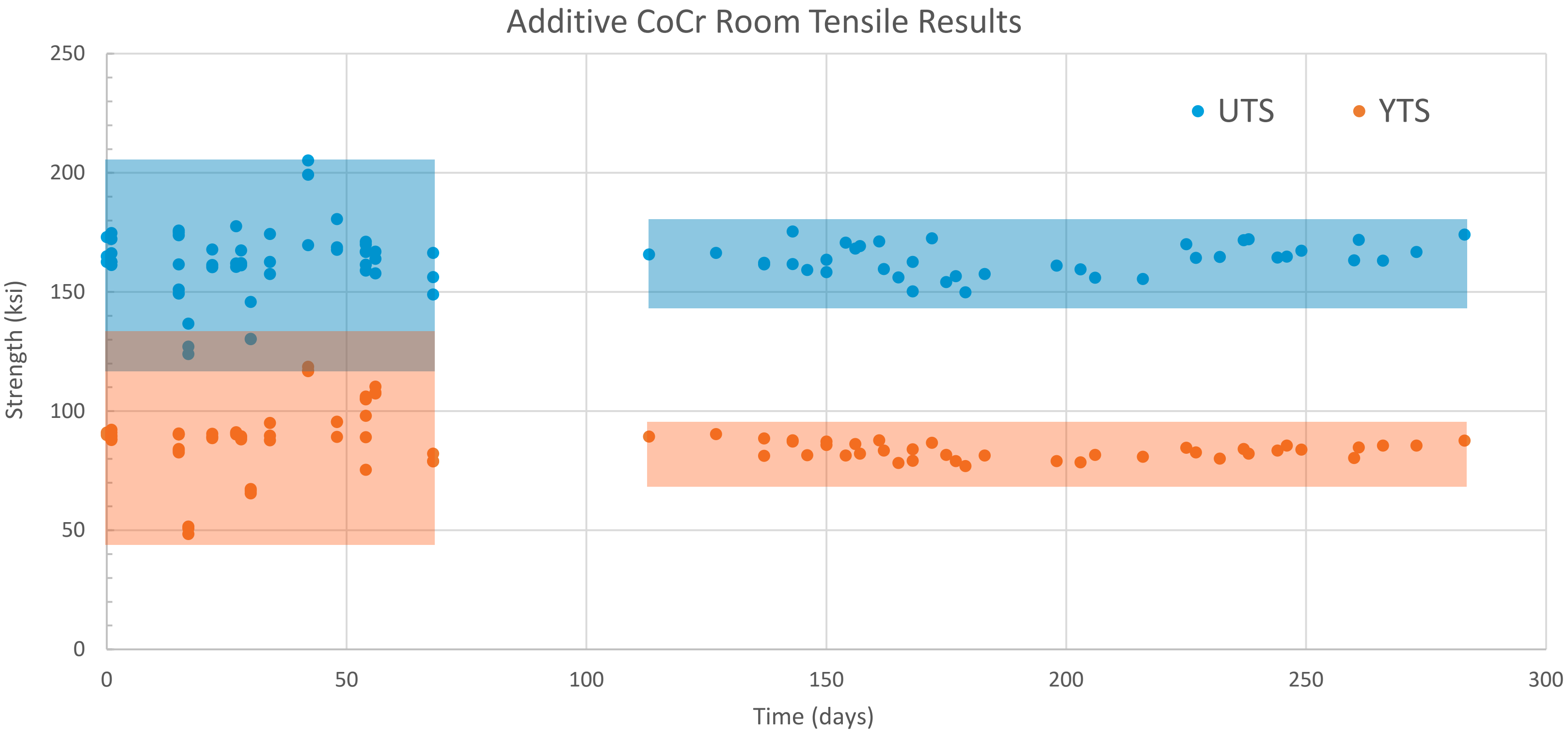
PROVOCATIVE THEORIES:

- Heat treating is a key factor to reducing process variation
- Laser based powder bed deposition process window is larger than previously believed.

INITIAL RUN CHART – ALL DATA AT A GLANCE



INITIAL RUN CHART – FIRST OBSERVATION



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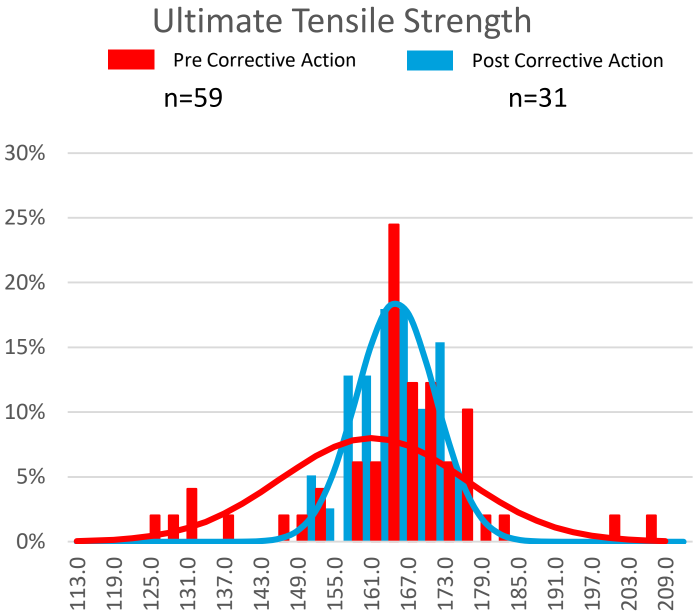
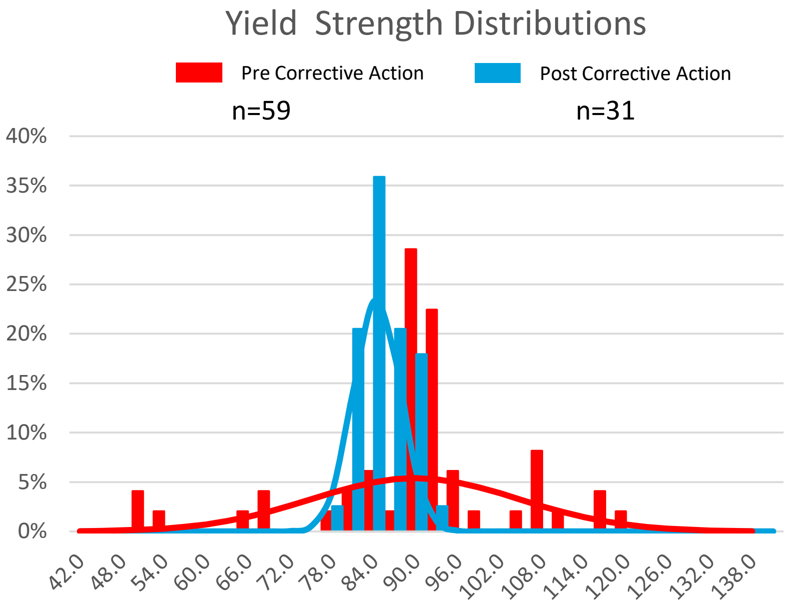
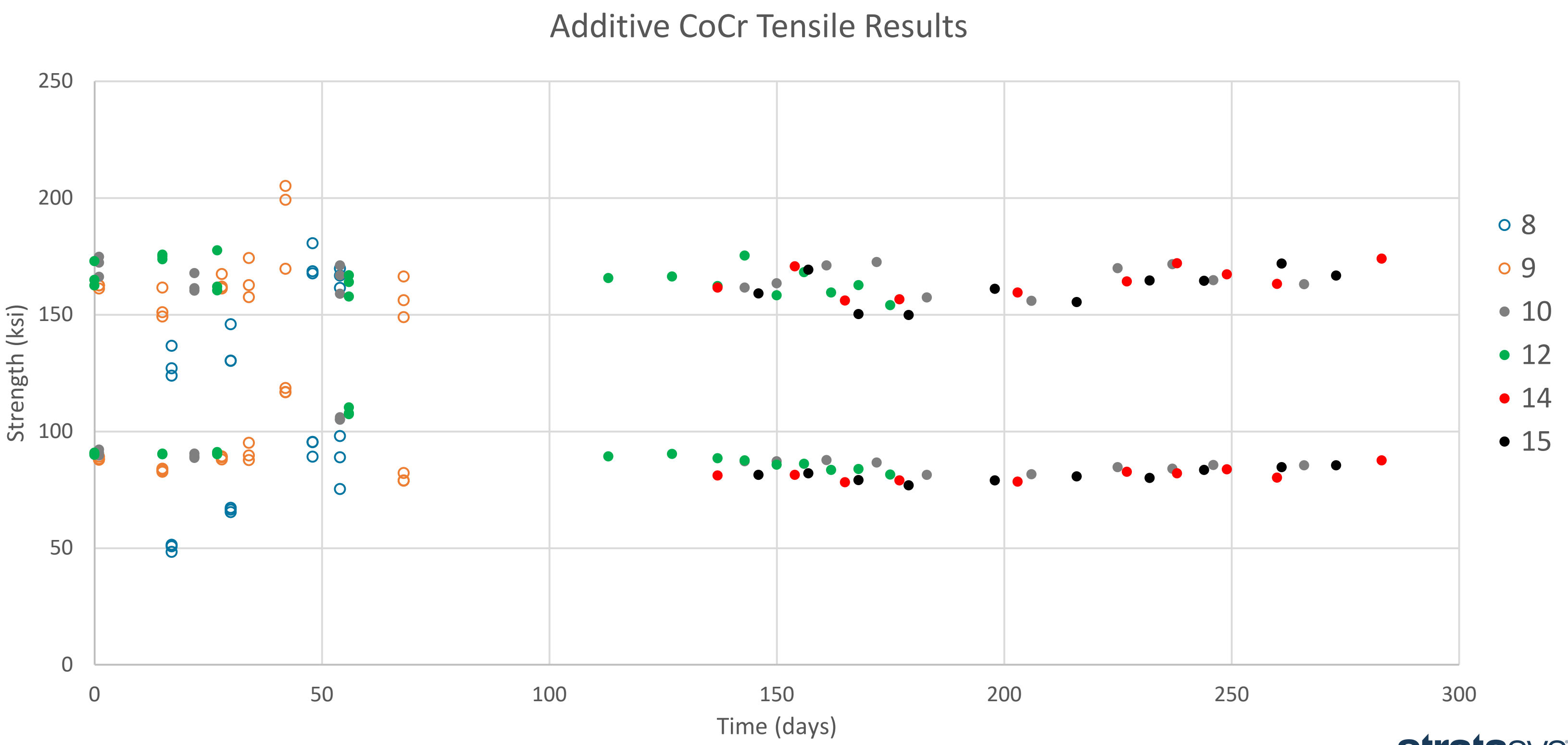
MECHANICAL PROPERTIES

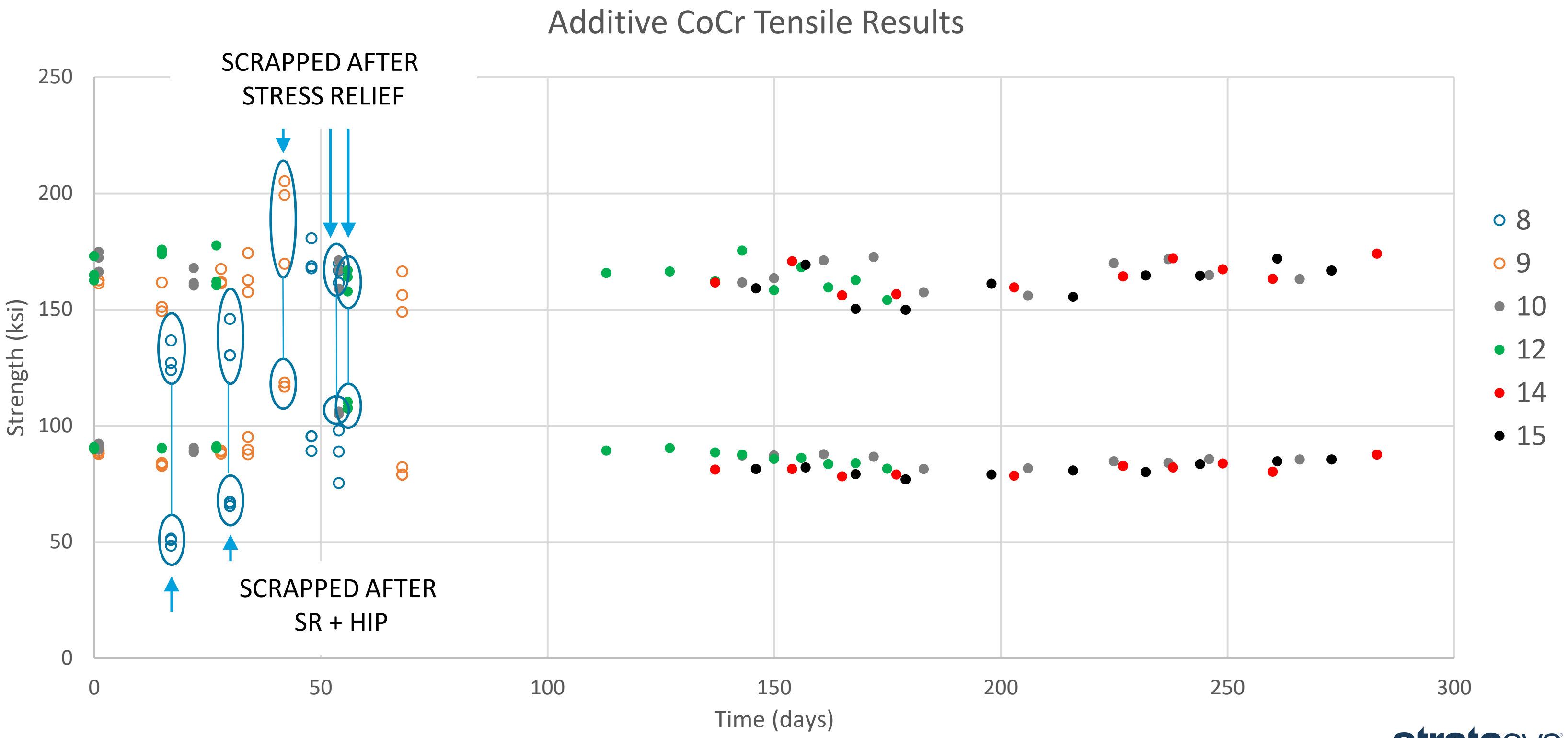




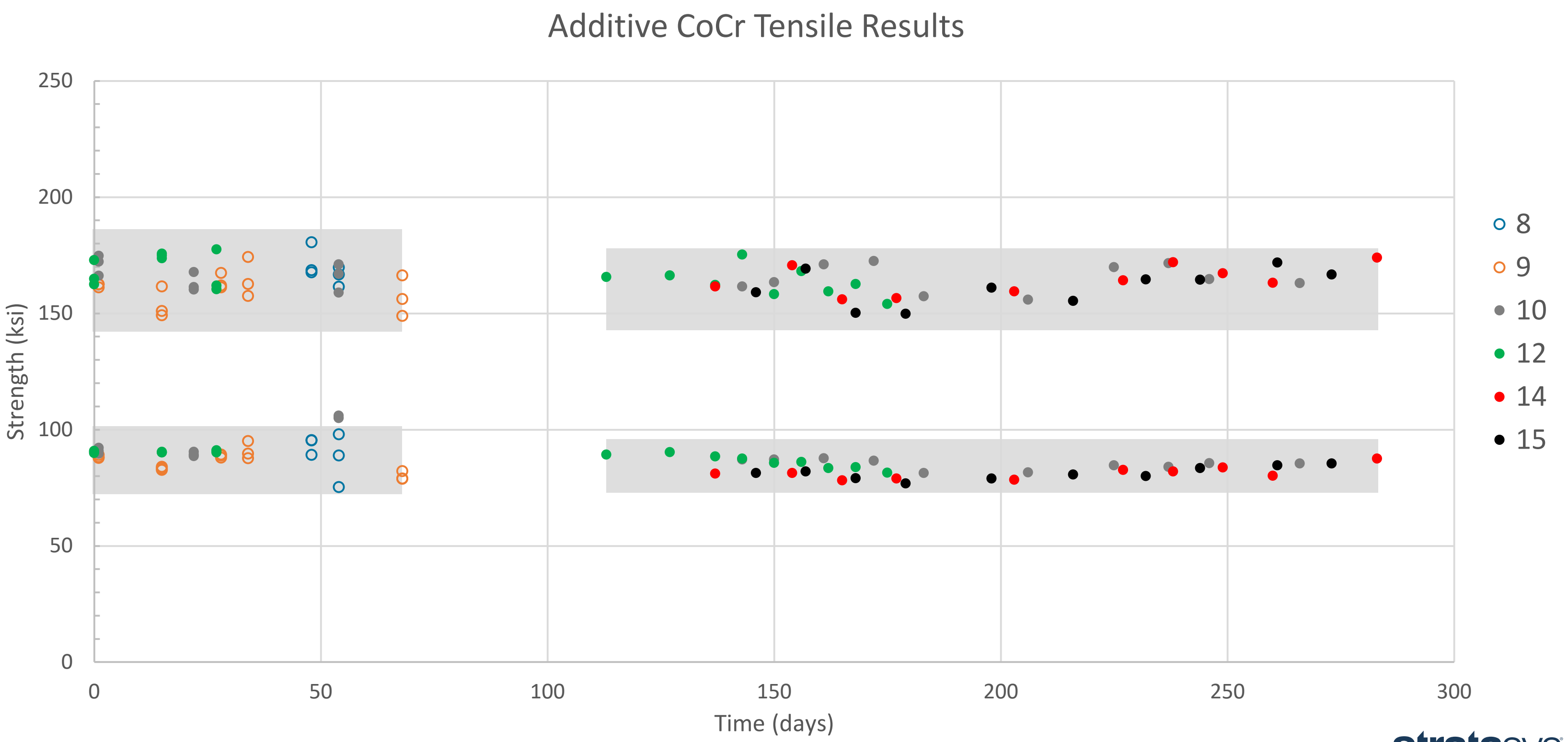
TENSILE RESULTS SEGMENTED BY POWDER EVO. NUMBER



TENSILE RESULTS SEGMENTED THREMAL TEREATMENT



TENSILE RESULTS ONLY REPRESENTING FULLY HEAT TREATED MATERIAL.



