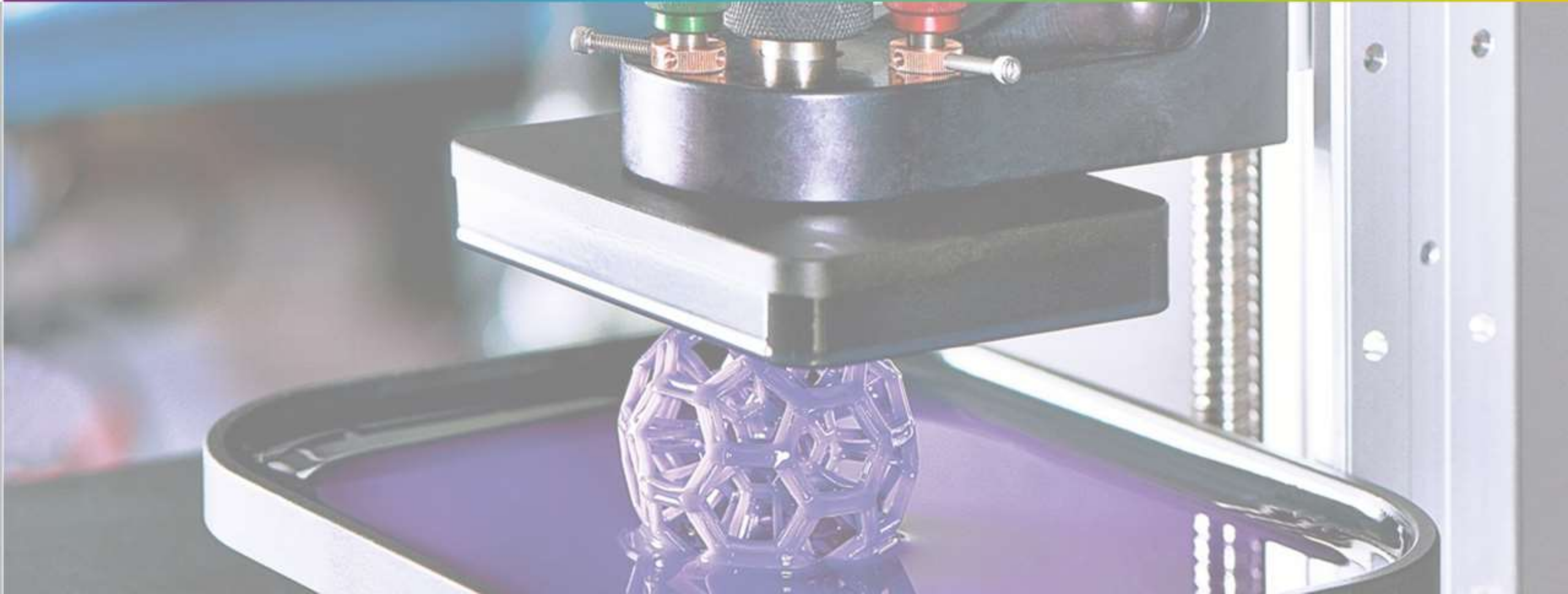
DIGITAL & ADVANCED MANUFACTURING
ADVANCES IN ADDITIVE MATERIALS



SILVERSTONE TECHNOLOGY CLUSTER

YOUR FEEDACK IS IMPORTANT TO US

Automation in Manufacturing

9:00	Registration and Networking
9:30	Welcome
9:35	AM Materials and Process Control – Ian Marsh
9:55	New Materials and Testing – Matt Jones
10:15	Addressing a few AM myths in the design office – Graham Barnes
10:35	Break
10:55	Additive Manufacturing In Defence – Alex Champion
11:15	PBF-LB Capability Development in High Strength Aluminium Alloys – Joseph Chamberlin
11:40	Panel Discussion and Closing Comments – Kieron Salter
12:00	Lunch and Networking
12:45	Tour

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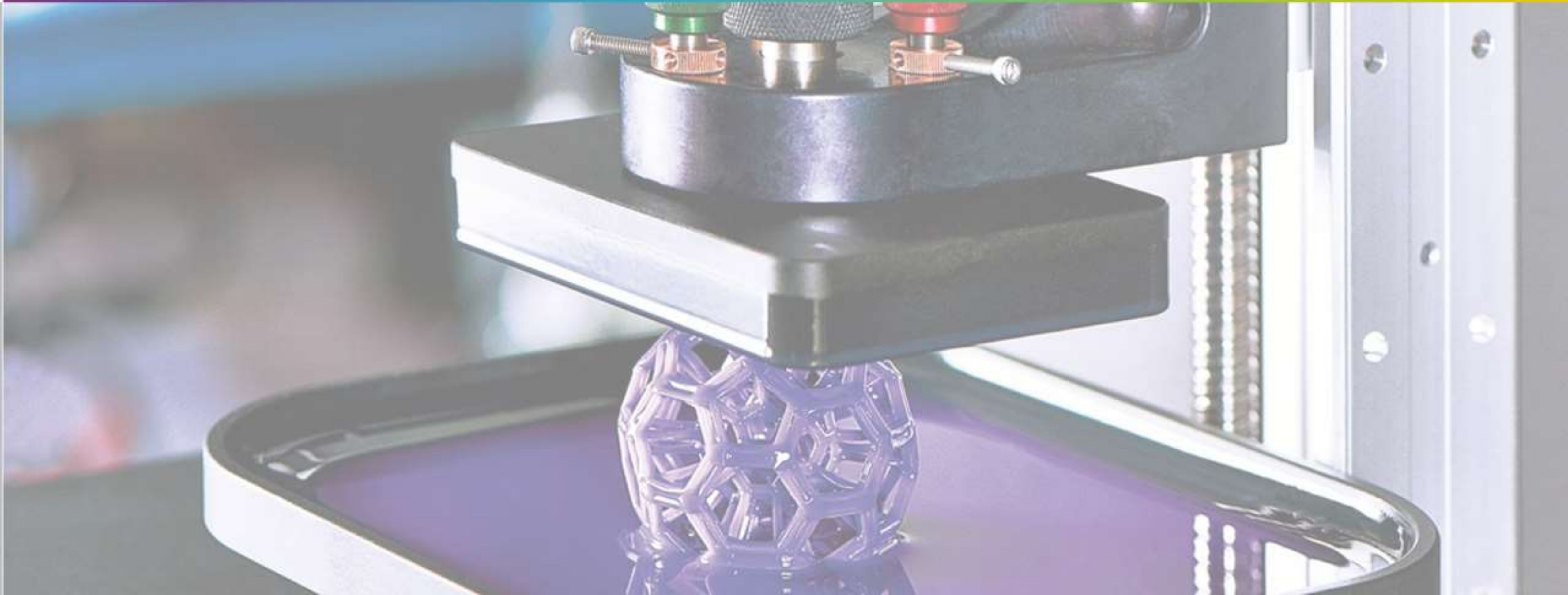


Process Control in Additive Manufacturing

Ian Marsh
19/10/2023

About Me

- Process Control Engineer at DMC
- Worked in Spain and the UK
- Studied at Loughborough University
- Enjoy playing sport
  - Primarily badminton
  - Competitive lifesaving

Overview

- What is Process Control – why do we need it?
- Process Control at DMC
- What does the future of Process Control Look like

What is Process Control

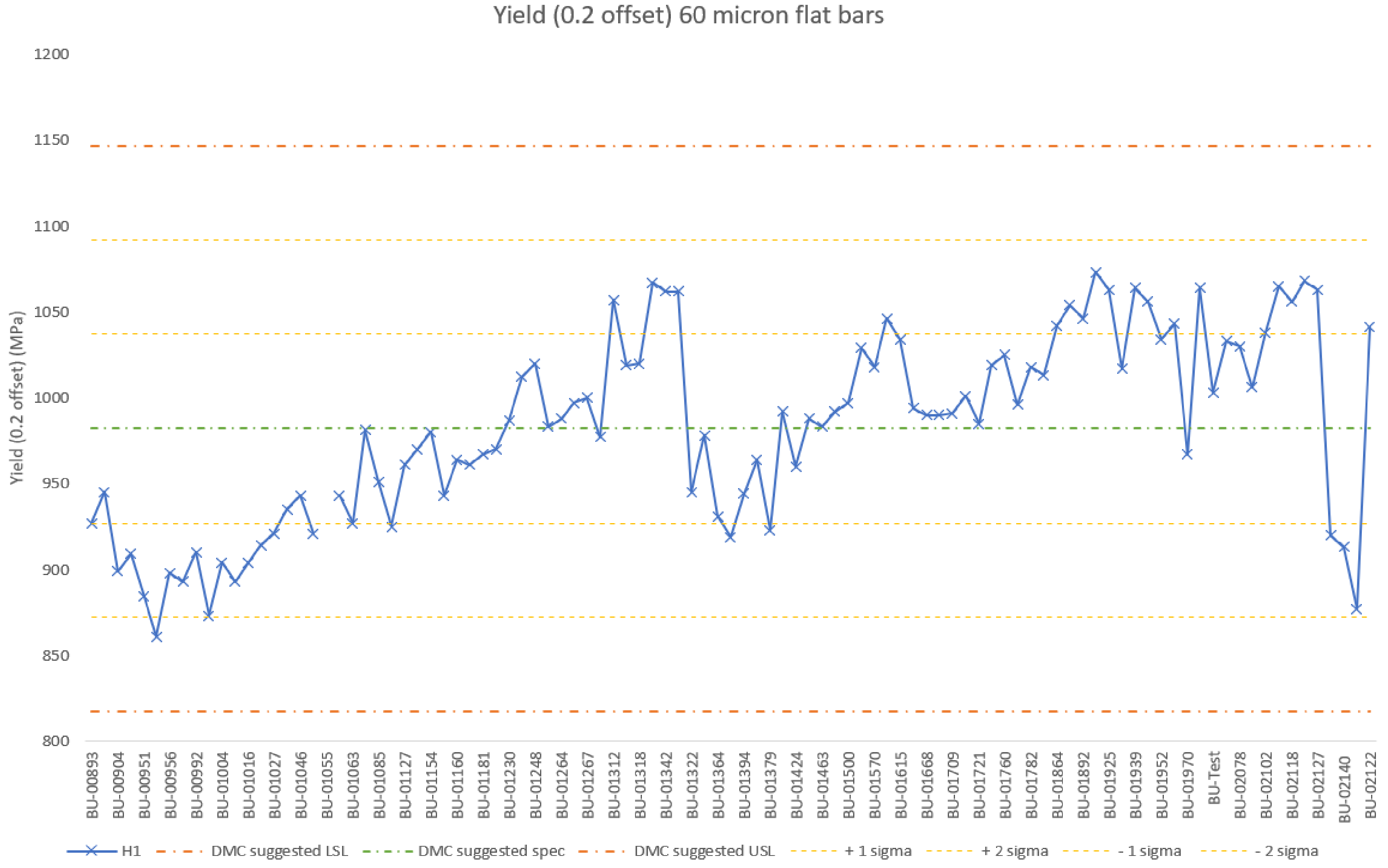
Process Control Definition

- Process Control is the ability to monitor and adjust a process to give a desired output
- The process involves active controlling of the variables based in the results at the time of monitoring
- Often involves the use of statistics such as control charts
- Can even lead to process improvements

What is a Process Control chart?

- A graph used to study how a process varies over time.
- Used to measure on-going performance by measuring the outputs of a process.
- A process is said to be **‘in control’** when it only contains common cause variation.
- Points above or below the LCL and UCL, or patterns in the data indicate ***possible*** special causes.
- Specific rules have been developed to help to determine when patterns should be investigated.

Journal of Quality Technology – Zones



2.14%	**Zone A**
13.6%	**Zone B**
34%	**Zone C**
34%	**Zone C**
13.6%	**Zone B**
2.14%	**Zone A**

Journal of Quality Technology Assignable cause tests

- Test 1. One Point Beyond Zone A
- Test 2. Nine Points in a Row on One Side of the Centre Line
- Test 3. Six Points in a Row Steadily Increasing or Decreasing
- Test 4. Fourteen Points in a Row Alternating Up and Down
- Test 5. Two Out of Three Points in a Row in Zone A or Beyond
- Test 6. Four Out of Five Points in a Row in Zone B and Beyond
- Test 7. Fifteen Consecutive Points within Zone C
- Test 8. Eight Points in a Row on Both Sides of Centreline with None in Zone C.

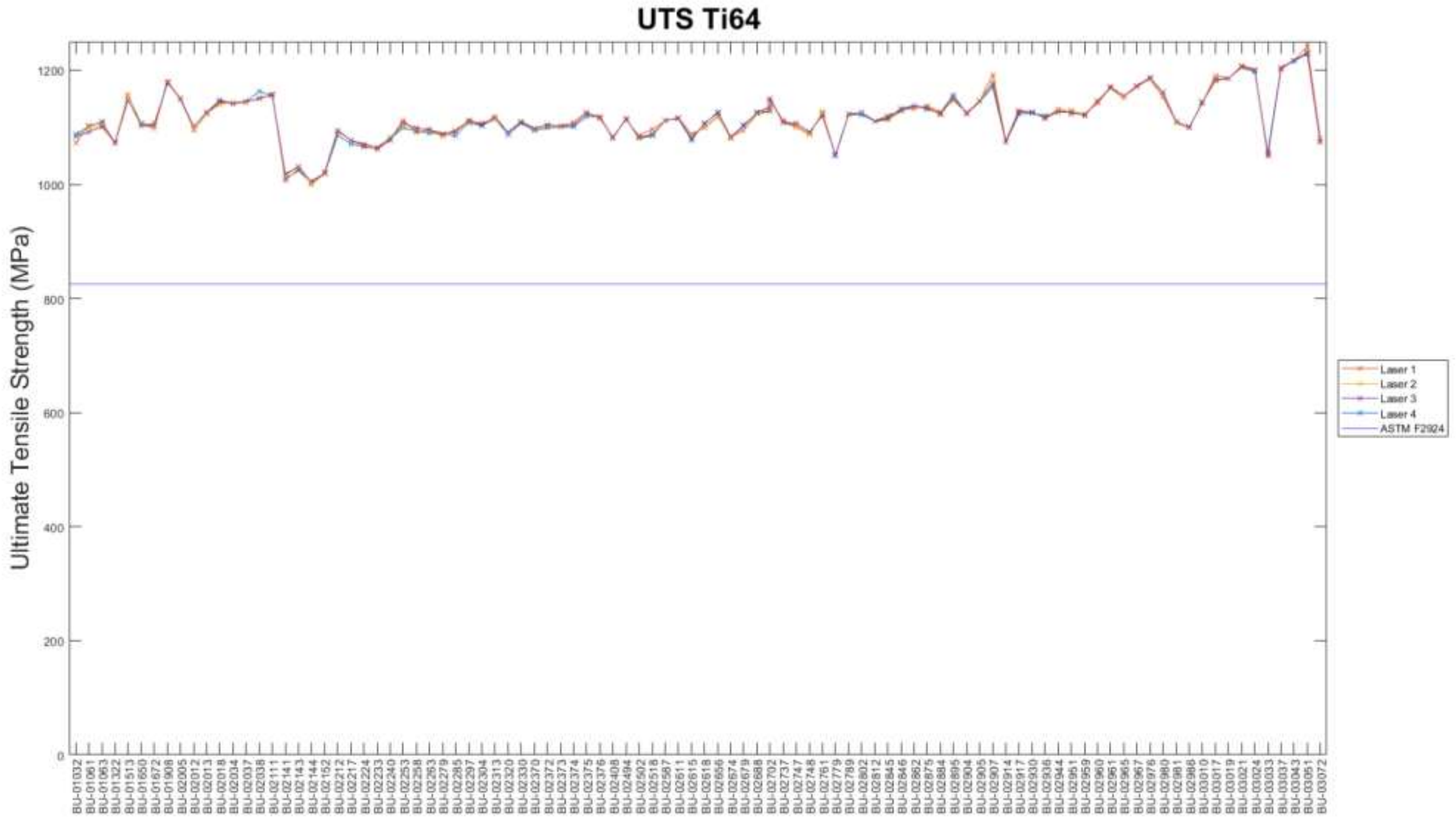
Applying the Tests for Special cause

- Typically only a subset of the 8 tests are applied to Control Chart interpretation
  - Tests 1 and 5 should be applied generally
  - Sensitivity to smaller process shifts may benefit from applying tests 2 and 6
  - Consistent mean shifts may be best detected by tests 4 and 8
  - Test 7 will uncover an improvement of the process
  - Tests 3 should be used if the process inherently drifts
- Applying too many of these tests increases the chance of a false alarm

Selecting special cause tests

- Test 1. One Point Beyond Zone A
- Test 2. Nine Points in a Row on One Side of the Centre Line
- Test 3. Six Points in a Row Steadily Increasing or Decreasing
- Test 4. Fourteen Points in a Row Alternating Up and Down
- Test 5. Two Out of Three Points in a Row in Zone A or Beyond
- Test 6. Four Out of Five Points in a Row in Zone B and Beyond
- Test 7. Fifteen Consecutive Points within Zone C
- Test 8. Eight Points in a Row on Both Sides of Centreline with None in Zone C

Ultimate tensile strength control chart



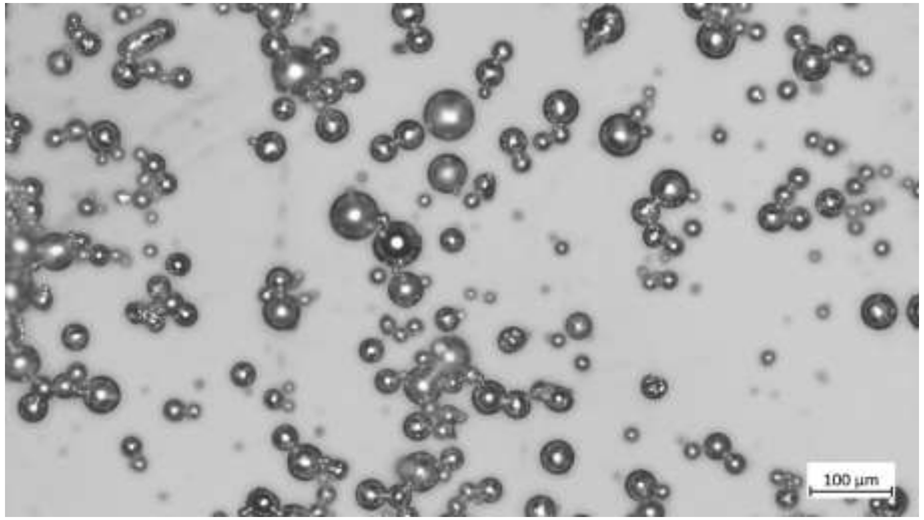
Process Control at DMC

Process Control at DMC

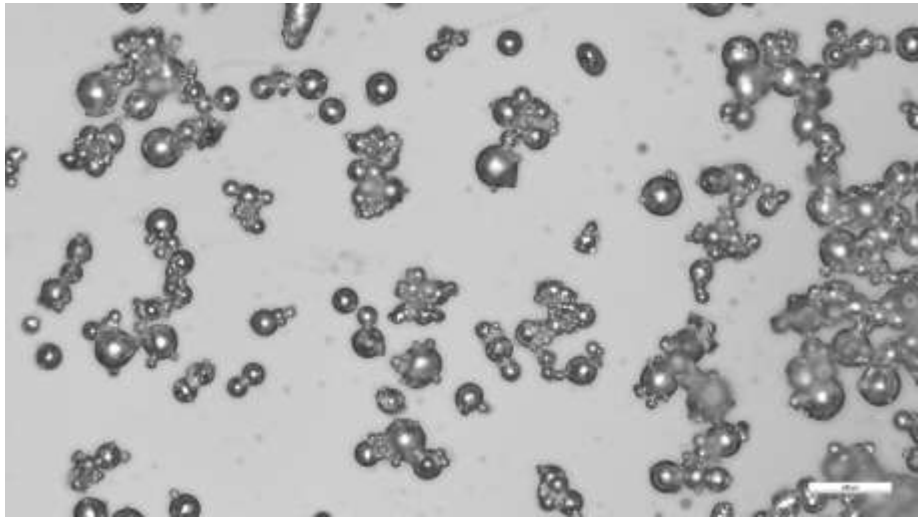
- Measuring the inputs (powder goods in)
- Monitoring the temperature and humidity in powder storage
- Measuring the outputs (tensile testing, porosity blocks)
- Use of control charts
- Use of industry accepted standards