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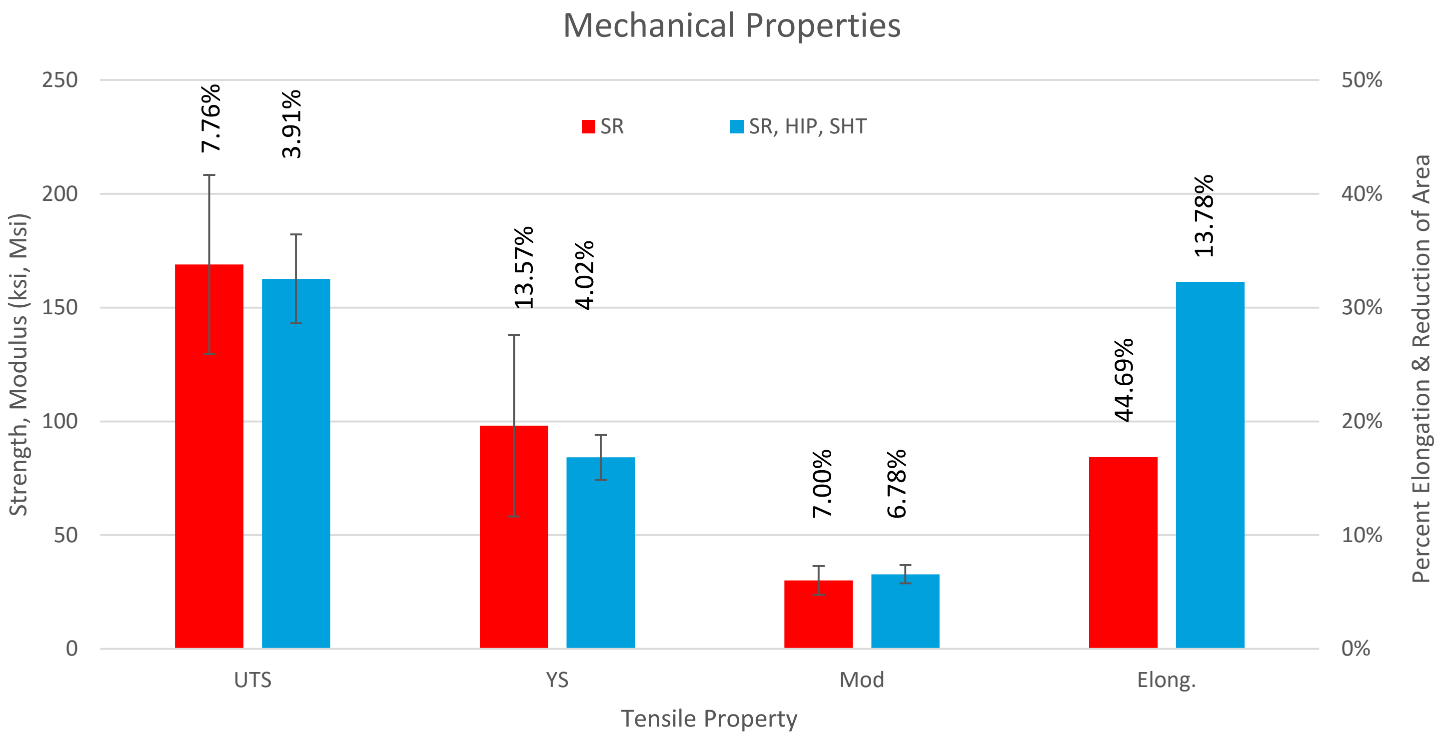
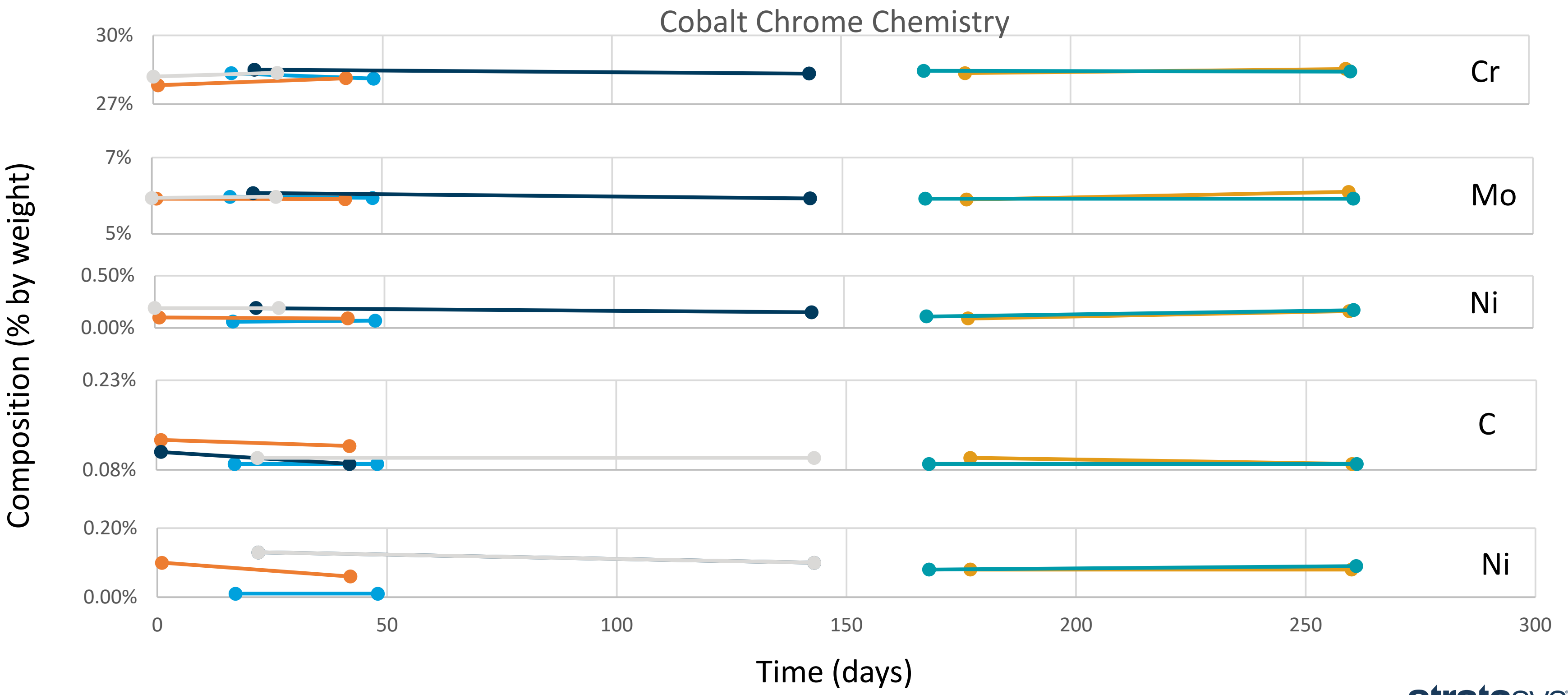
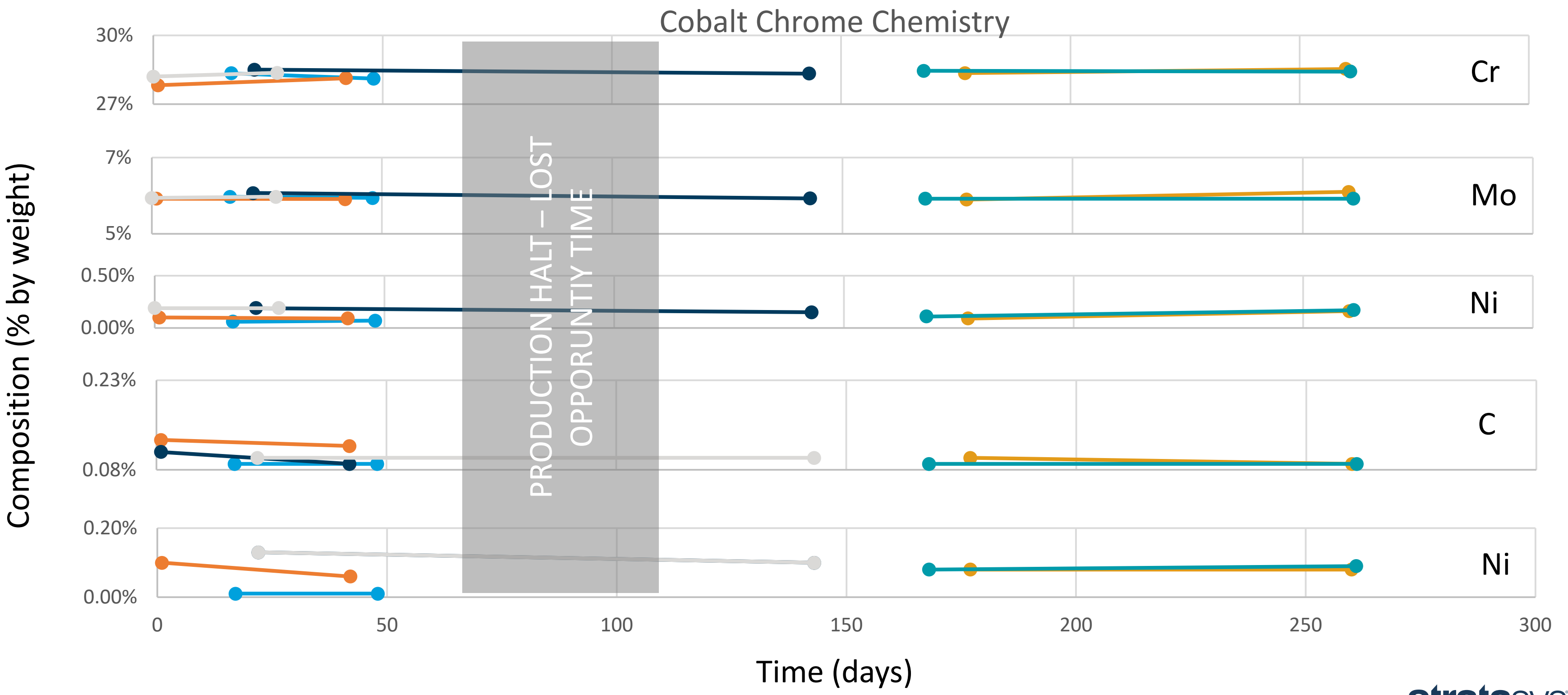
MECHANICAL PROPERTES VS. THERMAL CONDITION



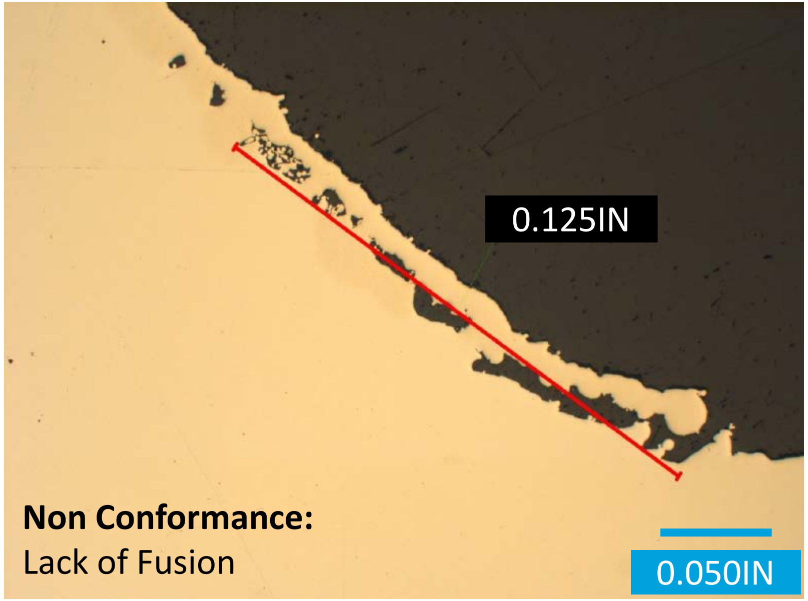
CHEMICAL RESULTS



CHEMICAL RESULTS



NON-CONFORMANCE - REVISITED



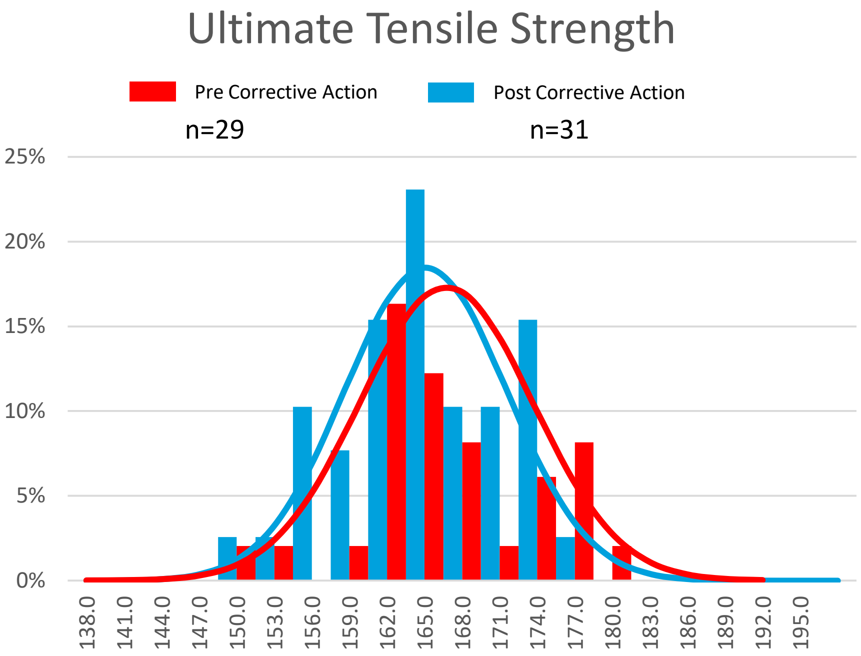
Issue: Lack of fusion

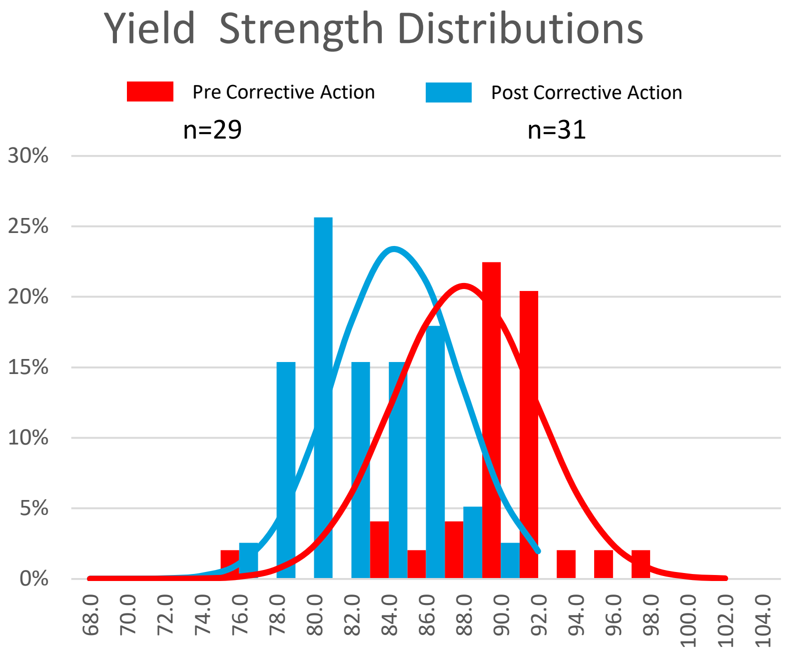
Location: The interface between contour and hatch.