Powder goods in

- Don’t just trust a suppliers CoC
- Checking for:
  - Hall/ Carney flow
  - Particle size distribution (PSD)
  - Powder morphology



Acceptable powder



Unacceptable powder

Job Pack for every build

- Powder sample
- Porosity cubes
- Tensile test specimens

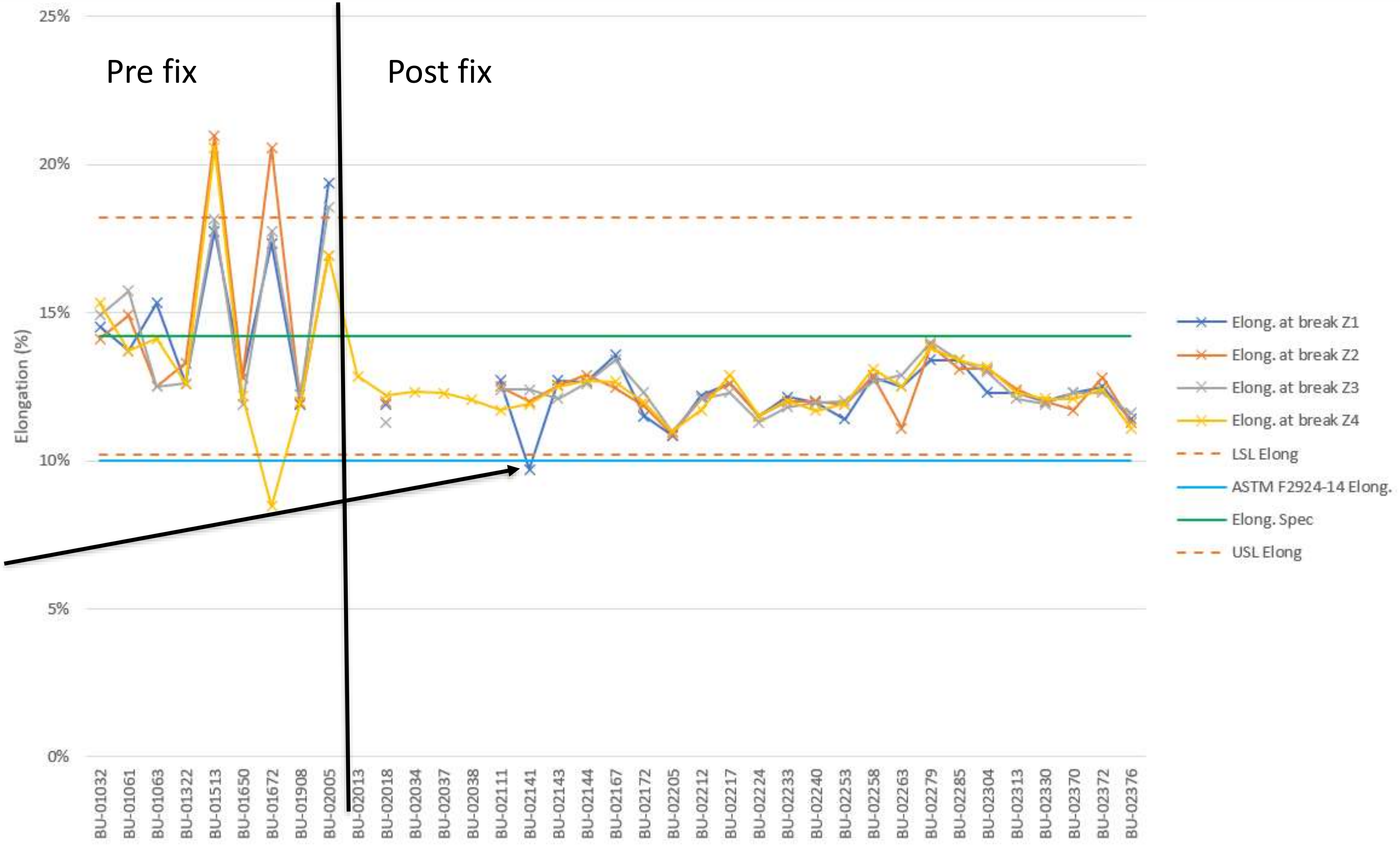
Why do Tensile Testing

- Ensure quality
- Give our customers confidence
- Process control
- Understand the material properties
  - Strength
  - Ductility
  - Elasticity
  - Stiffness

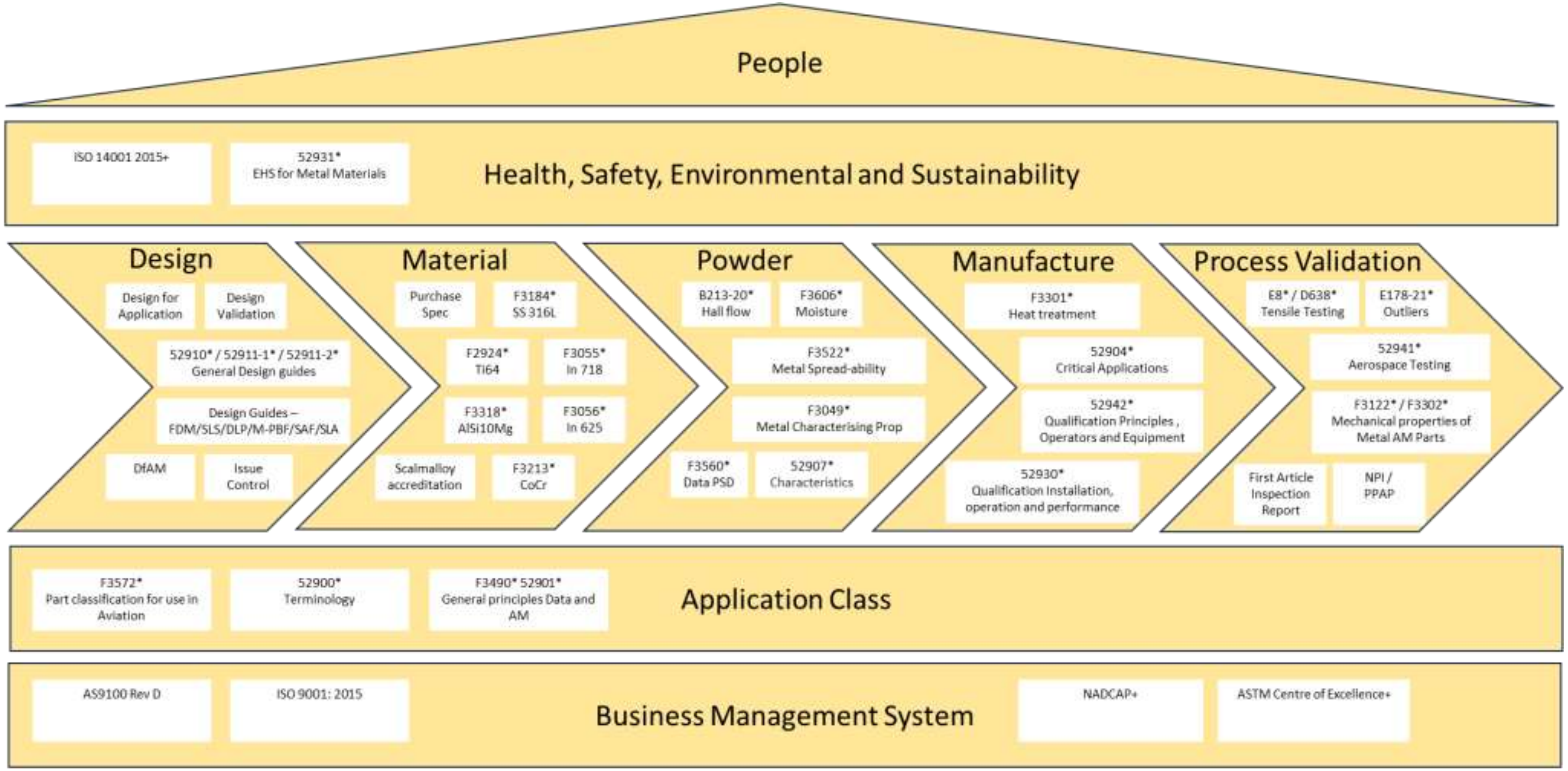
Continuous improvement using control charts