Change in process parameters:

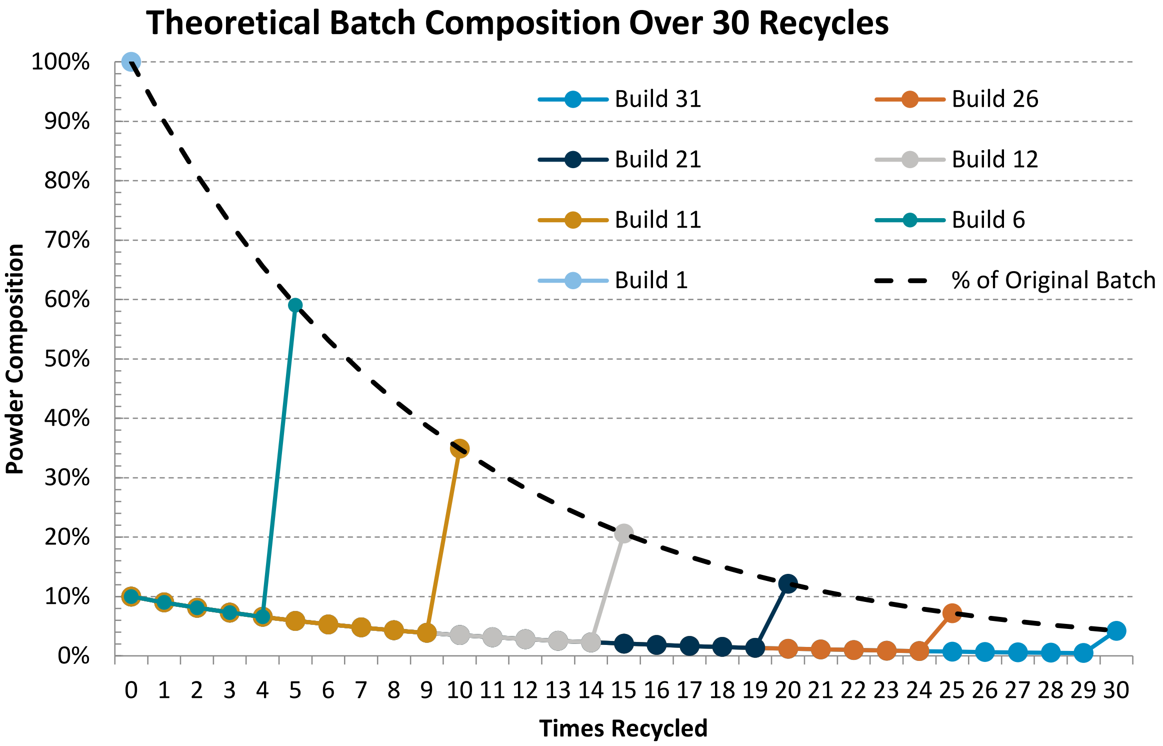
- ~60% increase in deposition speed
- ~50% increase in laser power
- 0.27 W/m^2 energy density (or flux)
- 9 part build to a 10 part build

BEFORE CORRECTIVE ACTION VS. AFTER CORRECTIVE ACTION



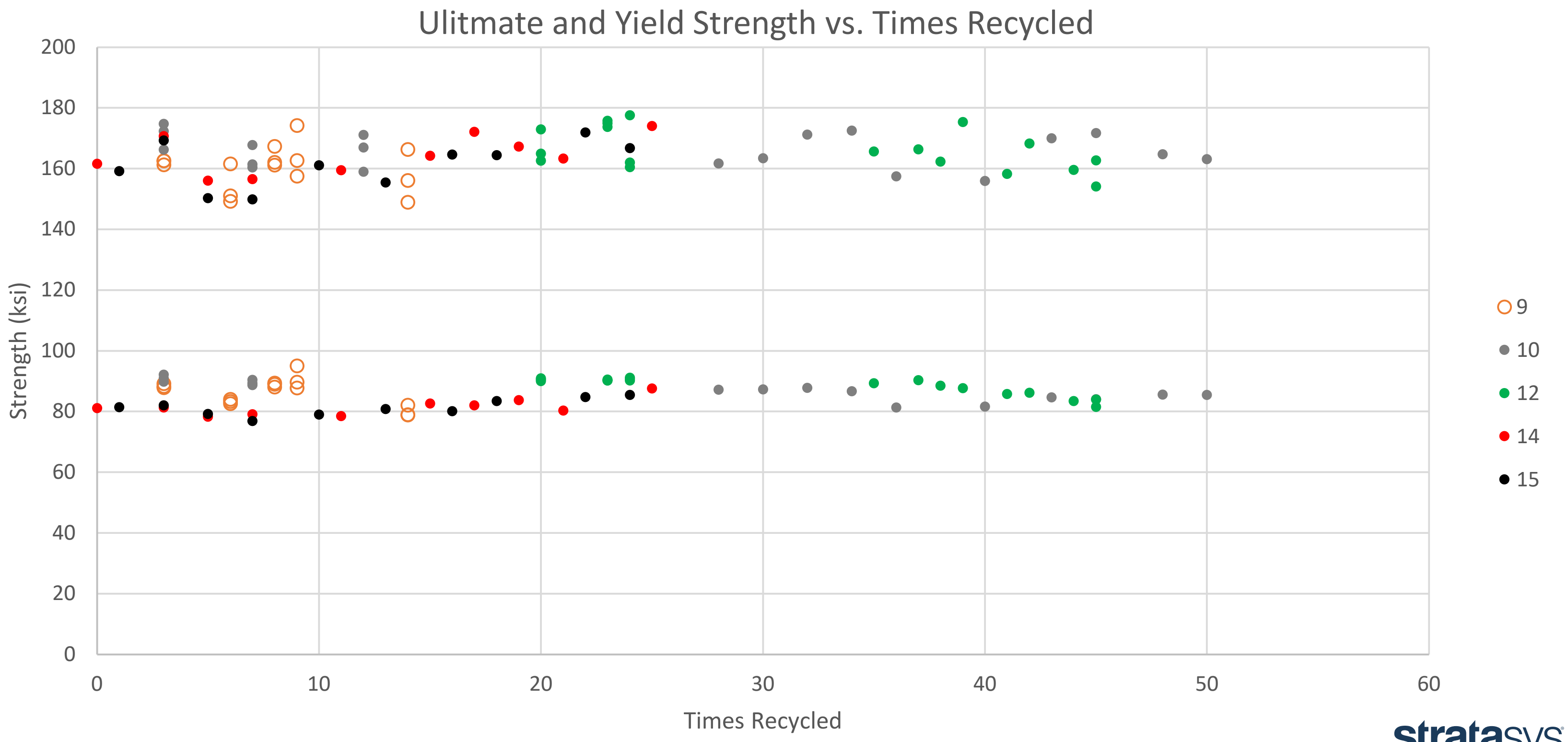


MATERIAL MANAGEMENT REVISITED



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

TIMES RECYCLED



CONCLUSIONS – ADDITIVE COBALT CHROME

Heat treatment is the larger factor in additive metal mechanical properties than previously beleived.

An ~60% increase in deposition speed through a reduction of 0.27 W/m^2 along with an 11% increase of deposited material had negligible affect on mechanical properties.

Stratasys Direct recognizes **a corrective as an opportunity to increase manufacturing efficiency** to provide the customer product faster at a reduced priced.

Stratasys Direct now provides industry with internal **tensile specification minimums for CoCr**.

ADDITIVE API IN718 STUDY

WHAT IS ADDITIVE API IN718?

API – American Petroleum Industry

API Standard 6A718 – Nickel Base Alloy 718 (UNS N07718) for Oil and Gas Drilling and Production Equipment.

- Chemistry
- Metallography
- Tensile
- Impact
- Hardness

MANUFACTURING STUDY PARAMETERS

Machine Systems: M280, M290, M400

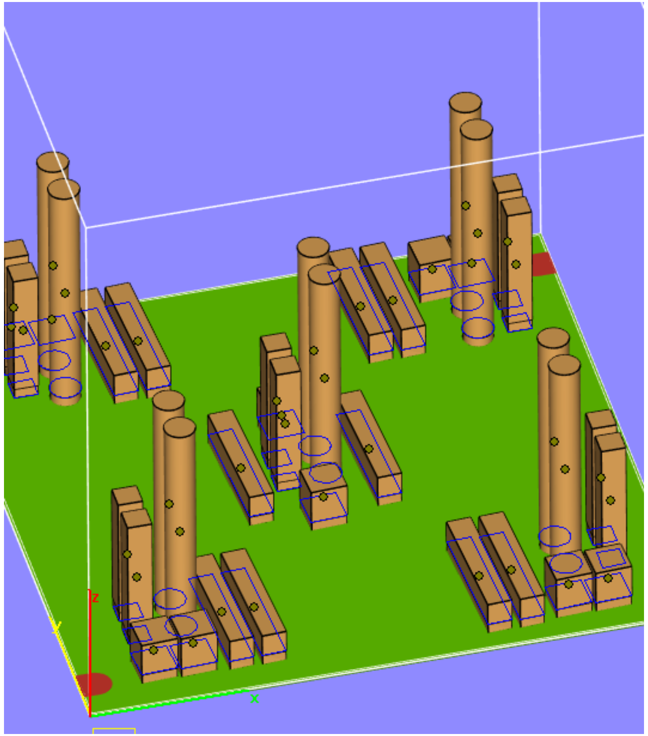
Builds Per Machine: 3 *(1 with 100% Virgin Material, 2 with highly recycled material)*

Locations on Build Plate: 5

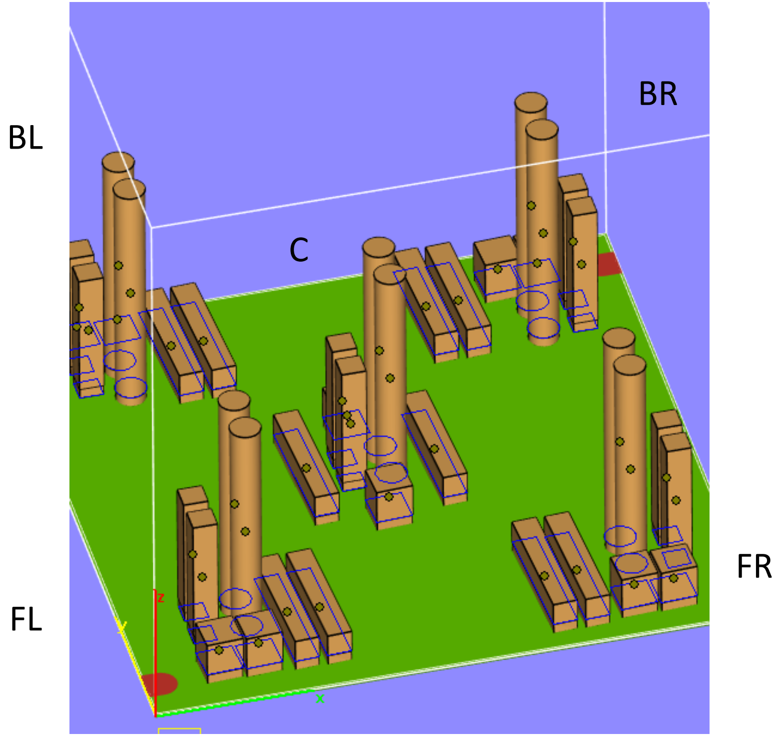
Samples at each location: 2 tensile, 4 (2 – z, 2 –y) impact, 2 microstructure

Total Tested Sample Size: 90 per mechanical property, 11 metallurgical samples

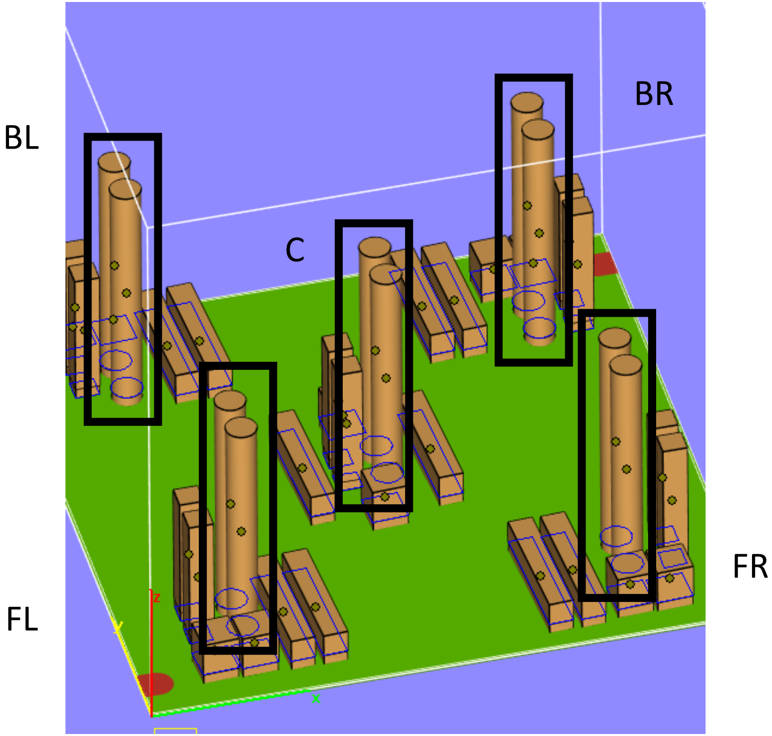
BUILD LAYOUT



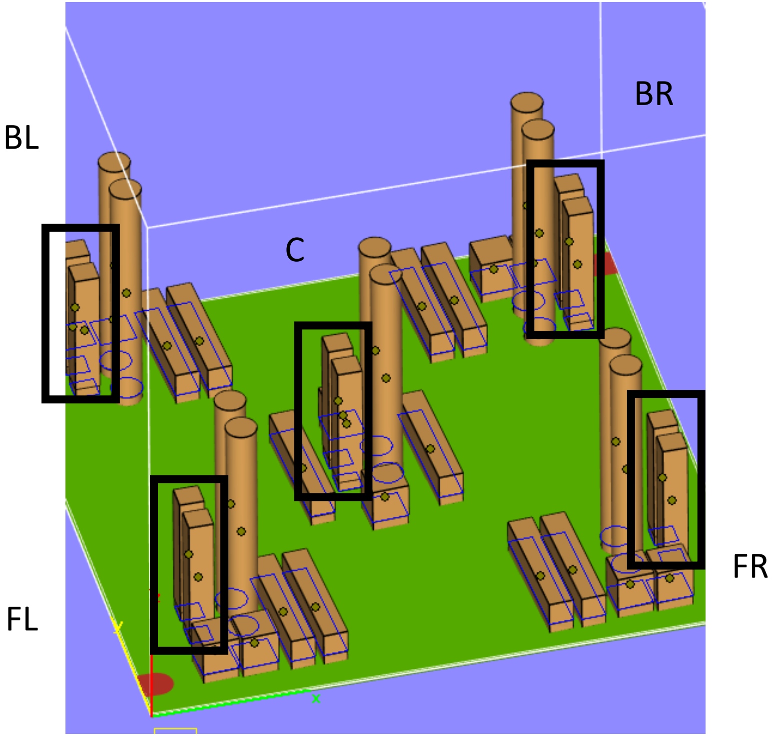
BUILD LAYOUT



BUILD LAYOUT



BUILD LAYOUT



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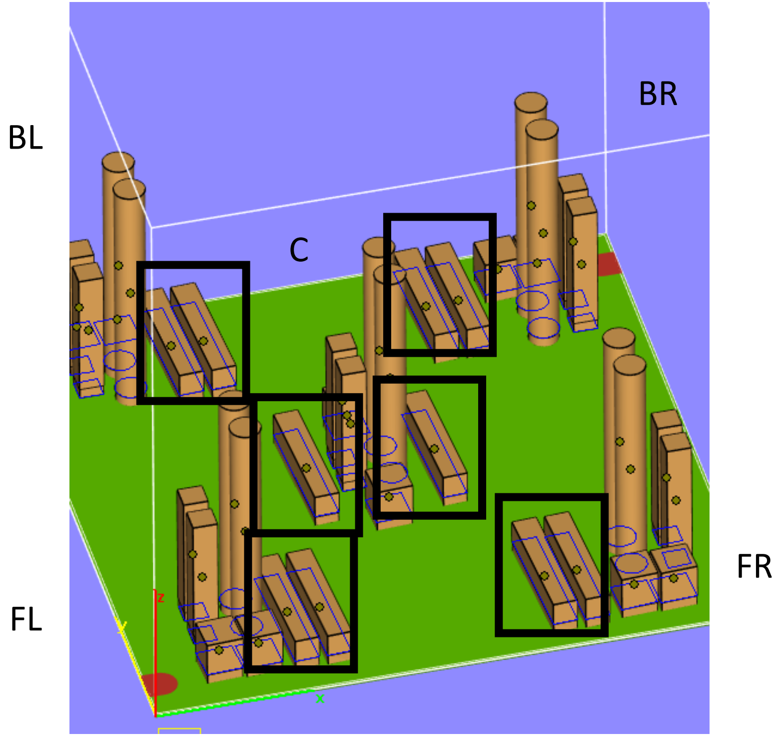
BUILD LAYOUT



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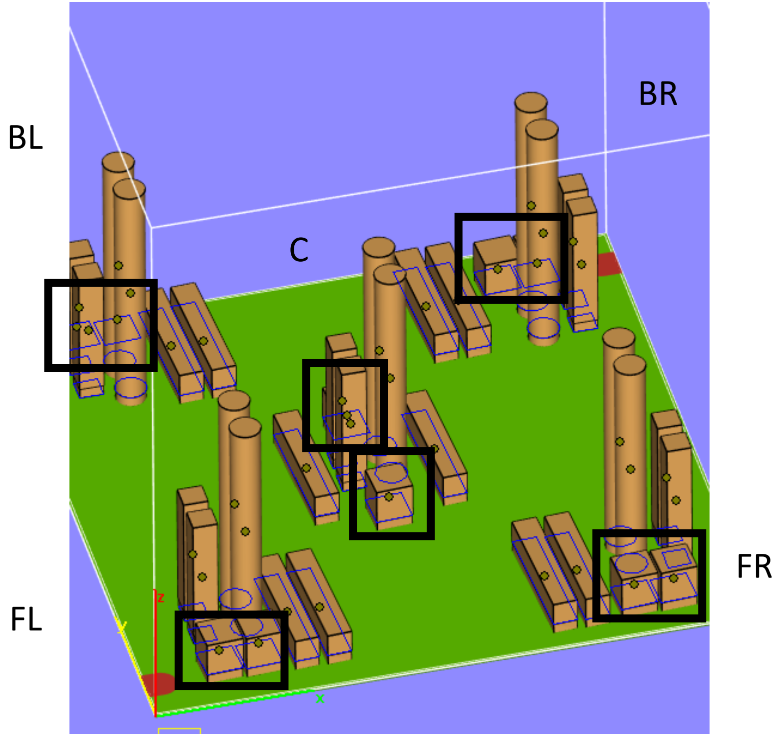
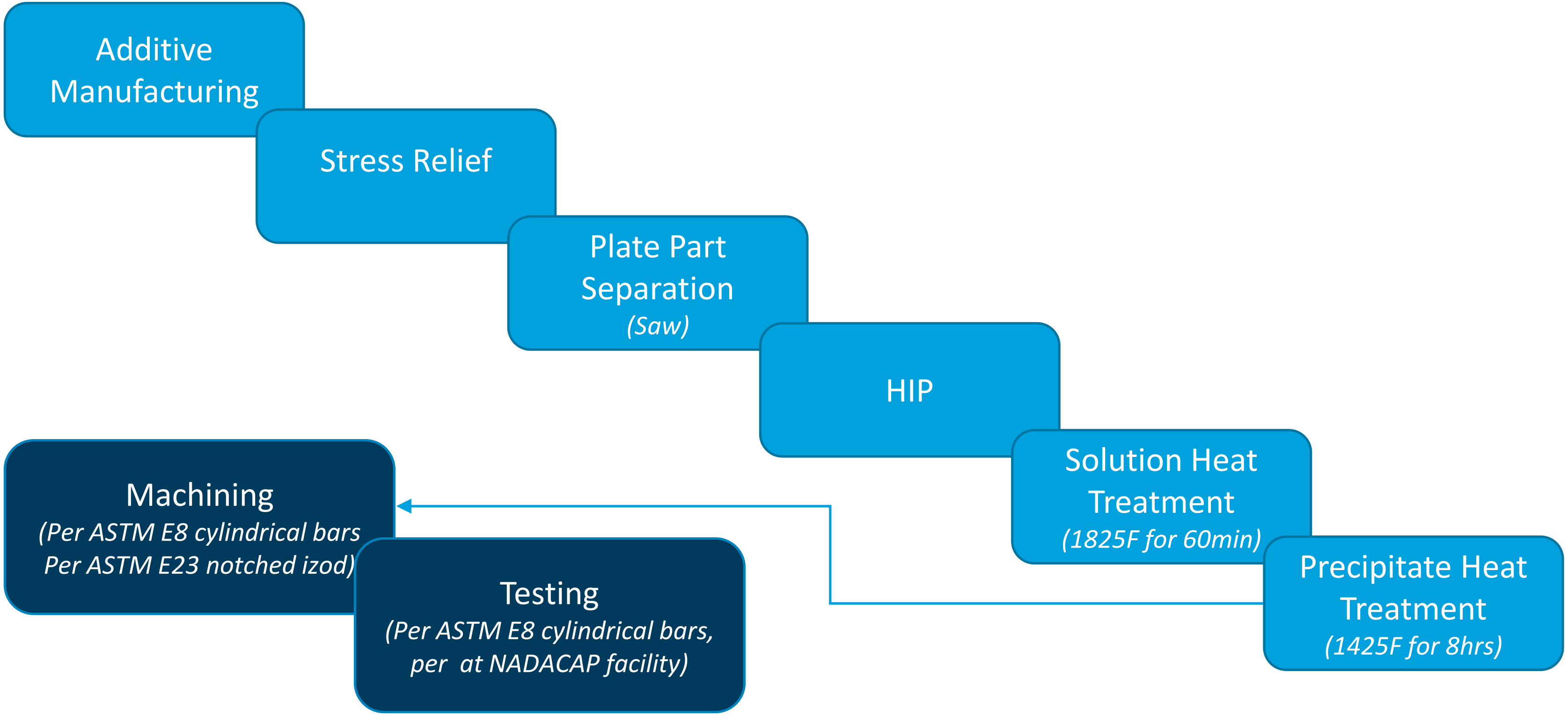
DIRECT MANUFACTURING

BUILD LAYOUT



PROCESSING – API SPEC'ED HEAT TREATMENTS



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Testing Standards and Study Comparisons

Mechanical Properties:

Tensile, ASTM E8 (gage length 4x gage diameter)

Impact, ASTM E23

Mechanical Property Comparisons:

Machine Systems

Build Locations

Material Recyclability

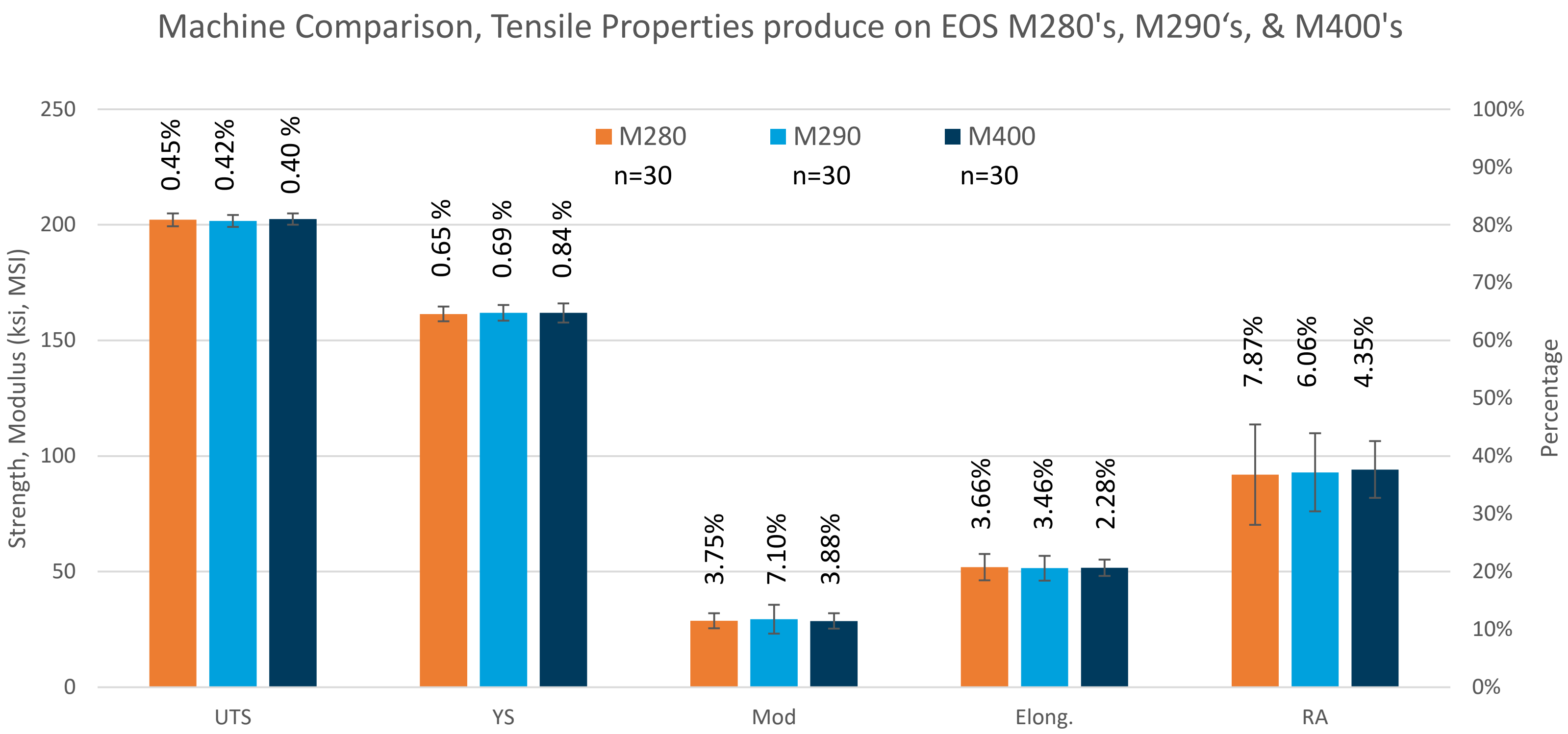
Orientation Dependent Izod Impact

Microstructure Comparisons:

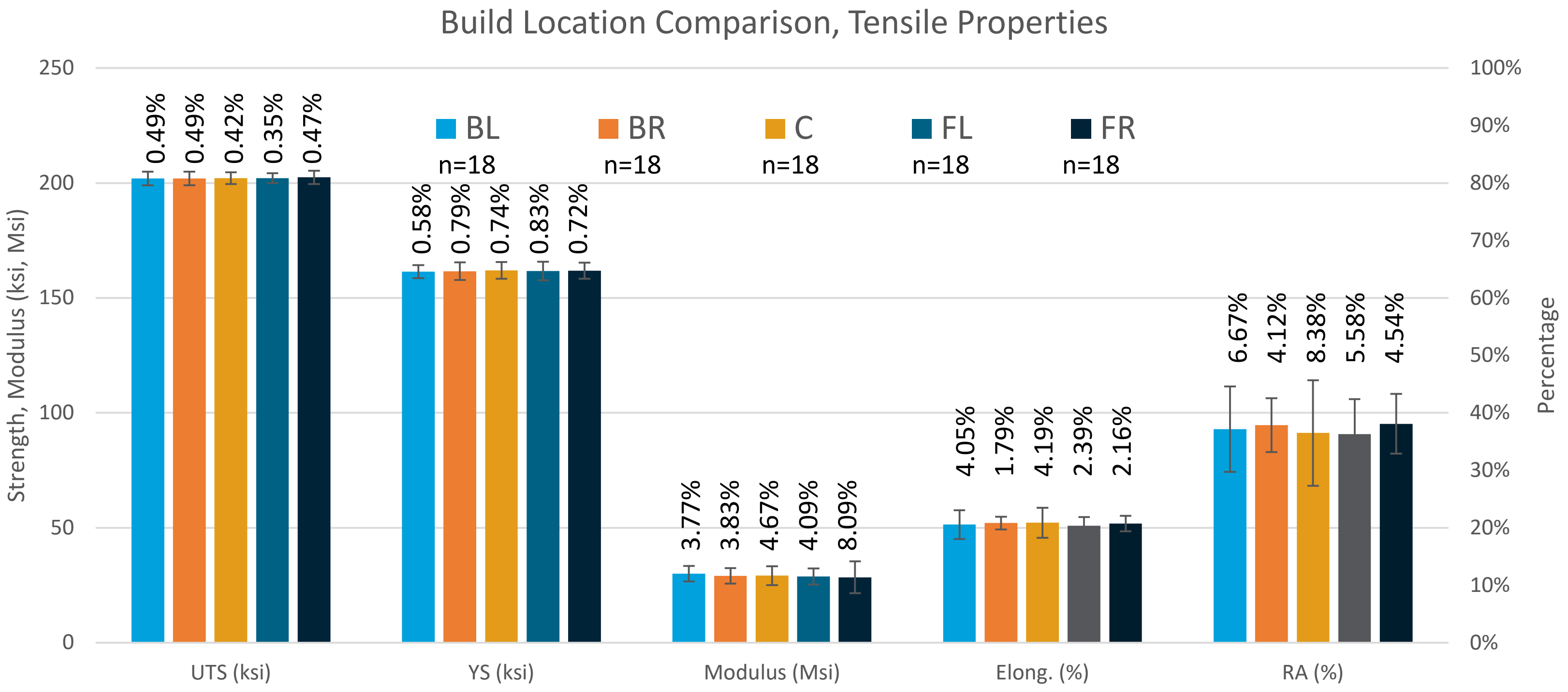
XY and YZ grainsize

Additive API IN718 vs. Wrought API IN718

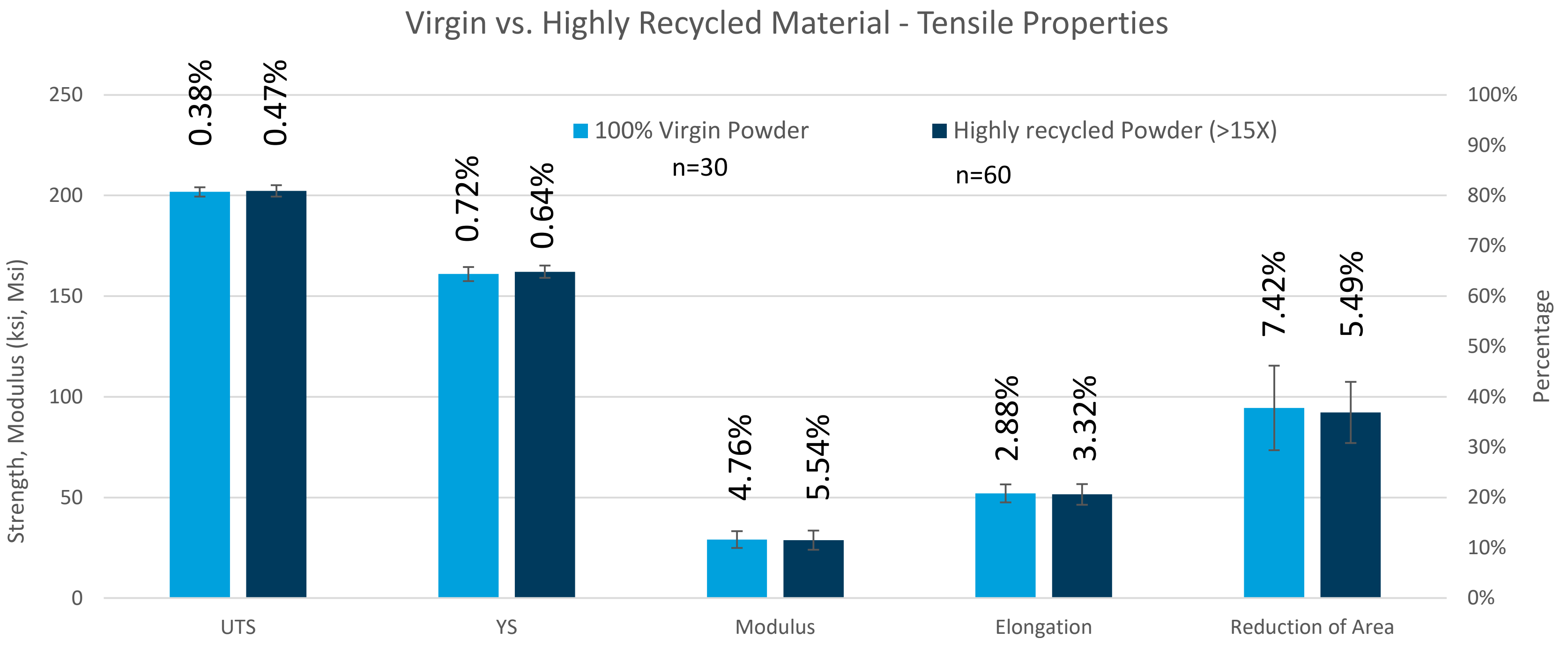
MACHINE SYSTEM COMPARISON – TENSILE RESULTS



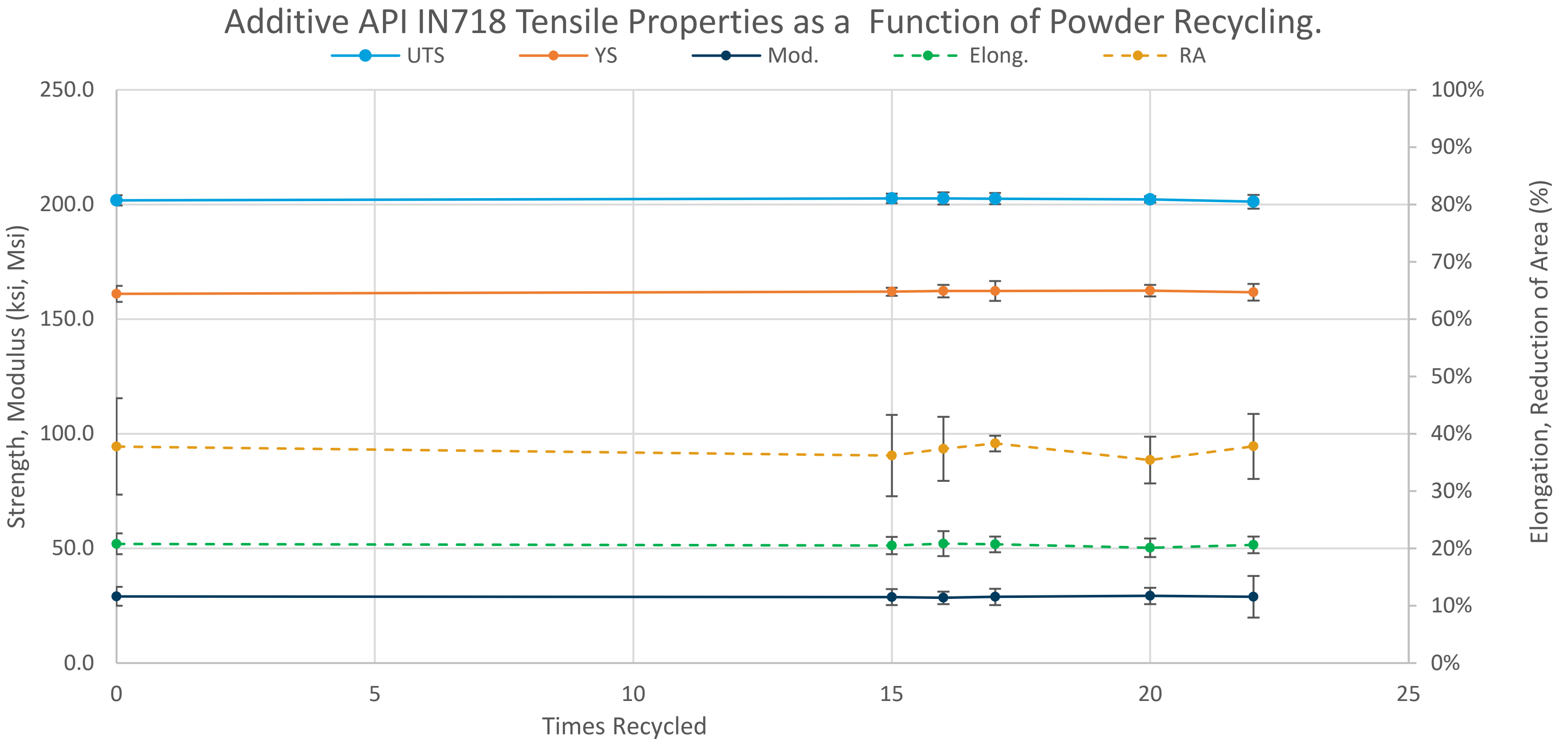
BUILD LOCATION COMPARISON – TENSILE PROPERTIES



TENSILE PROPERTIES PRODUCED WITH VIRGIN VS. HIGHLY RECYCLED POWDER



TENSILE PROPERTIES AS A FUNCTION OF TIMES RECYCLED



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NOTCHED BAR IMPACT

Reported Measurements:

Absorbed Energy (ft-lbs): difference in energy of the striking unit at the instant of impact.

Lateral Expansion Measurement (mils): the sum of material expansion on both sides of the sample perpendicular to the striking direction.

Percentage of shear fracture (%): difference between total fractured area and the area of unstable fracture region.

All impact testing was performed at -75F per API specification.

Lateral Expansion:
Larger of A2 or A4 plus the larger of A1 and A3.

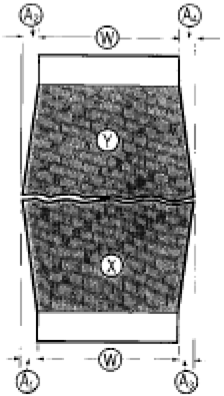
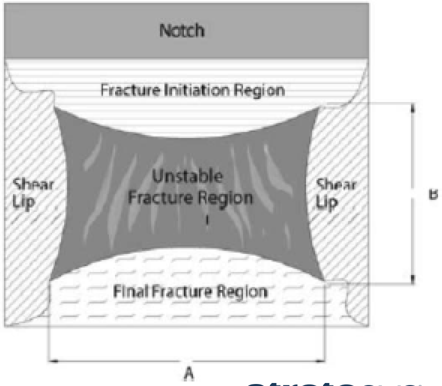


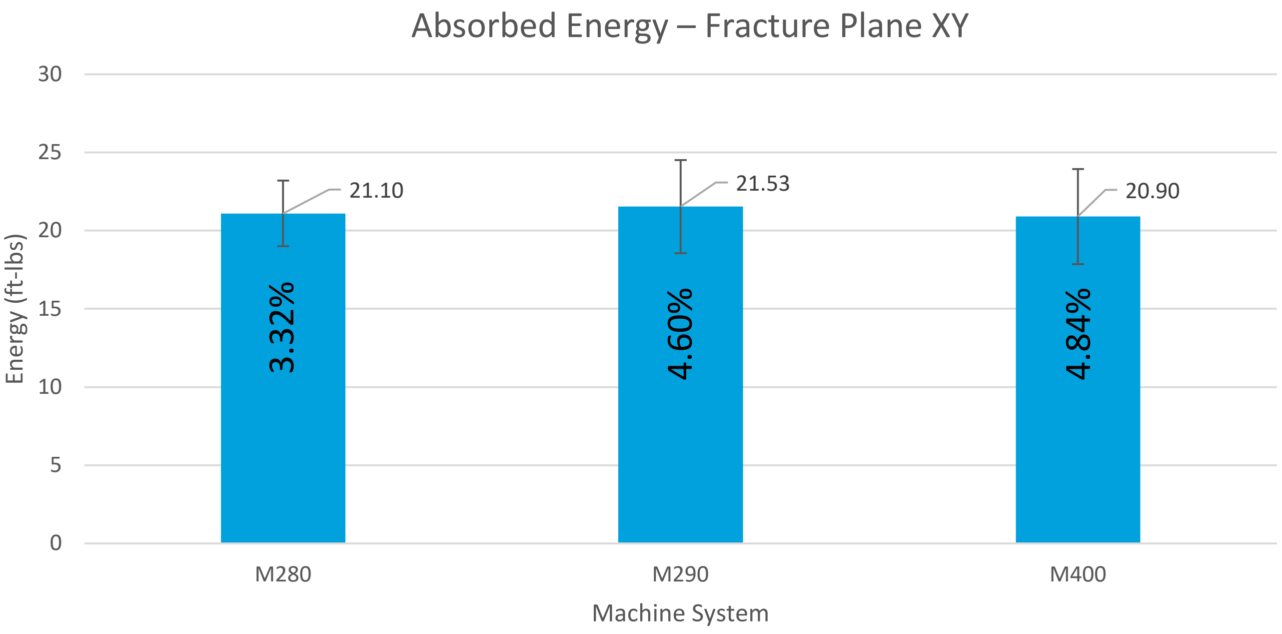
FIG. 6 Halves of Broken Charpy V-Notch Impact Specimen Illustrating the Measurement of Lateral Expansion, Dimensions A_1, A_2, A_3, A_4 and Original Width, Dimension W

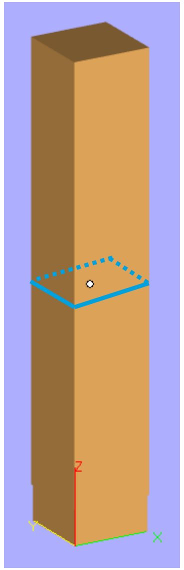
Percent of Shear Fracture:
*A*B/total fracture region*



*Figures from ASTM E23, "Standard Test Methods for Notched Bar Impact Testing of Metallic Materials."