- Pre and post furnace fix
- Gas optimisation fix

Can be removed as a statistical outlier



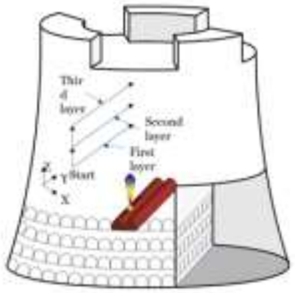
Standards in DMC



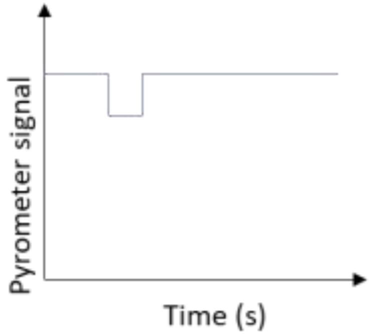
*ATSM Standard
+DMC Roadmap

Process Control in the Future

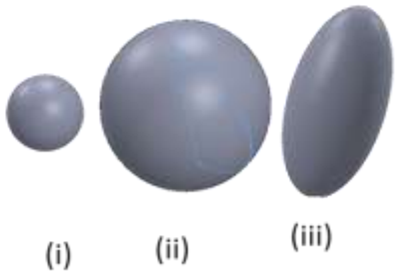
An idea for the future



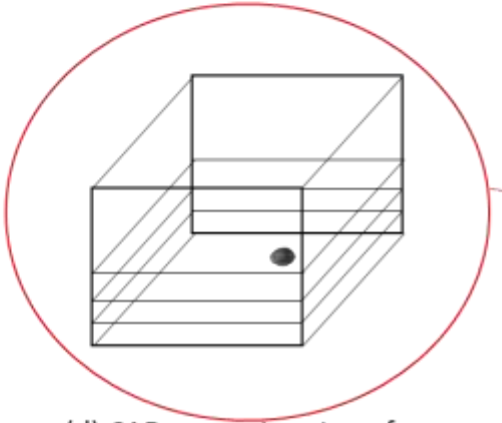
(a) Scan strategy



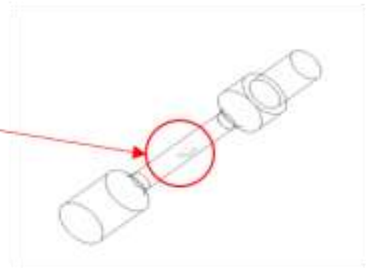
(b) Laser power variation



(c) Pore library (i) small (ii) large (iii) elongated



(d) CAD approximation of location of defects based on laser power variation



(e) Tensile test of model

DIGITAL MANUFACTURING CENTRE

Thanks for listening

Ian Marsh
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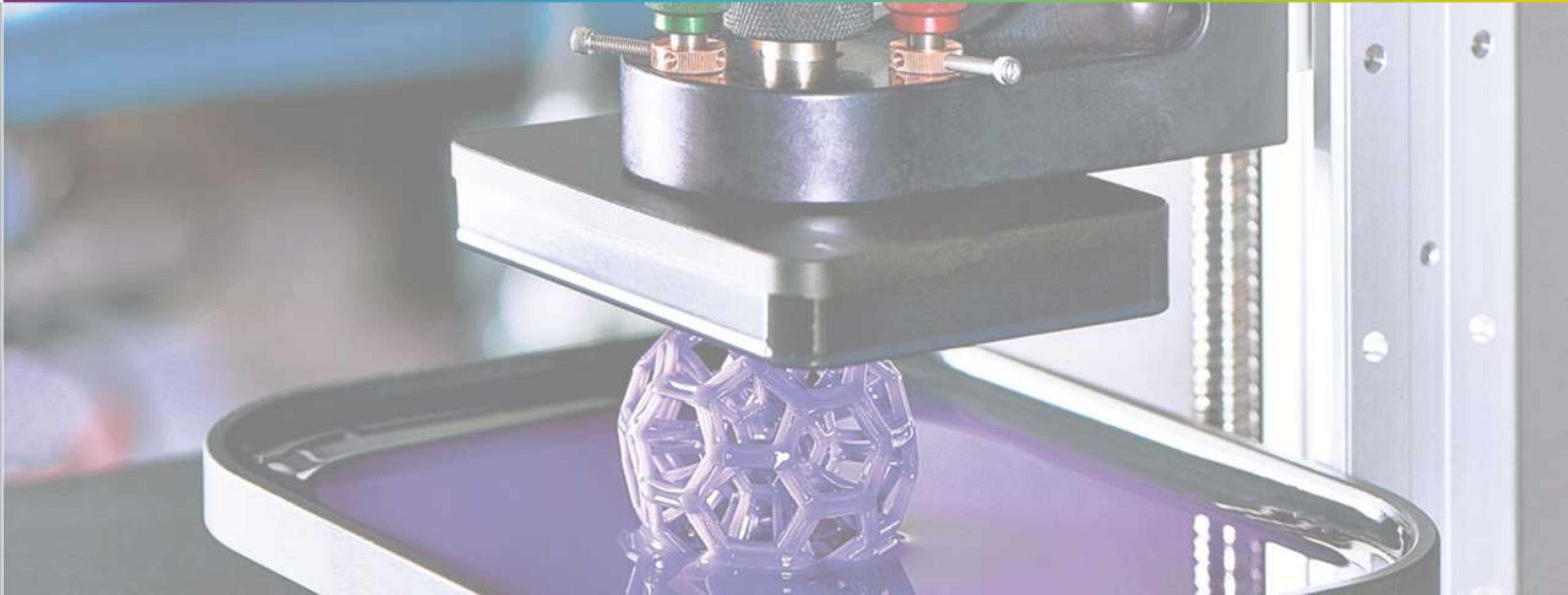
DIGITAL & ADVANCED MANUFACTURING
ADVANCES IN ADDITIVE MATERIALS

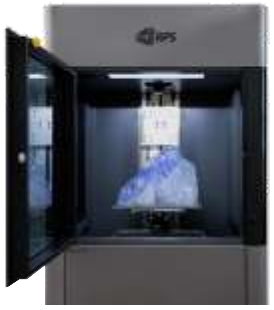


Stratasys Polymer Materials

October 2023

Best-in-class portfolio for the entire product value chain

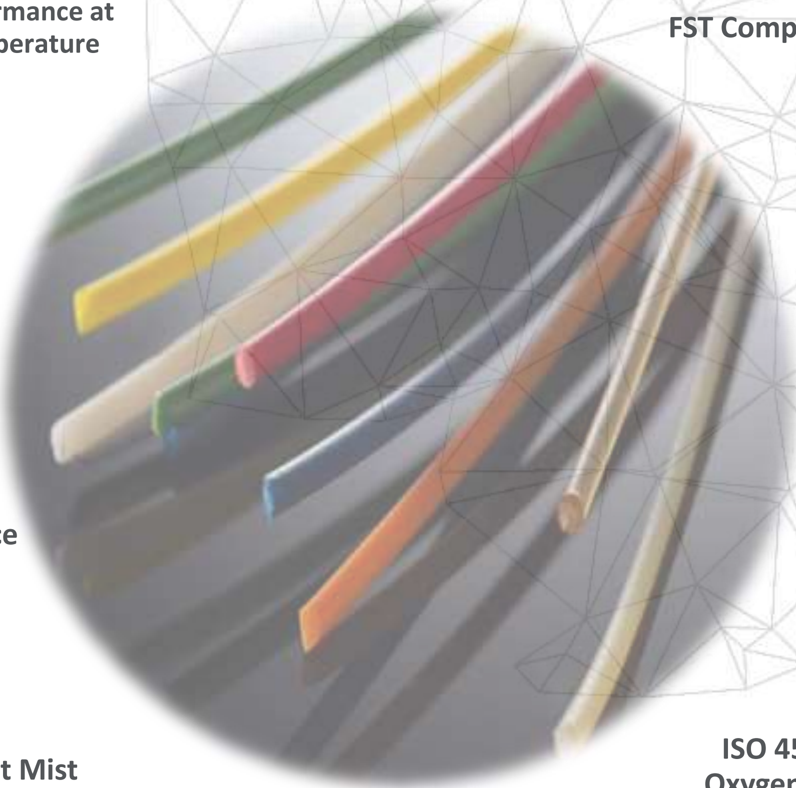
5 Leading Additive Technology Platforms

PolyJet	Stereolithography	Industrial FDM	Origin P3	SAF
				
Prototypes / Medical Modeling	**Prototypes / Tooling / Molds**	**Manufacturing Tools / Production Parts**	**Mass Production**	**Mass Production**
Detailed, multi color, multi-material realism	Proven reproducibility and dependability with powerful industrial-grade materials	World-class accuracy and consistency, and unmatched material breadth	Highly intricate and accurate parts, and broad third-party material options	Cost-effective parts of all sizes with production control

Enterprise Application Integration for Industry 4.0 Scale

GRABCAD SHOP | GRABCAD PRINT | GrabCAD SDK | **GrabCAD Software Development Partners**

Material Performance



- Electrical Directive
- EASA – NCAMP
- FST Compliant
- ESD Compliant
- UL 94 Blue Card
- ISO 4589-2 Oxygen Index
- ISO 4589-3 Temp Index
- SOLAS 74 - ISO 18079
- Salt Mist
- Chemical Resistance
- UV Resistance
- Performance at Temperature

Fortus 450mc

Specifications:

- **Build envelope 406 x 355 x 406 mm**
- **Material Delivery (2 bays material and 2 bays for support)**
- Size (51 x 35.5 x 78.1 in; 406 x 355 x 406 mm)
- Weight (1325 lbs, 601kg)
- Power (208VAC, 3 phase, 50/60hz)
- Certifications (CE, cTUVus, EAC, FCC Part B)

Features and Software:

- **Insight™ and Control Center™**
- **GrabCAD Print**
- MTConnect ready
- Connectivity API's
- STIG Compliant/RedHat
- OpenAM™
- **Onboard compressor means no shop air required**
- **Small footprint and wheels allows quick placement and startup.**

Preferred Materials:

- ASA
- ABS-M30, ABS-M30i, ABS-ESD7
- Antero 800NA
- Antero 840CN03
- PC-ABS, PC-ISO, PC
- ULTEM™ 9085 resin
- ULTEM™ 1010 resin
- FDM Nylon 12
- FDM Nylon 12CF
- ST-130

92 ci, 184 ci, 500 ci spool size

Validated Materials:

- VICTREX AM™ 200
- Kimya Kepstan® PEKK-SC
- Kimya PC-FR
- Addigy® PA6/66-GF20 FR LS
- FDM® HIPS
- PC-ABS Red
- PC Red
- PC Black
- ULTEM™ 9085 resin Red
- ULTEM™ 9085 resin Jana White
- ULTEM™ 9085 resin Dream Gray
- ULTEM™ 9085 resin White 7362
- ULTEM™ 9085 resin Gunship Gray
- ULTEM™ 9085 resin Aircraft Gray

92 ci spool size

**9085, 1010 and ULTEM™ are trademarks of SABIC, its affiliates or subsidiaries.*

FDM Material portfolio

Preferred Materials | **Validated Materials**

	Preferred Materials	Validated Materials
High Performance	ULTEM™ 1010 resin ULTEM™ 9085 resin PPSF / PPSU Antero 840CN03 (ESD) Nylon 12CF Antero 800NA	ULTEM™ 9085 resin (colors) Victrex AM™ 200 (LMPAEK)
Engineering Plastics	FDM Nylon12 Diran 410MF07 FDM Nylon6 PC PC-ISO PC-ABS ABS-CF10 Nylon-CF10	Kimya PC-FR Addigy® PA6/66 GF20 FR LS PC (color options) PC-ABS (color options)
Standard Plastics	ABS-M30 ABS-ESD7 ABSi ASA	FDM® HIPS

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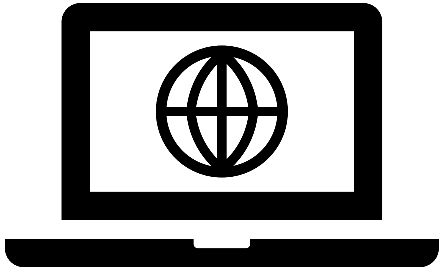
Stratasys OpenAM™ Elements for Success