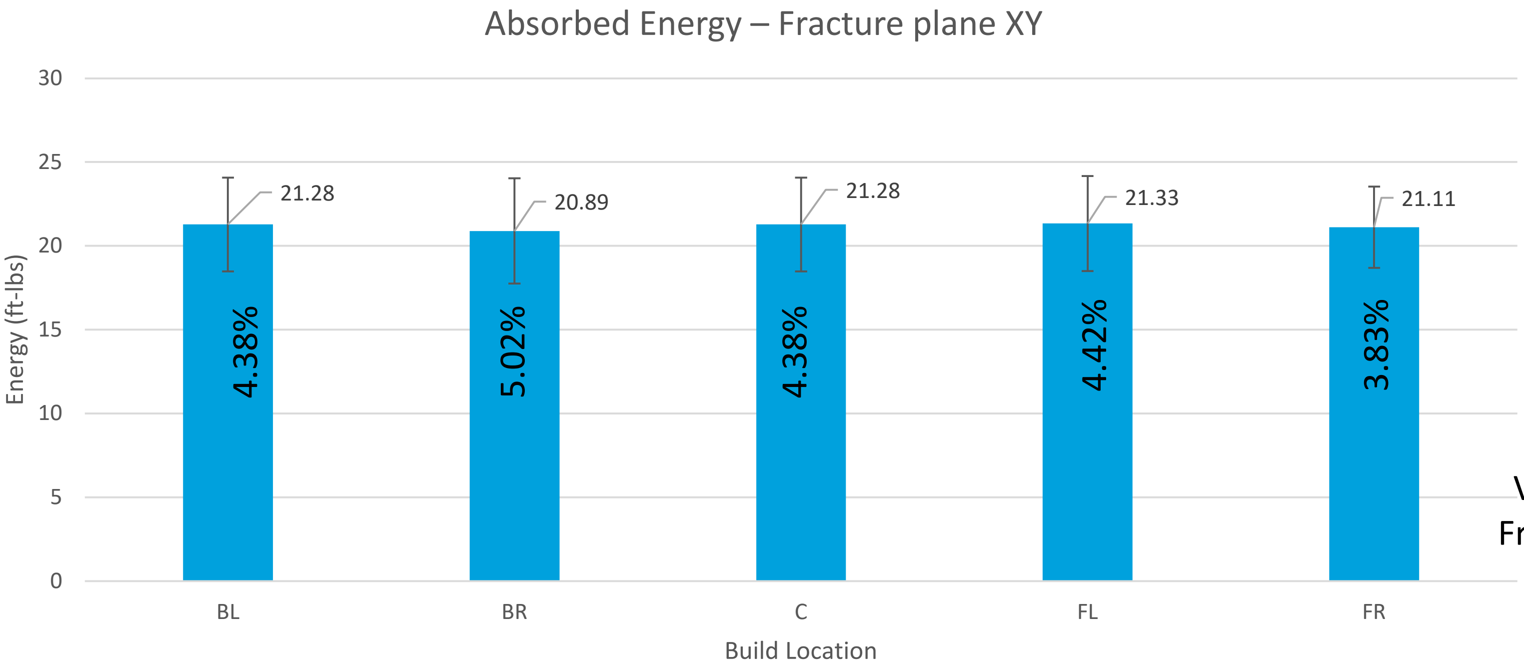
MACHINE SYSTEM COMPARISON – IMPACT

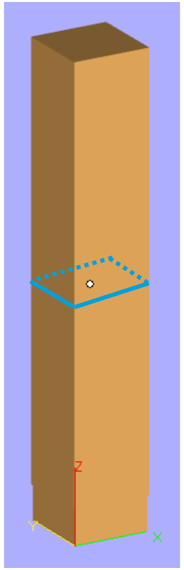




Vertical-sample Fracture Plane XY

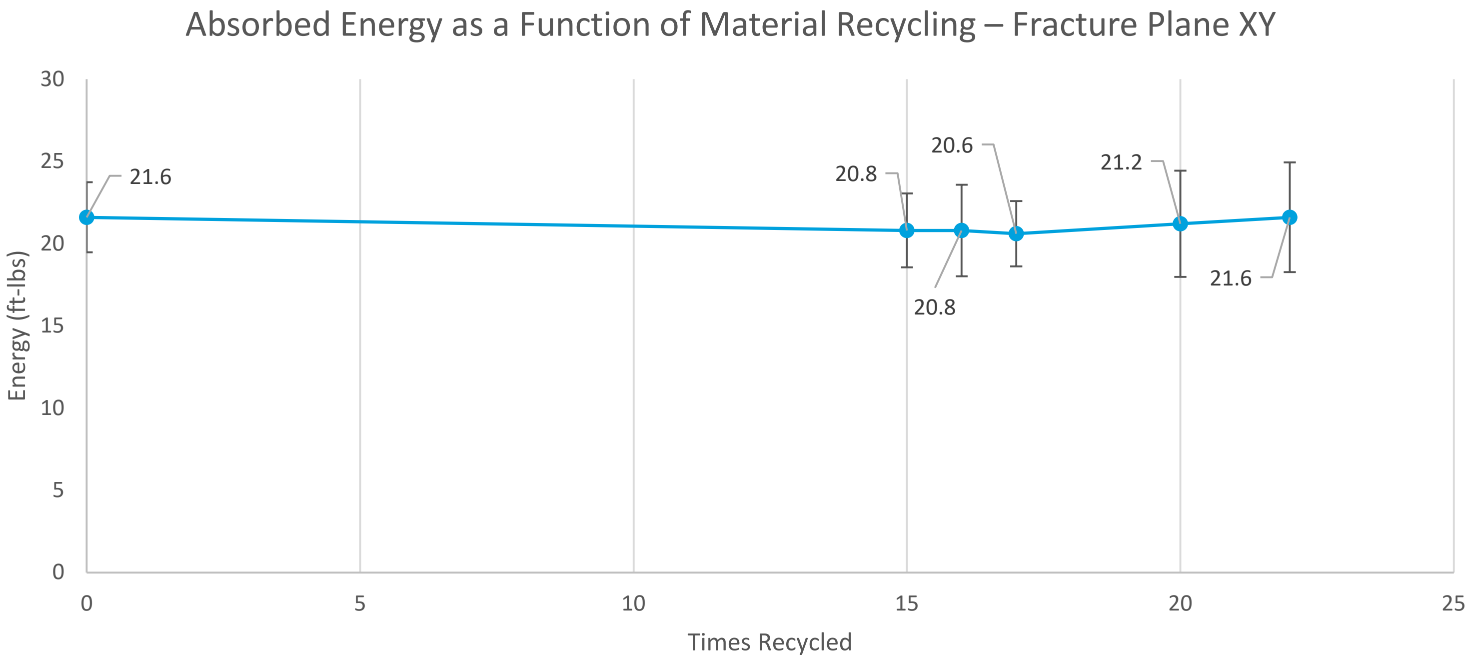
BUILD LOCATION COMPARISON – IMPACT

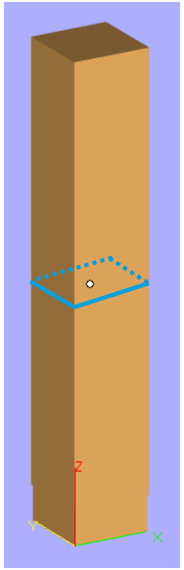




Vertical-sample
Fracture Plane XY

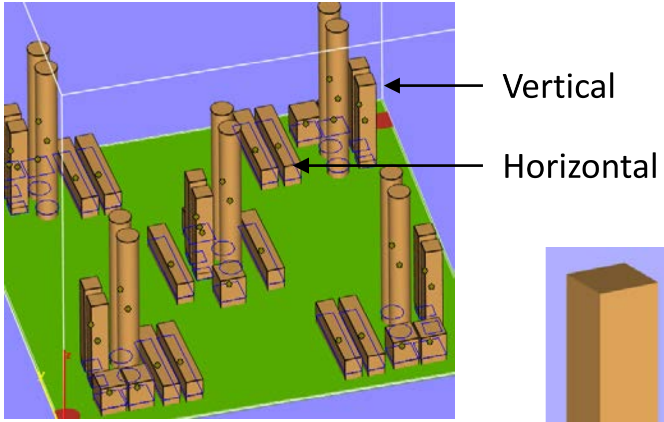
IMPACT PROPERTIES PRODUCED WITH VIRGIN VS. HIGHLY RECYCLED POWDER

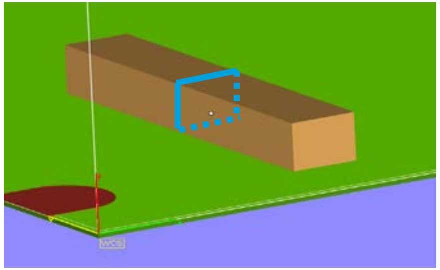




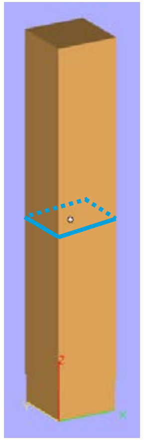
Vertical-sample Fracture Plane XY

VERTICAL VS HORIZONTAL IMPACT PROPERTIES

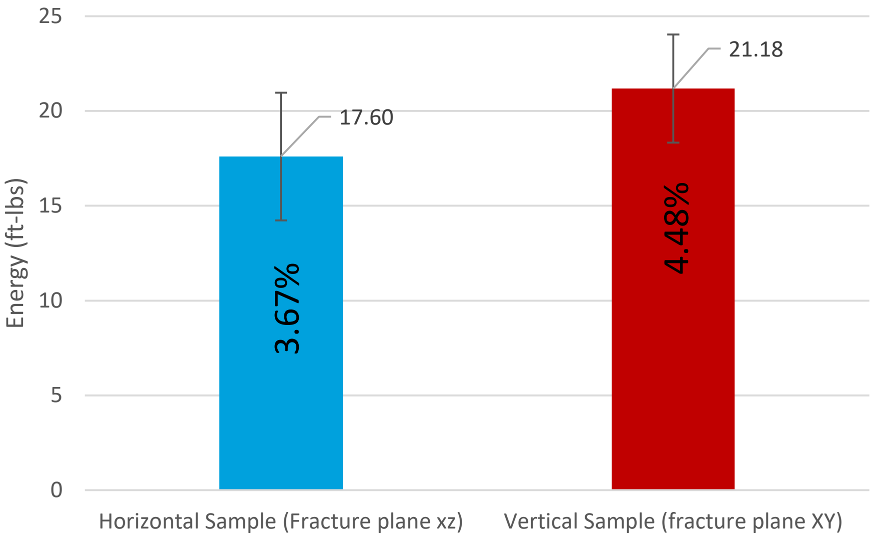




Horizontal-Sample
Fracture Plane XZ



Vertical-sample
Fracture Plane XY



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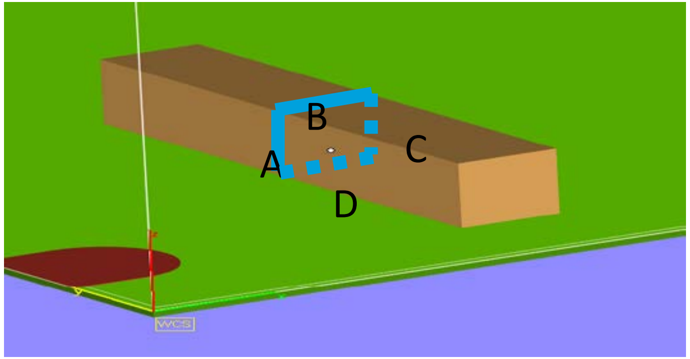
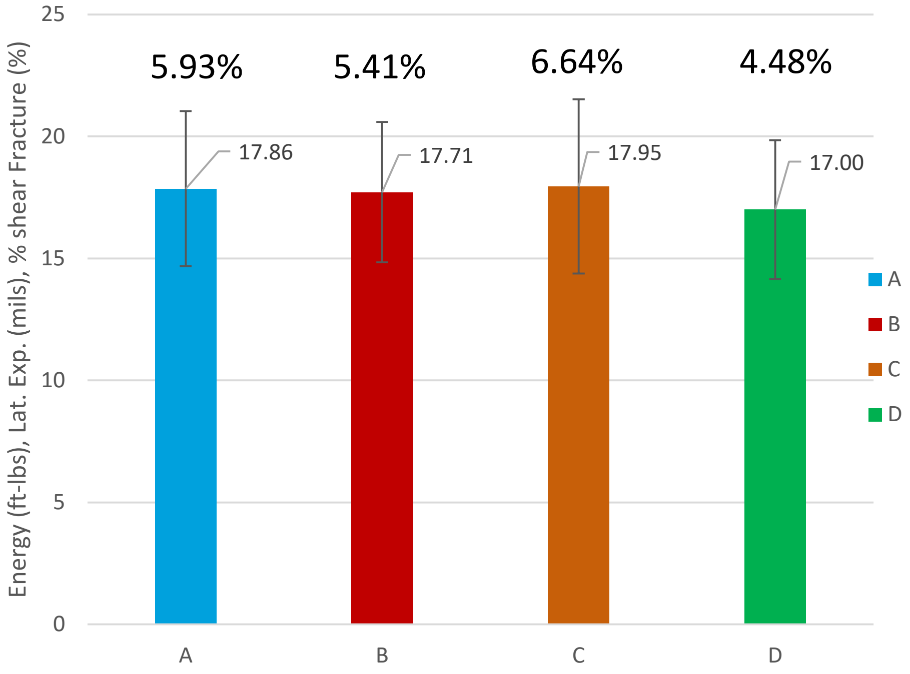
HORIZONTAL DIRECTIONAL IMPACT PROPERTIES



Notch Location	Fracture Direction
A	X+
B	Z-
C	X-
D	Z+

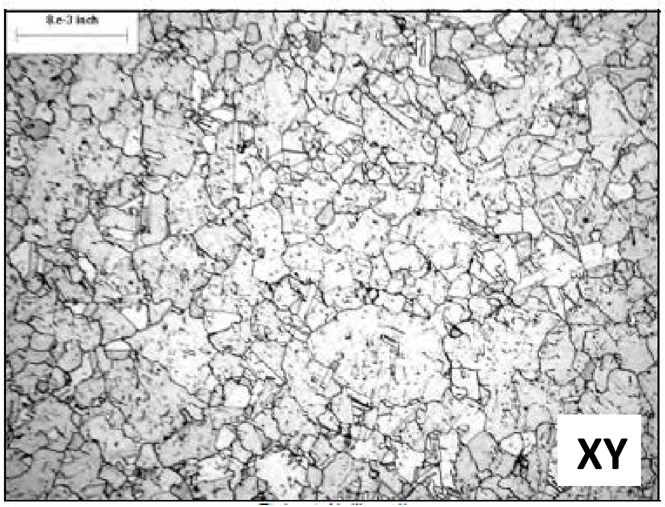


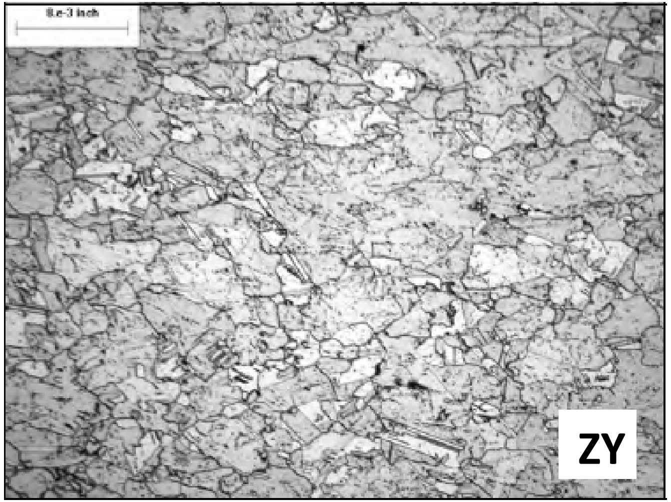
ADDITIVE API718 METALLOGRAPHY

XY vs. ZY

XY has a higher frequency of equiaxed grains than ZY

Wider range of duplex grain structure in the ZY plane.





CONCLUSTIONS – ADDITIVE API IN718

SECTION Three

Elevated Temperature Tensile Results – IN718 and IN625

FRAMING THE SCOPE OF THE STUDY

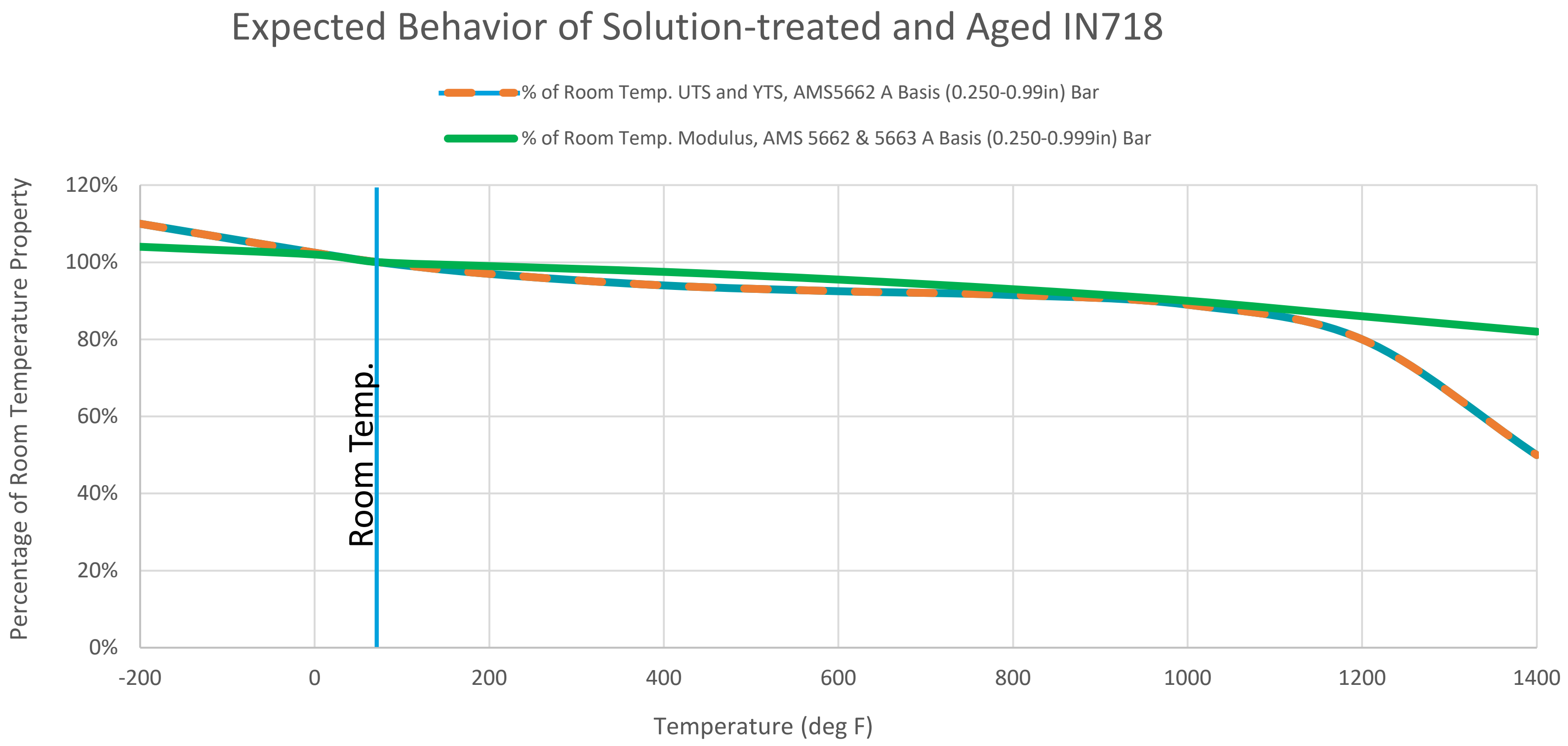
Metallic Materials Properties Development and Standardization (MMPDS) Handbook

- A source of accepted A, B, and S basis allowables for metallic material and fasteners.
- It is recognized by the FAA, DoD, and NASA