System, Software, Expertise

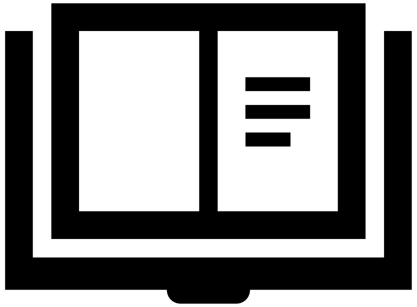
System

The Fortus 450mc printer, fully hardened (upgrade may be needed) and an OpenAM print head



OpenAM™ Software

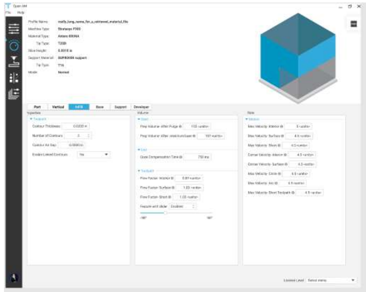
Stratasys OpenAM software plus Insight and GrabCAD Print



Expert Guidance

Detailed tuning support guide with Stratasys best practices

OpenAM Workflow



OpenAM Software:
Creates Profile for new material; uploads Set to server

1

Upgrade Server:
Validates Framework; Creates and returns Package to user's printer *and* workstation software

2

Workstation
(GC Print or Insight): Updates application w/ new parameters; slices part and generates CMB

3

Unlocked Fortus 450:
Upgrades printer software with new parameters, load CMB file, start build

4

Profile → Tuning → Set → Package → Upgrade

Software overview

Key differentiators of OpenAM

Feature based tuning

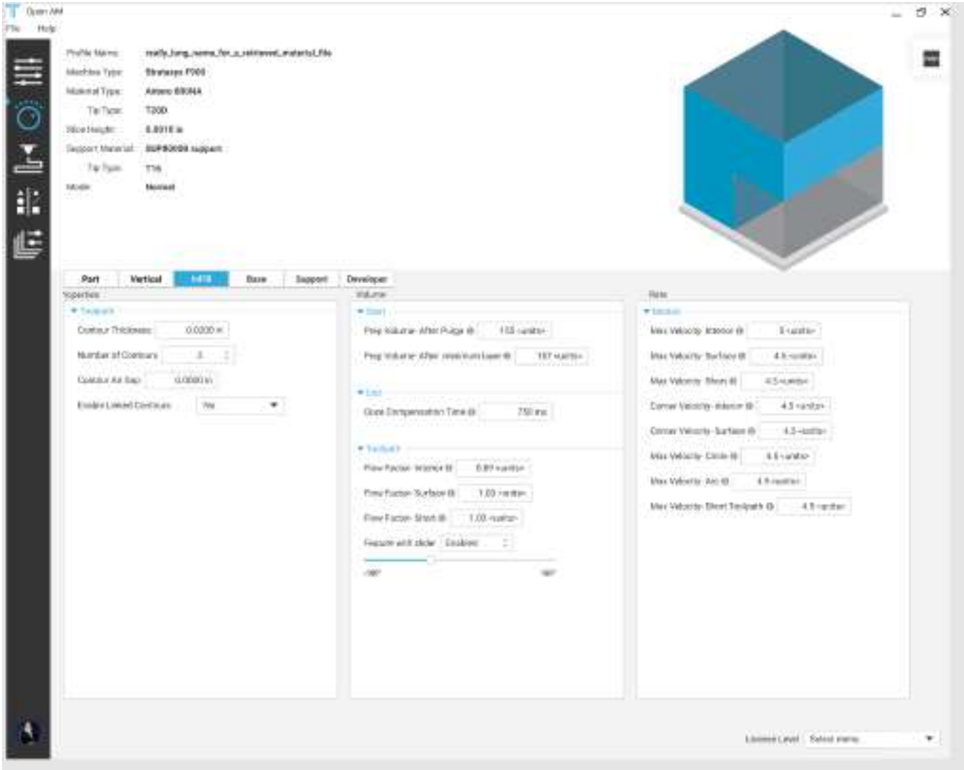
- Quickly adjust desired characteristics by going to the feature tabs (Part, Vertical, InFill, Base, or Support)

Material class specific defaults and safe ranges

- Choose from a long list of polymers, via generic material chips, to get a head start on tuning success
- Max/Min parameter ranges set to reduce costly failures and lost time

Easy to use software

- Helpful tuning tool tips in the software paired with the Stratasys Tuning Guide help you achieve repeatable success



Generic Material Chips

OpenAM generic chips determine the default starting parameters and the max/min ranges based on the base material profile

Generic Chip Base Materials

- ABS
- ASA
- PC
- PEI-HT (high temp)
- PEI
- PA12
- PA12CF
- PEKK
- More to come!!

Reusable Fortus Plus Cannisters and Spools available for purchase

Key Editable Parameters

Open Parameters Include:	Bead Modes:
Liquefier Temperature	Surface
Oven Temperature	Solid Raster
Max Velocity	Sparse Raster
Corner Velocity	Short Toolpath
Flow Factor	Base
Toolpath Prep Volume	First Layer
Toolpath End Volume	Sparse Support
Stringing Control	Support Interface
Min Layer Time	
Purge Time	
Extruder Fan Duty Cycle	
Plus, the option to set defaults for many GrabCAD Print and Insight slicing parameters	

OpenAM™ Tuning Guide

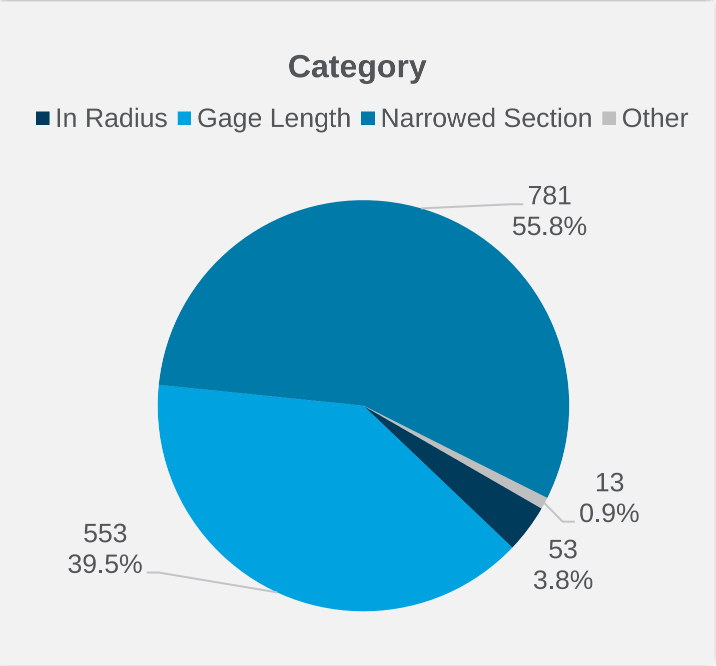
Detailed guide to help you get faster, more reliable and repeatable results with OpenAM

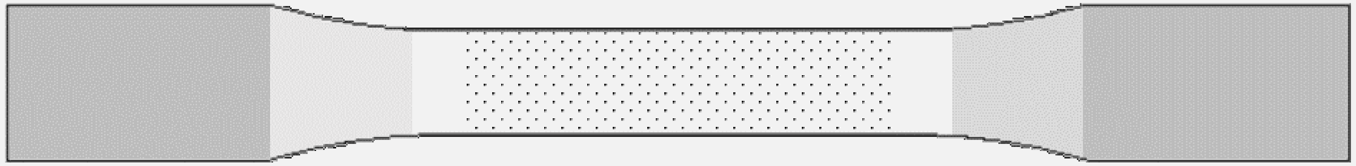
- Stratasys tuning theory best practices
- How to do feature-based part tuning
- Troubleshooting suggestions
- Workflow suggestions for tuning new materials
- Tips, support, build sheet cross reference guides

Repeatability study

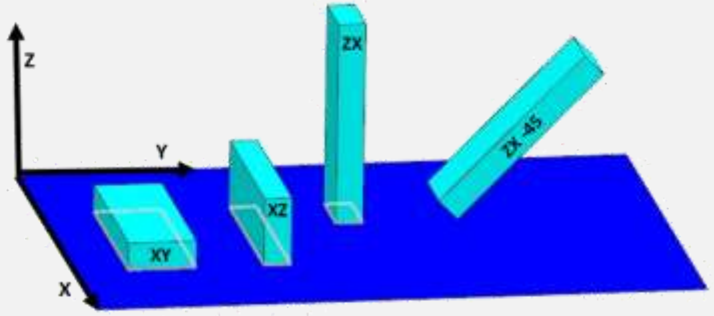
Mechanical Strength Testing

- Mechanical performance of FDM parts was characterized by tensile testing by ASTM D638
- Printed in XZ (on edge) and ZX (upright) orientations
  - XZ demonstrates proper extrusion rate of toolpaths
  - ZX demonstrates layer-to-layer cohesion strength
  - Both orientations are important in overall part strength (XY and Z45 are hybrid variants of these orientations)
- In accordance with good practice for additively manufactured D638 coupons, only coupons that broke in either the gage length or narrowed section were included in the analysis





ASTM D638 Type I Coupon



Mechanical Strength

Material	Machine	XZ (on edge)						ZX (upright)					
		Ult. Tensile Strength (psi)		Tensile Modulus (psi)		Elongation at Break (%)[1]		Ult. Tensile Strength (psi)		Tensile Modulus (psi)		Elongation at Break (%)[1]	
		Average	COV	Average	COV	Average	COV	Average	COV	Average	COV	Average	COV
ASA	450mc	4.558	5.5%	235.000	11.6%	6.3%	21.5%	3.643	6.0%	243.000	7.6%	1.9%	11.5%
	Datasheet (F900)	4.750		311.000		9.0%		4.300		298.000		3.0%	
Nylon 12CF	450mc	10.879	3.5%	1.225.000	16.6%	3.3%	5.3%	4.373	6.9%	406.000	22.4%	1.8%	14.2%
	Datasheet (F900)	9.190		1.370.000		1.9%		4.170		434.000		1.2%	
ULTEM™ 9085 Resin	450mc	11.215	4.7%	340.000	6.9%	5.8%	8.4%	6.467	11.1%	299.000	5.1%	2.5%	13.0%
	Datasheet (F900)	9.950		348.000		5.8%		6.100		309.000		2.2%	