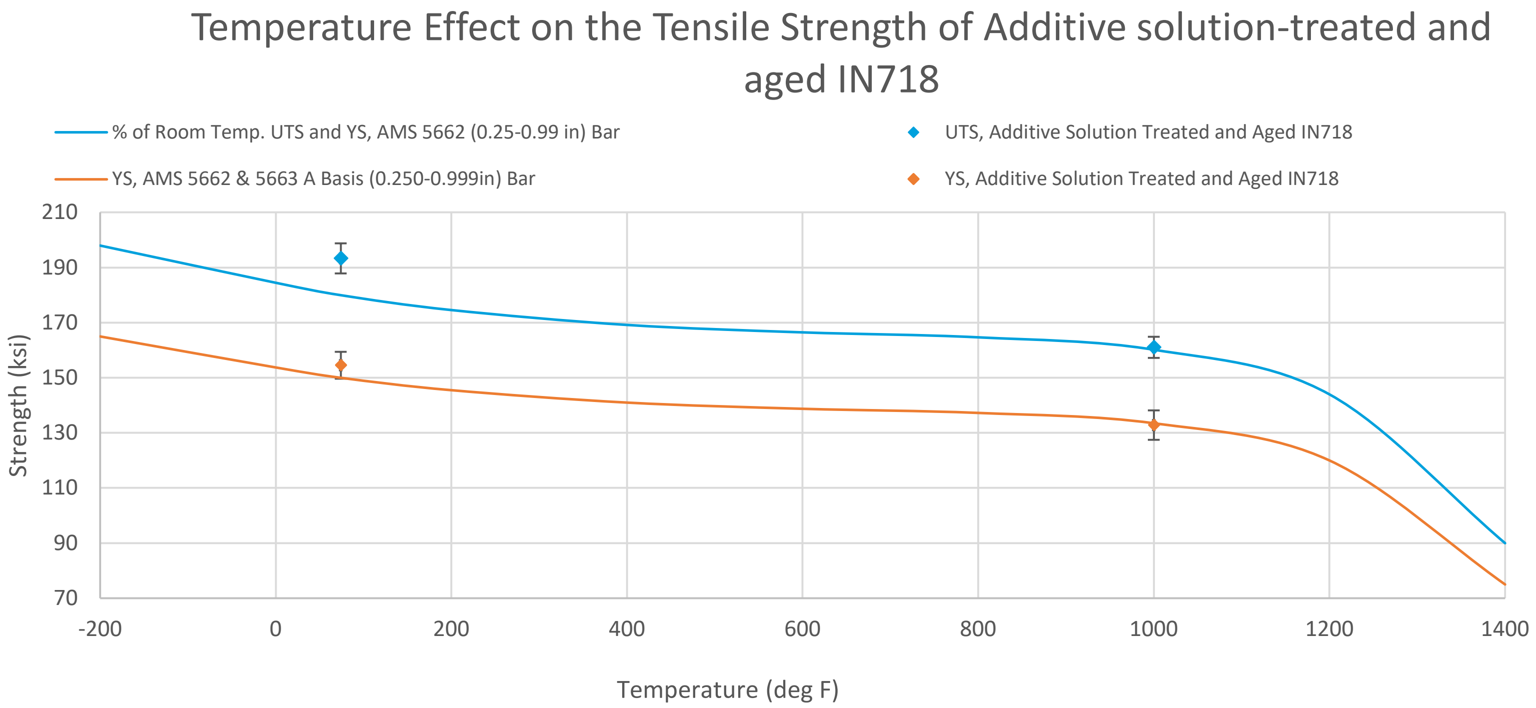
Properties at Elevated Temperature:

- At temperatures above room temperature **generally result in a decrease in strength and an increase in ductility**.
- Data is plotted as **percentages of room temperature allowable property** against temperature.

IN718 EXPECTED BEHAVIOR



IN718 – FIRST GLANCE



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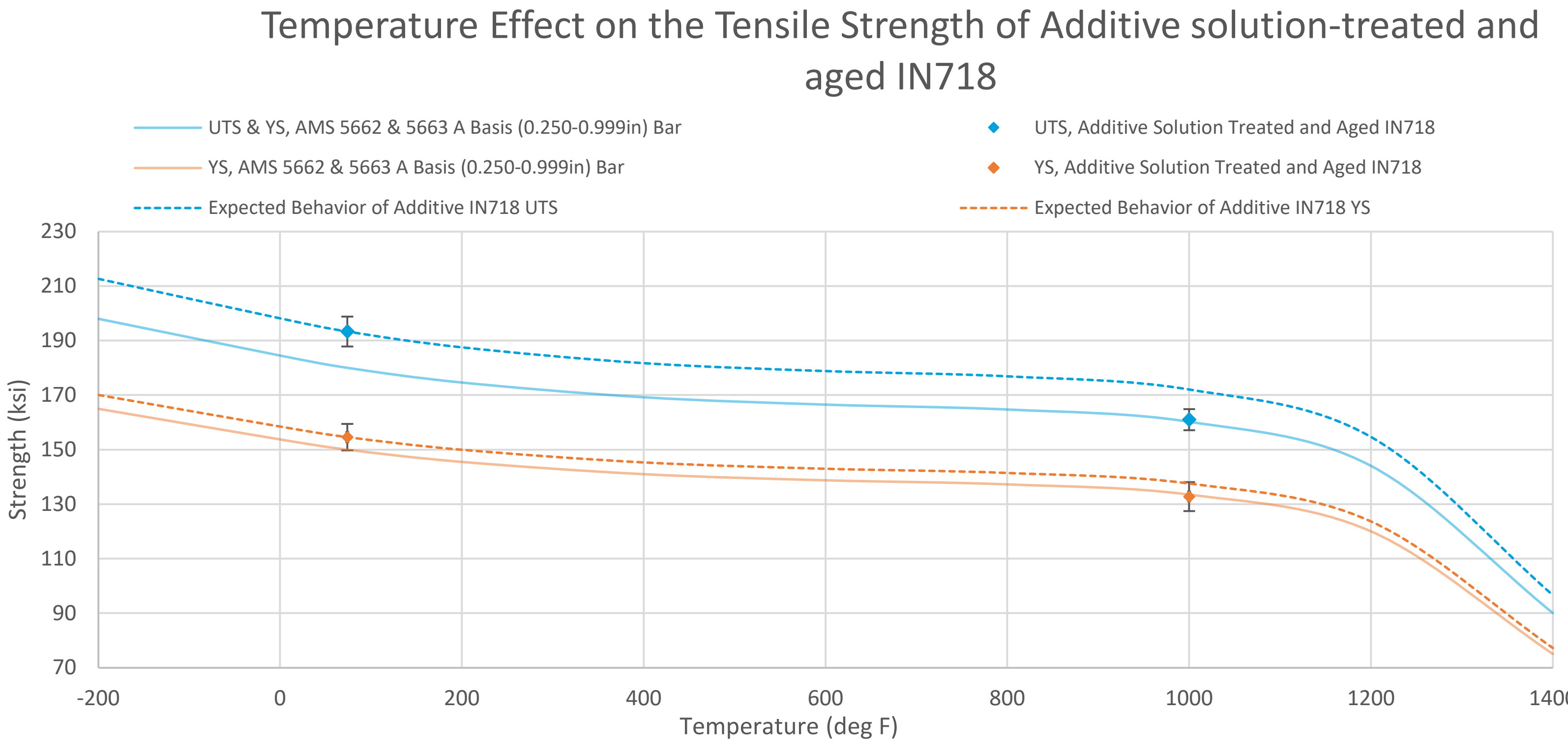
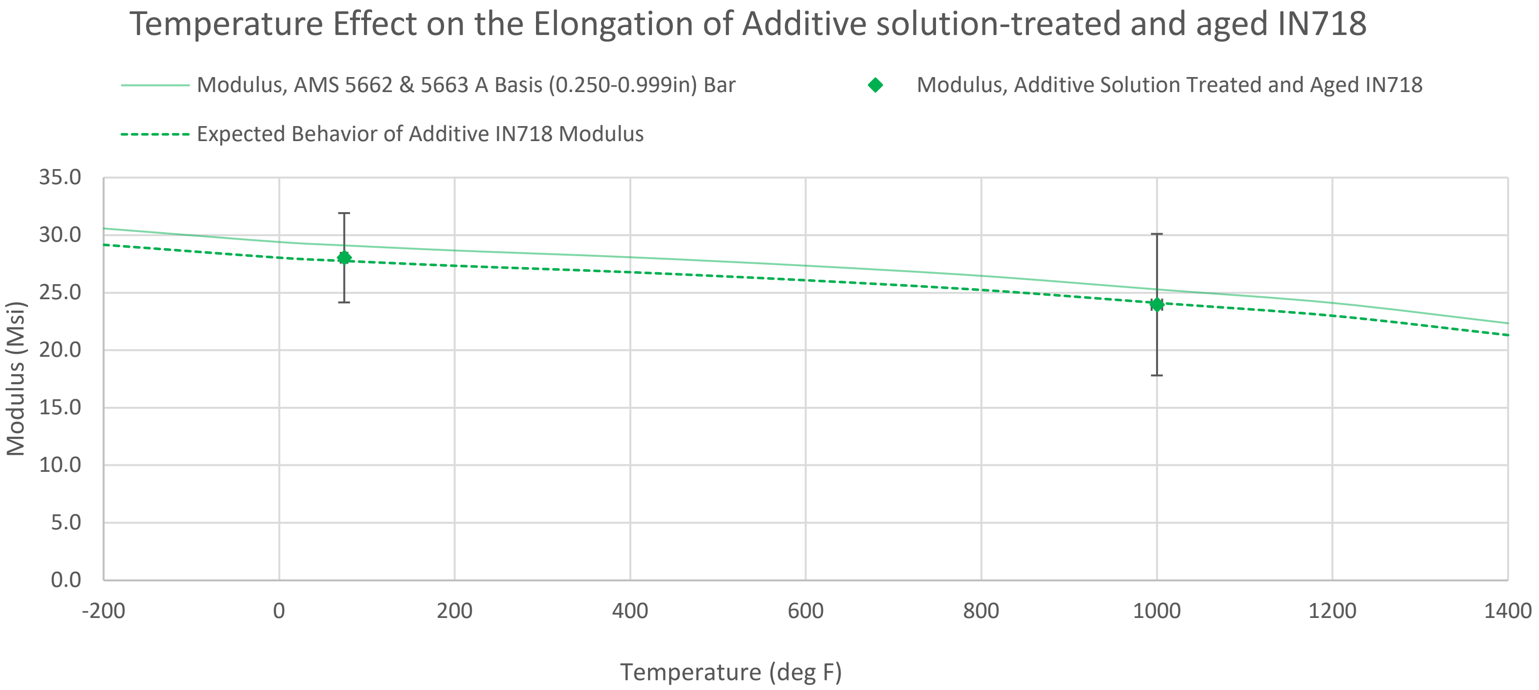
EXPECTED BEHAVIOR OR ADDITIVE IN718

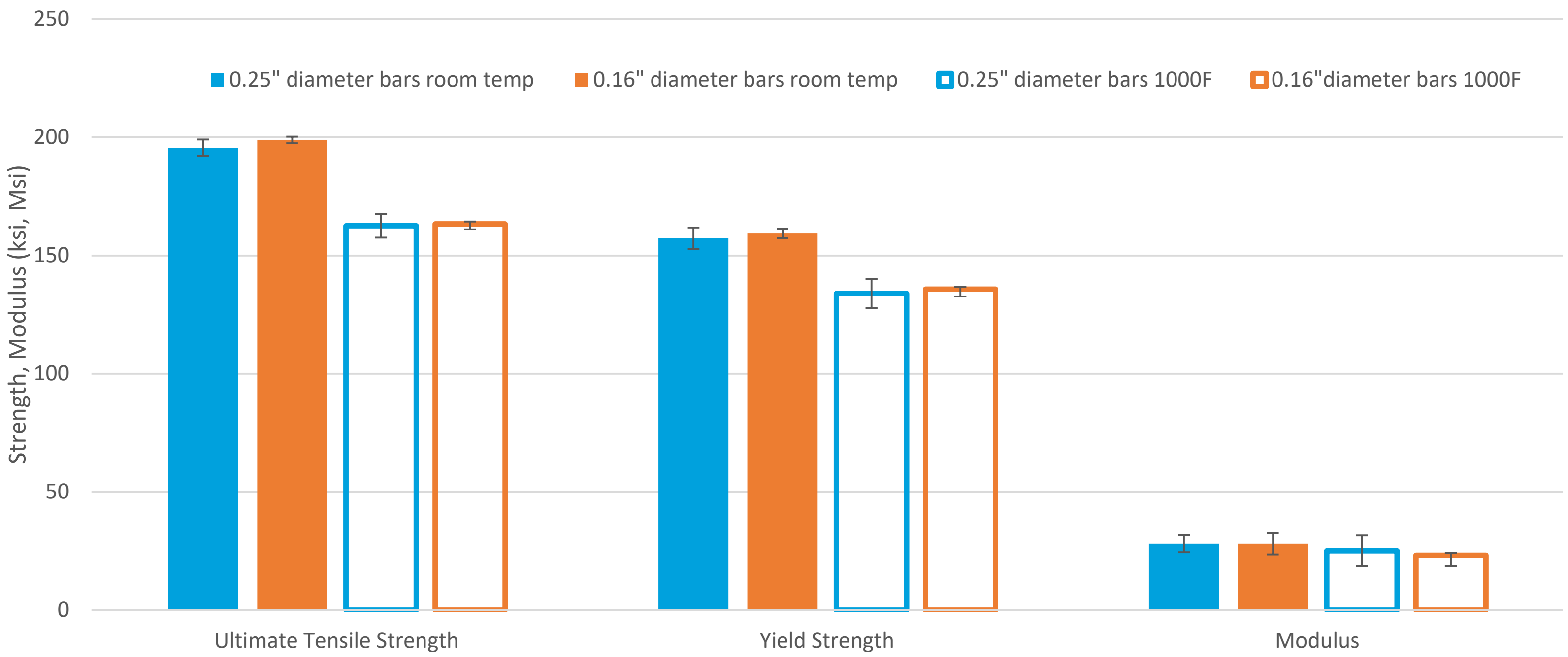


EXPECTED BEHAVIOR OR ADDITIVE IN718

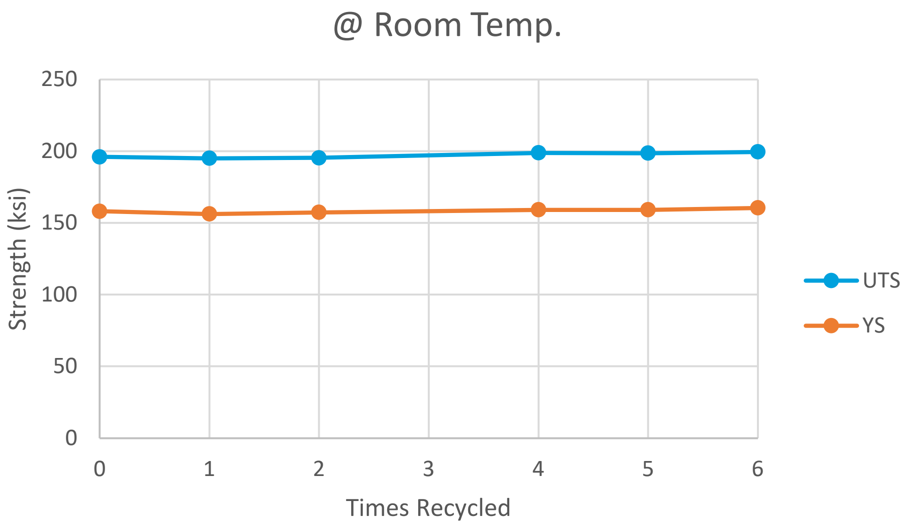


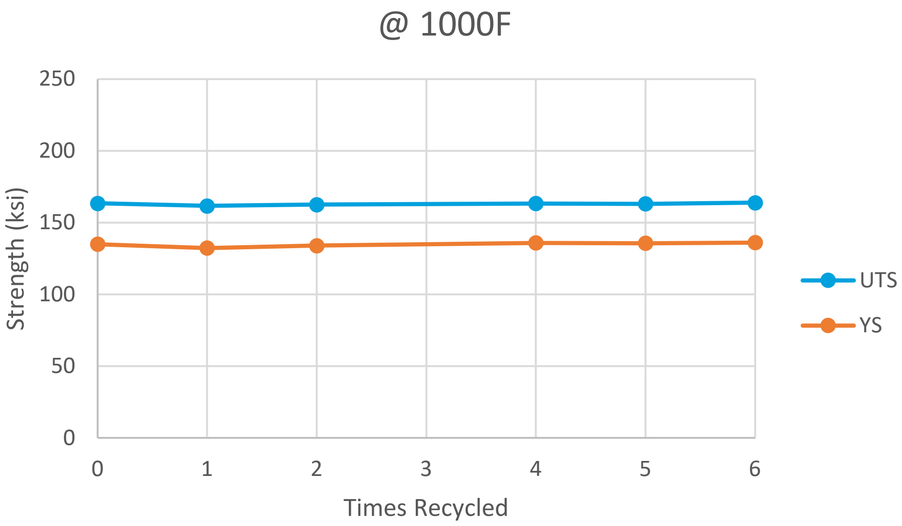
SMALL (0.16”) VS. LARGE (0.25”) DIAMETER BARS