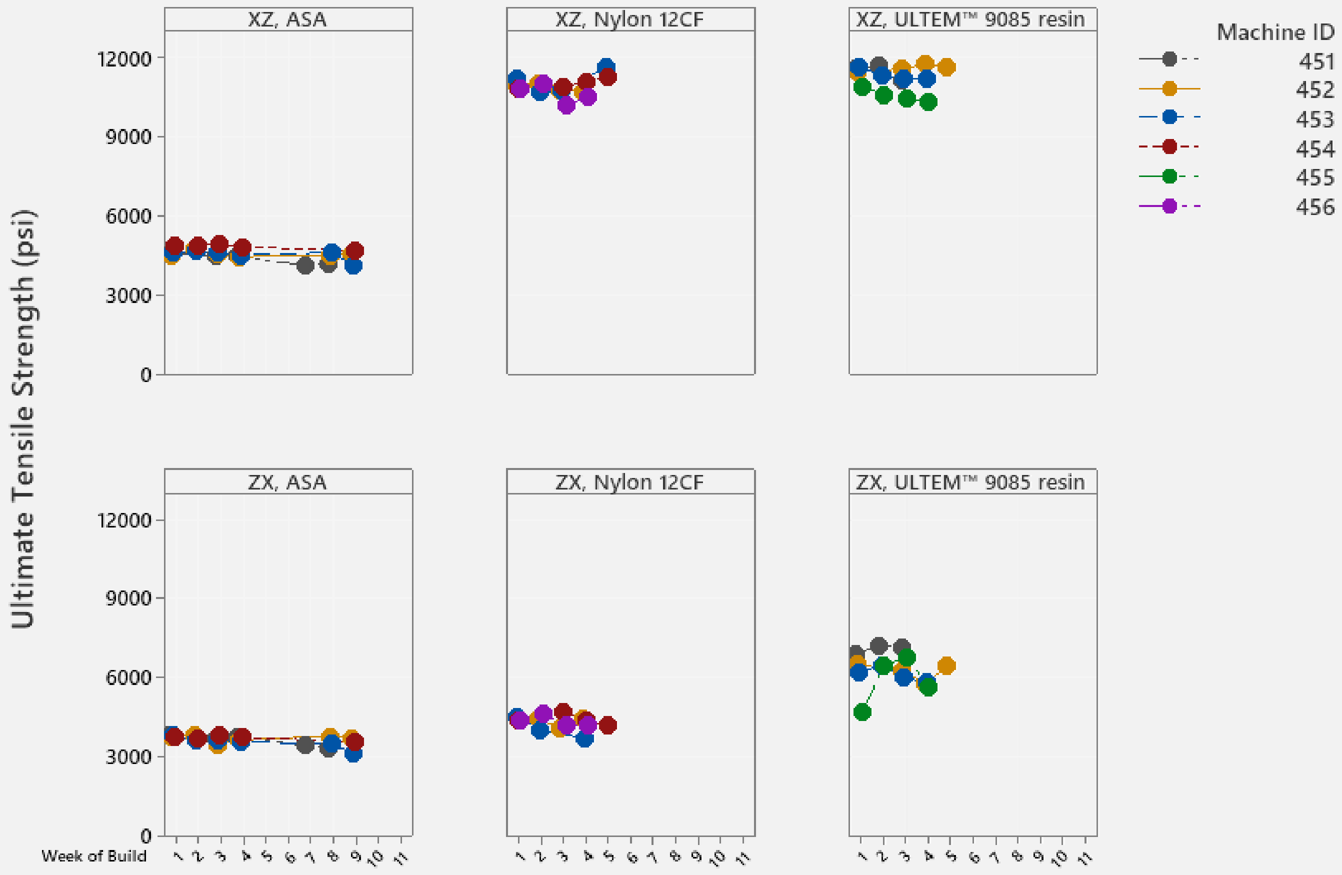
Key Takeaway: Study data matches past characterization of Stratasys materials

Note: ULTEM™ is a registered trademark of SABIC or affiliates; 1. Xxx

Mechanical Strength Results

Repeatable over time

Reproducible between machines

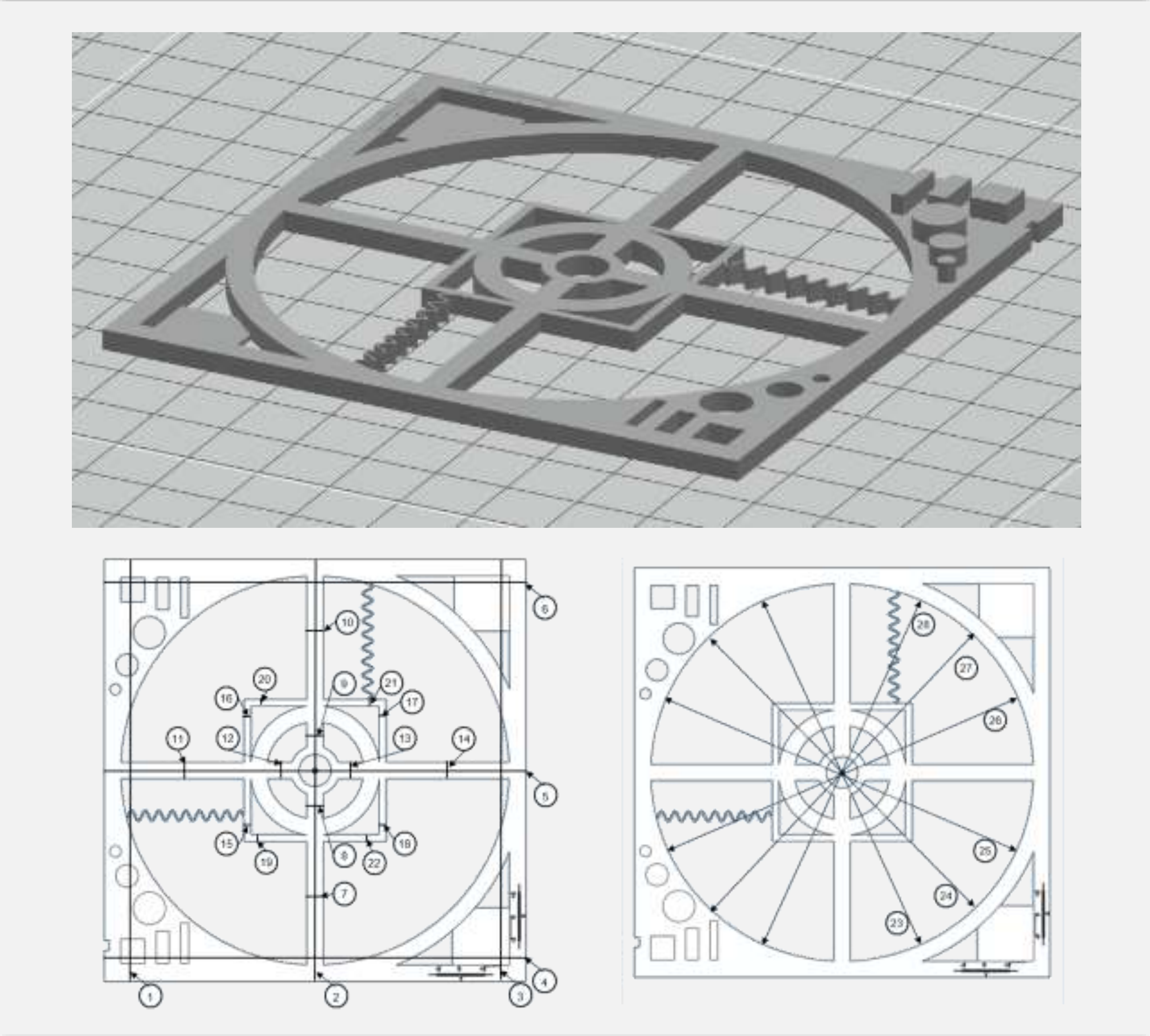


Key Takeaway: Mechanical strength (ex. tensile) is consistent between machines and over time

Dimensional Precision (1/2)

- Dimensional measurements conducted on a coordinate measuring machine (CMM)

- 228mm check part test geometry provides
  - Large number of features per part (43 unique measurements)
  - Good range of feature sizes (3,5 to 228mm)
  - Mixture of bosses and holes
  - Mixture of curved and straight toolpaths
  - Ability to be printed on all machine types in study



Dimensional Precision (2/2)

Aggregated Feature Checks

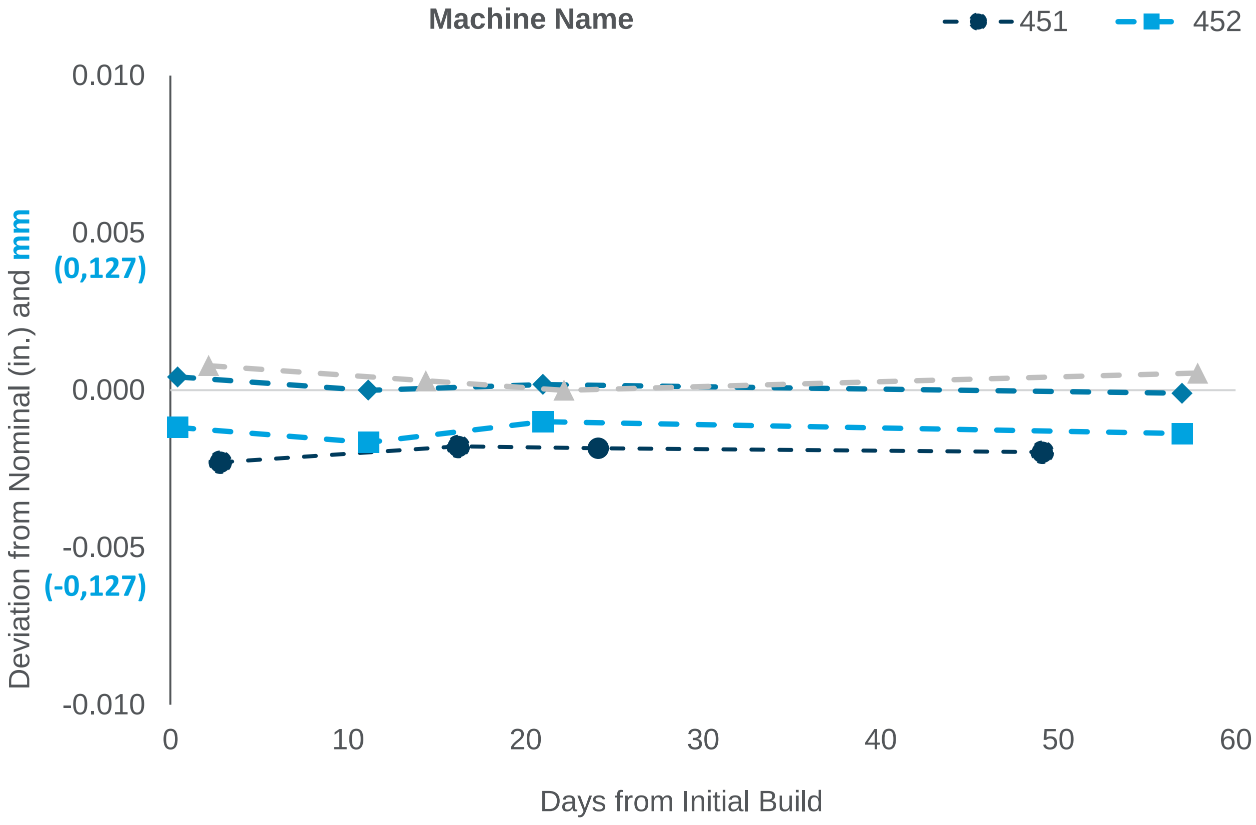
Average Standard Deviation for Features 50,8 mm	Average Standard Deviation for Features over 203 mm
0,023 mm	0.036 mm

Single Feature Check Example (AA1)

Repeatable over time

Reproducible between machines

Feature AA1 Width Measurement



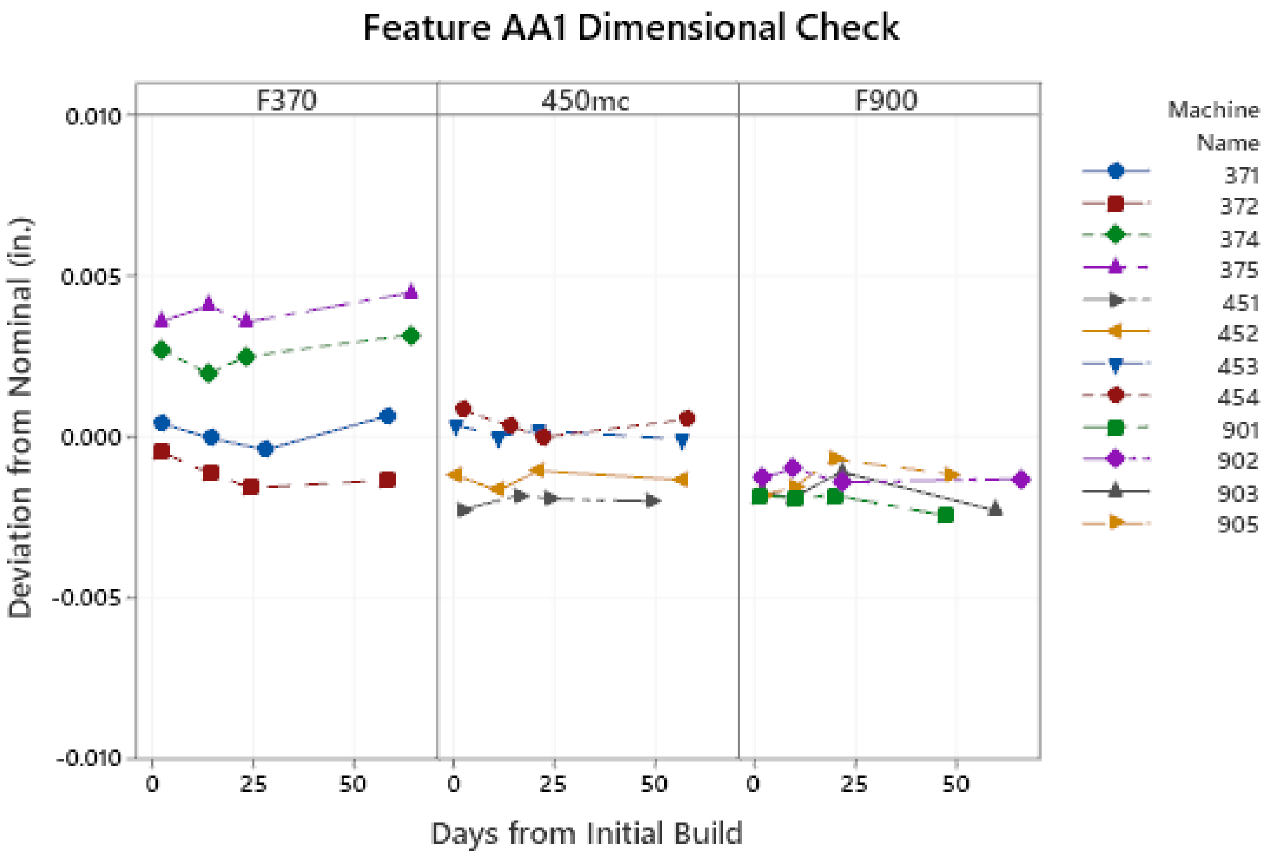
Key Takeaway: High precision allows for high yield of dimension-critical parts

Precision

Single Feature Example

- 4 separate 9” (228.6mm) check parts printed and measured over the course of the long build sequence
- Each machine type shows **excellent repeatability of individual machines**
- Machine to machine matching improves in the order **F900**>**Fortus 450mc** >**F370**

Model	Standard Deviation Feature AA1
F370	0.053 mm
Fortus 450mc	0.028 mm
F900	0.013 mm



Thank You

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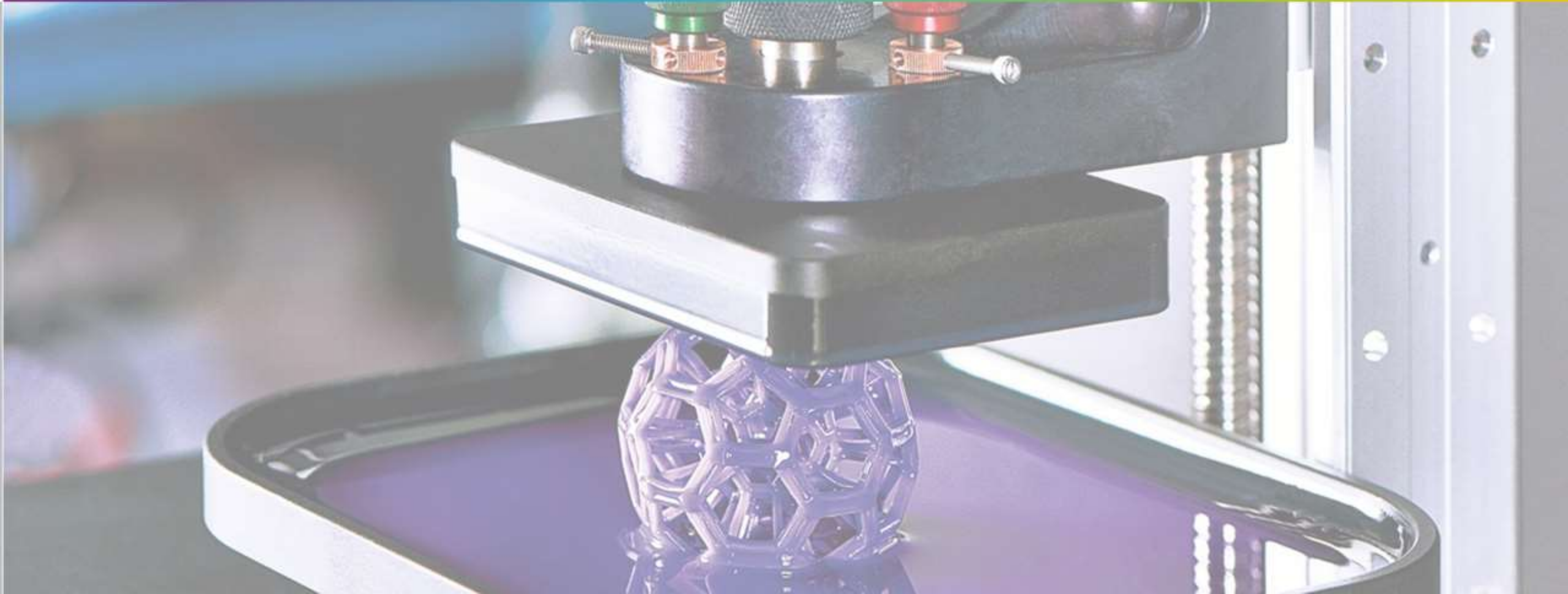


Addressing a few AM myths in the design office

Advances in Additive Materials - **Digital & Advanced Manufacturing Special Interest Group**

19th October 2023

Graham Barnes CEng MIMechE

Introduction

- AM materials are developing very quickly and working with KWSP during the formation of the DMC has highlighted a number of myths in the design and engineering community to the reliability and predictability of the AM solutions.

  - How will we ever deal with the anisotropy of the AM materials?
  - The material properties are hugely different build to build, how will we ever prove it is strong enough?
  - Isn't it better we just machine them from solid?

Memories are short – weren't all metals isotropic?

- Not a current stem design but novel for its time. The USE Atom stem had an interesting clamp mechanism which suited their anti-dive fork.
- The faceplate was pretty conventional
- All the prototypes machined from 7075 T6 billets
- All passed rig test and competition riding
- Time for volume manufacture

All 7075-T6 materials are not the same; Plate is anisotropic

Material	UTS X (MPa)	UTS Z (MPa)	Diff X/Z	Yield X (Mpa)	Yield Y (MPa)	Diff X/Z
7075-T6 Plate	489	455	7.5%	434	386	12.4%

WSP

Scalmalloy – a serious alternative for 7075 T6 for AM

DMC are in the top 1% of Scalmalloy suppliers in the World.

The difference in manufacturing orientation is approximately 1%

Material	UTS X (MPa)	UTS Z (MPa)	Diff X/Z	Yield X (Mpa)	Yield Y (MPa)	Diff X/Z
7075-T6 Plate (Min.)	489	455	7.5%	434	386	12.4%
7075-T6 General	572	-		503	-	
Scallmalloy AM	542	537	0.9%	522	516	1.1%
Difference	-5%			+4%		

DMC DIGITAL MANUFACTURING CENTRE

Scalmalloy

Datasheet

Scalmalloy is a high strength aluminium alloy which was specifically designed for additive manufacturing. It combines excellent ductility, high strength, and the low density of aluminium and therefore allows for weight reductions that cannot be achieved by any other AM aluminium alloy on the market. It also offers great corrosion resistance which can be improved further by anodising or coatings.