ASTM E8, Round Bars, gage length 4X gage diameter



ADDITIVE IN718 TENSILE PROPERTIES AS A FUNCTION OF RECYCLING

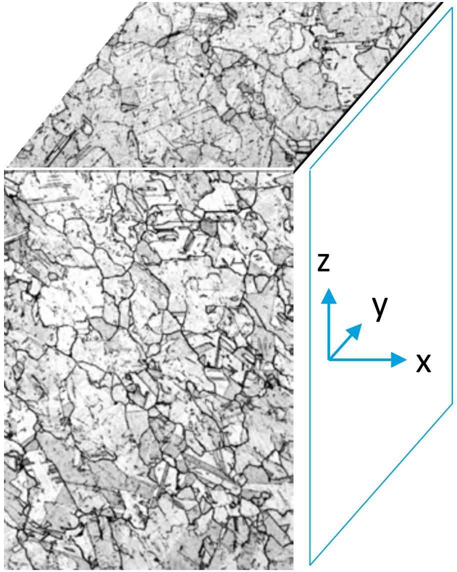




ADDITIVE IN718 METALLOGRAPHY

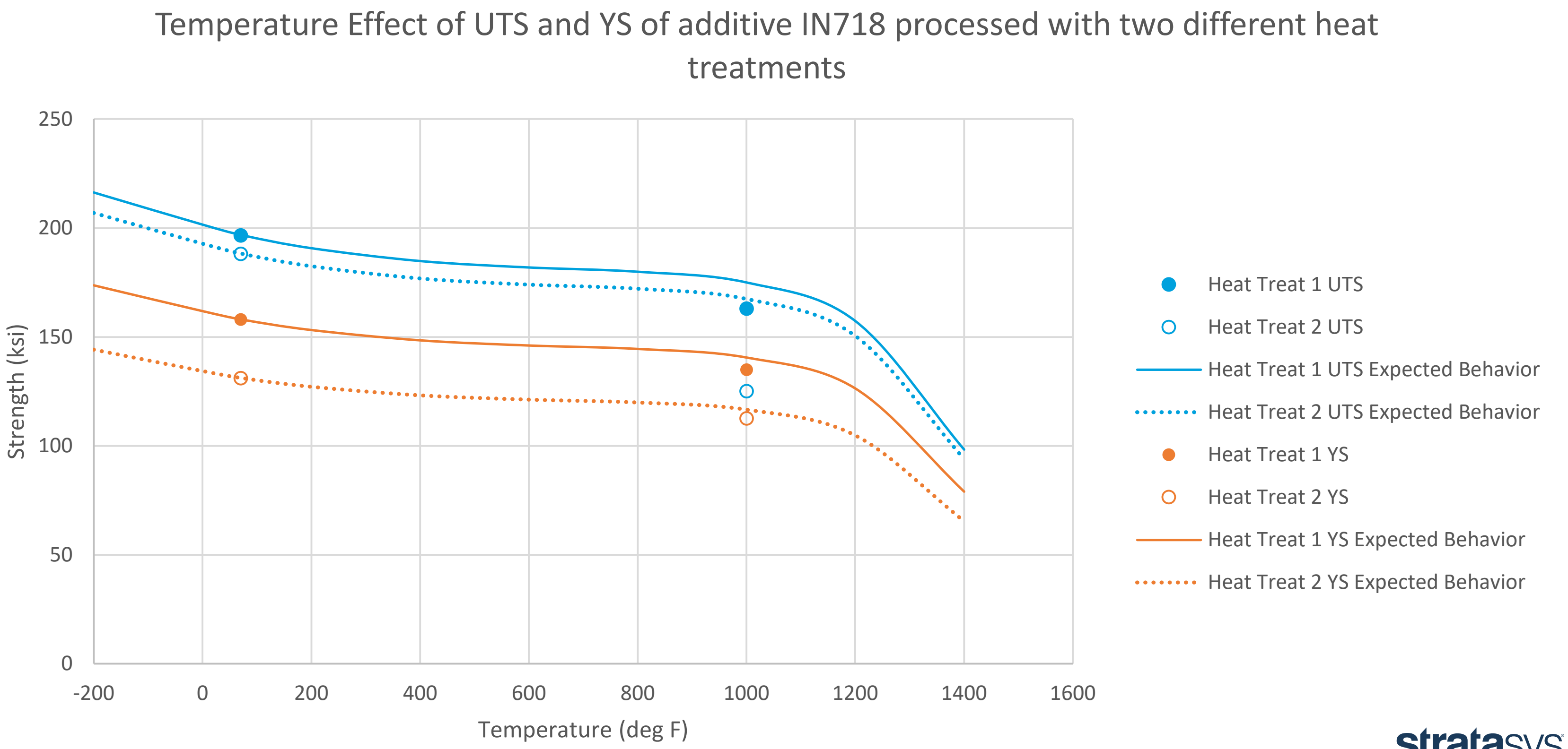
Tested 6 Samples for Grain Size in the XY and XZ planes.

Every sample (regardless of orientation) has an average grainsize ASTM No. 3.5 to 4.5.

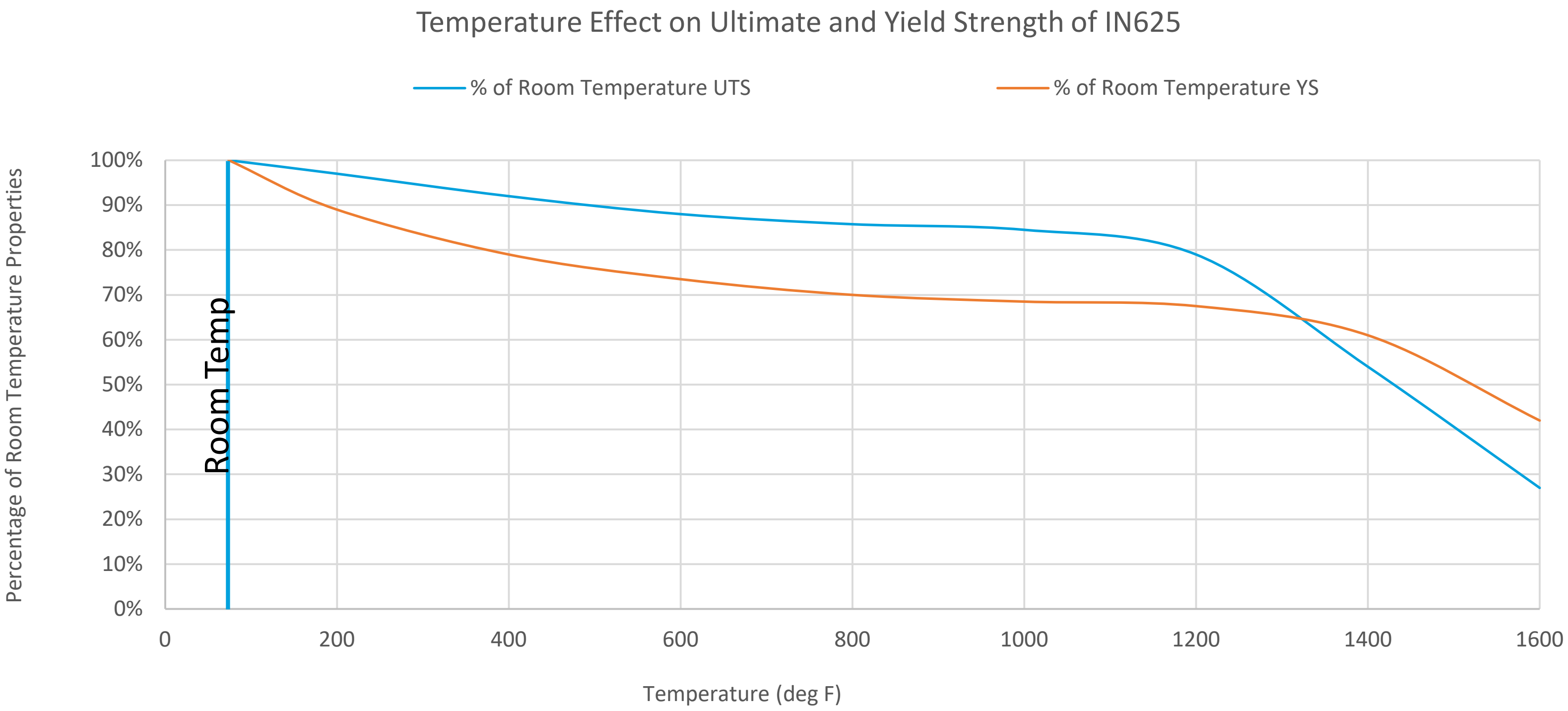


Precipitation Hardened,
Solution Heat Treated,
HIP'ed, Stress Relieved,
Additive IN718(100x)

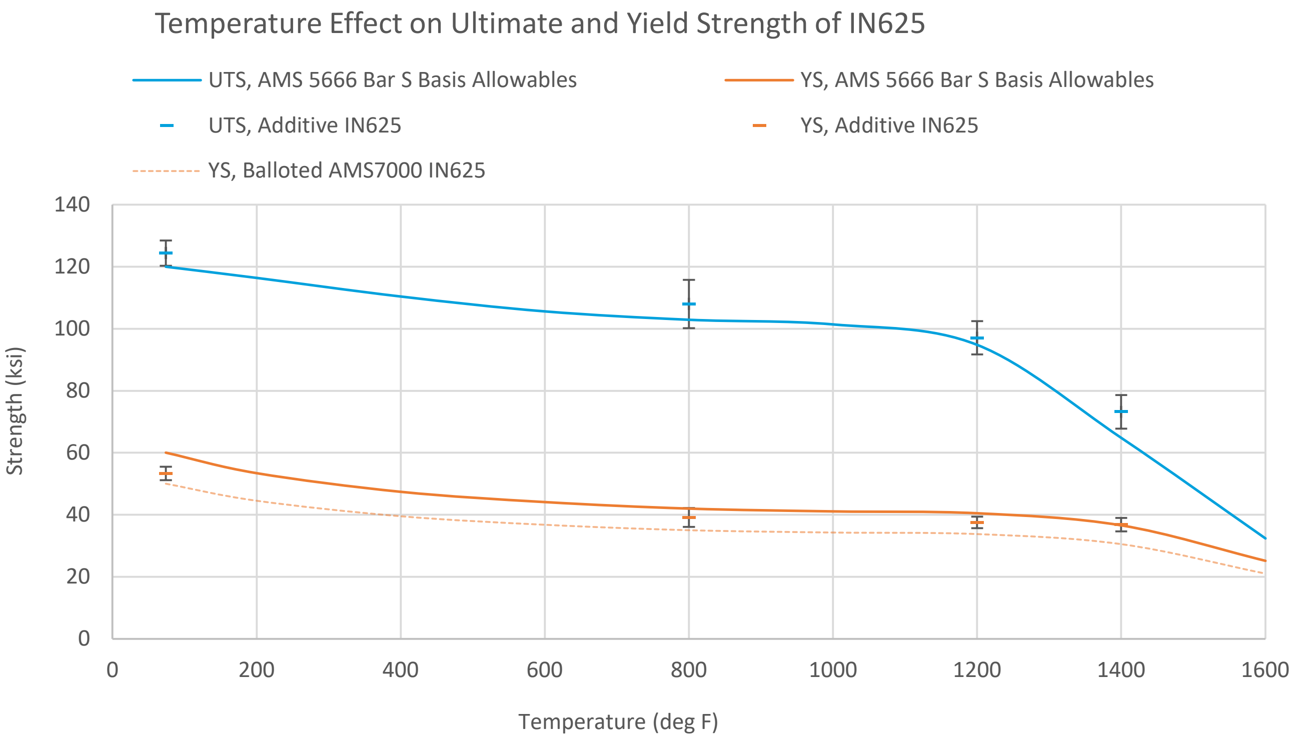
A COMPARISON OF DIFFERENT THERMAL PROCESSING



IN625 EXPECTED BEHAVIOR



ADDITIVE IN625 AT FIRST GLANCE



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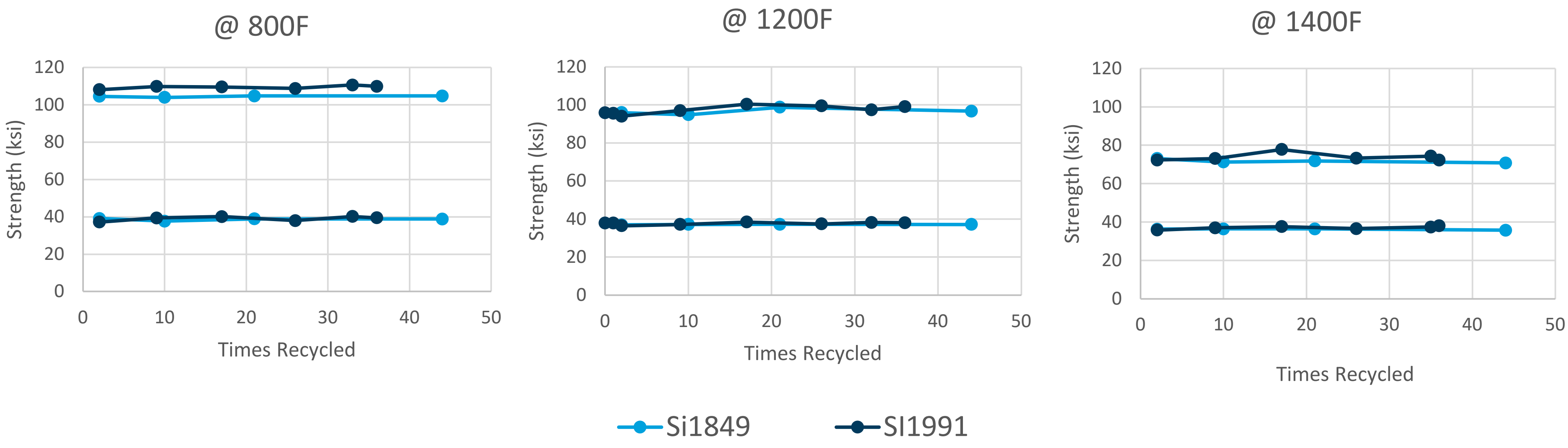
ADDITIVE IN625 TENSILE PROPERTIES AS A FUNCTION OF RECYCLING

Ultimate Tensile and Yield Strength of Additive IN615



Material Properties are consistent regardless of the time recycled.

CONCLUSIONS – ELEVATED TEMPERATURE TENSILE

The elevated temperature tensile response of **additively produced nickel base super alloys is similar to the expected behavior or wrought** materials.

Recycling of feedstock material has little to no influence on room or elevated temperature properties of IN718 and IN625.

The appropriate heat treating is required to achieving expected behavior in tensile response at elevated temperatures.

Stratasys Direct Manufacturing, committed to promoting the wide spread adoption of Additive Manufacturing as a viable means of producing end-use critical components makes these manufacturing studies available to industry.

CONCLUSIONS

CONCLUSION

THANK YOU

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Austin, TX
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