Density	2.67 g/cm^3
Porosity	<0.5%

Mechanical Properties

Property	Heat treated*2
Tensile Strength (UTS)*1	
Horizontal	542 MPa ± 5 MPa
45°	540 MPa ± 5 MPa
Vertical	537 MPa ± 6 MPa
Yield Strength (0.2% Offset)*1	
Horizontal	522 MPa ± 4 MPa
45°	522 MPa ± 5 MPa
Vertical	516 MPa ± 5 MPa
Young's Modulus*1	
Horizontal	70 GPa ± 3 GPa
45°	70 GPa ± 3 GPa
Vertical	69 GPa ± 2 GPa
Elongation to failure*1	
Horizontal	15.2 % ± 2.0 %
45°	13.4 % ± 2.0 %
Vertical	14.4 % ± 2.0 %
Hardness	172 HV5 ± 5

*1 Mechanical properties were obtained by testing fully machined round bars according to ASTM E8. Tolerance bands represent ±3-sigma.
*2 Standard heat treatment cycle: 325°C (±10°) for 4hrs (-0/+30mins), with furnace cool.

Chemical composition

Element	Al	Mg	Sc	Zr	Mn	Fe	Si	Ti	O	H
Min.	Bal.	4.20	0.60	0.20	0.30					
Max.		5.10	0.88	0.50	0.80	0.40	0.40	0.15	0.05	0.01

Publication date: 09/07/2021 Rev. 01

AM Titanium 6AL-4V Properties - On the face of it a little daunting for selection

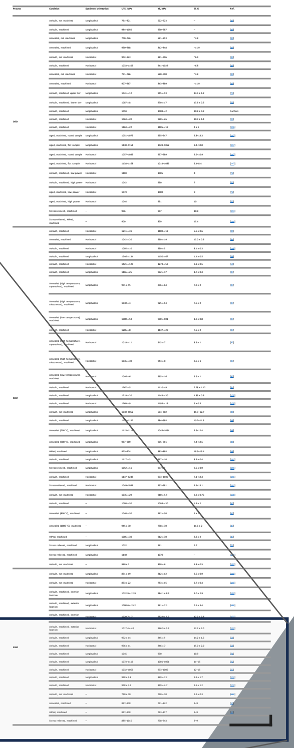
Process	Condition	Specimen orientation	UTS, MPa	YS, MPa	El, %	Ref.
DED	As-built, not machined	Longitudinal	761–821	522–523	–	[49]
	As-built, machined	Longitudinal	984–1050	930–987	–	[49]
	Annealed, not machined	Longitudinal	700–726	621–653	~4.8	[49]
	Annealed, machined	Longitudinal	930–968	812–848	~11.9	[49]
	As-built, not machined	Horizontal	902–923	881–906	~6.4	[49]
	As-built, machined	Horizontal	1033–1109	941–1029	~6.8	[49]
	Annealed, not machined	Horizontal	751–766	620–708	~4.8	[49]

High

Low

Titanium 6AL-4V Properties - Quite a range but a little easier

Wrought	–	Longitudinal	942 ± 8	836 ± 9	12.5 ± 1.2	[58]
	–	Horizontal	933 ± 7	832 ± 10	13.0 ± 1.5	[58]
	–	–	1063	966	~13.8	[49]
	–	–	870 ± 10	790 ± 20	18.1 ± 0.8	[148]
	–	–	995	930	14	[87]
	–	–	960 ± 10	880 ± 3	14 ± 4.1	[132]
Forged	Mill annealed	–	1030	970	16	[72]
	Mill annealed	–	1006 ± 10	960 ± 10	18.37 ± 0.88	[51]
Cast	–	–	980	865	13.5	[87]
	–	–	875 ± 10	750 ± 2	4.5 ± 0.2	[132]
ASTM F136	–	–	>860	>795	>10	[58,84]



Titanium 6AL – 4V ASTM and DMC data

DMC has clear data showing typical production values and ASTM F2924-14 minimums

Where <u>required</u> the typical production values can be considered;

<u>Caution</u>

Consider carefully as to whether minimums are not sufficient as they will adversely affect schedule and cost.

Form	ASTM	UTS (Mpa)	Yield (Mpa)	Elongation (%)
AM	F2924-14	895	825	10

With the design flexibility of AM, the structural benefits significantly outweigh the increase in headline properties.

DMC DIGITAL MANUFACTURING CENTRE

Ti6Al4V (60μm layer)

Process Control Datasheet

Ti6Al4V is the most used titanium alloy in the world. It is extremely versatile due to its relatively high specific strength, temperature capabilities and corrosion resistance. It is used in industry sectors stretching from aerospace and medical to high-end automotive and motorsport.

Density	4.42 g/cm³
Porosity	<0.5%

Mechanical Properties

Property*1,4	Heat treated*2
Tensile Strength (UTS)	
Vertical (Typical Value)	1092 MPa
Minimum Value (ASTM F2924-14)	895 MPa
Yield Strength (0.2% Offset)	
Vertical (Typical Value)	1039 MPa
Minimum Value (ASTM F2924-14)	825 MPa
Young's Modulus*3	
Vertical (Typical Value)	119 ± 3 GPa
Minimum Value (ASTM F2924-14)	N/A
Elongation to failure	
Vertical (Typical Value)	12.2 %
Minimum Value (ASTM F2924-14)	10%

*1 Mechanical properties were obtained by testing fully machined round bars according to ASTM E8.
*2 Standard heat treatment cycle: 800°C (±10°) for 2hrs (-0/+10mins), with forced furnace cool.
*3 Young's Modulus is not specified in ASTMF2924-14 but is monitored by DMC.
*4 ASTM F2924-14 (Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion) Class A.

Chemical composition*5

Element	Ti	Al	V	Fe	O	C	N	H	Yt	Res.
Min.	Bal.	5.50	3.50							<0.10 each
Max.		6.50	4.50	0.25	0.13	0.08	0.05	0.012	0.005	<0.40 total

*5 Chemical Composition of material specification from DMC supplier(s). If chemical composition for material is required, DMC can provide CoC of batch used. Any other requirements outside specification above to be agreed upon order agreement.

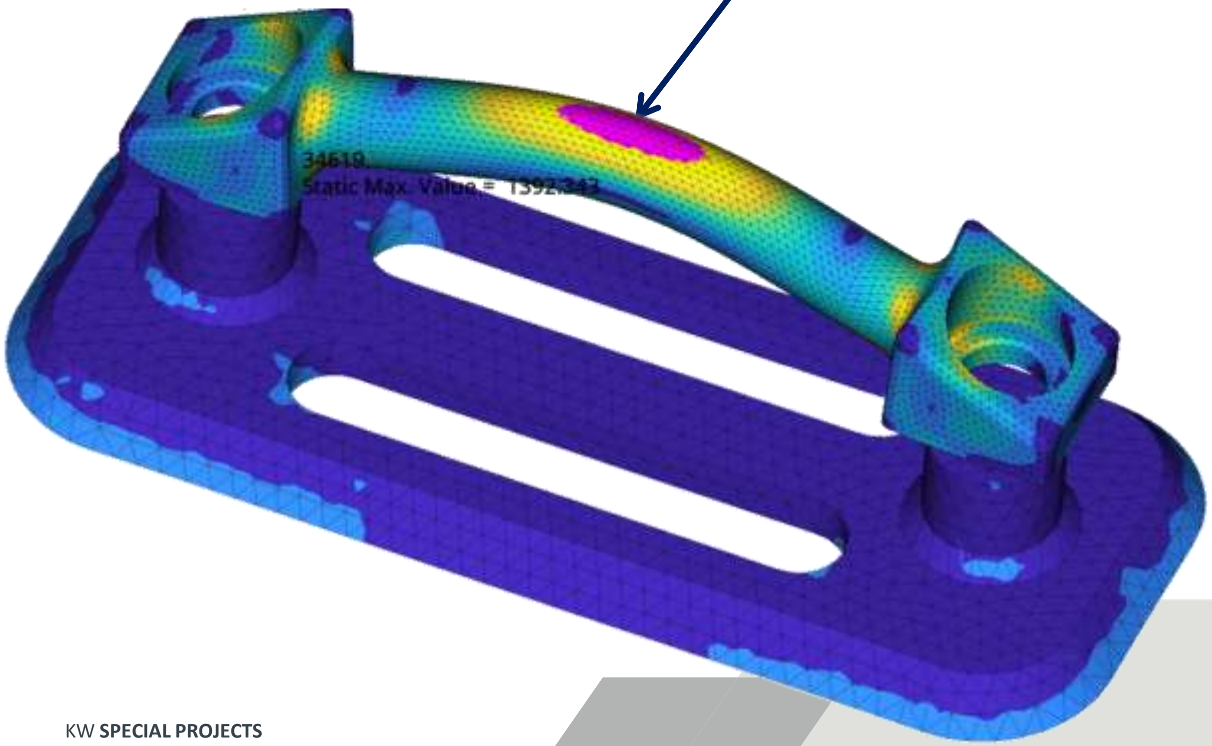
The mechanical properties reported above are typical values for the DMC, as tested in DMC's Laboratory, for our process control. For further clarification and information surrounding mechanical properties and assurance for achievable minimum value requirements please contact us at the DMC.

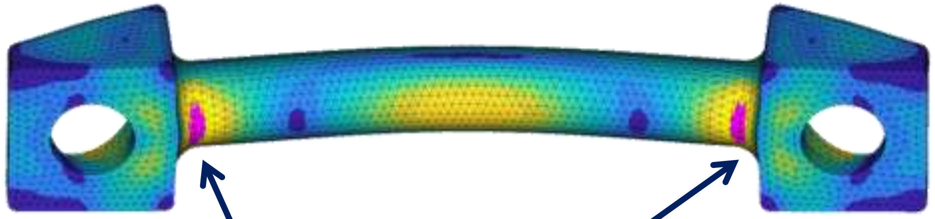
Publication date: 24/05/2023 Rev. 02

Ductility of Ti 6AL-4V AM 60µm

- Against the typical Yield values from DMC of 1039 MPa the indication is that the component not going to yield at the certification loadcase.
- However, what how will the ductility of the material at 10% elongation affect failure mode.
- Safety is paramount in this component.

1.5 FoS on Yield

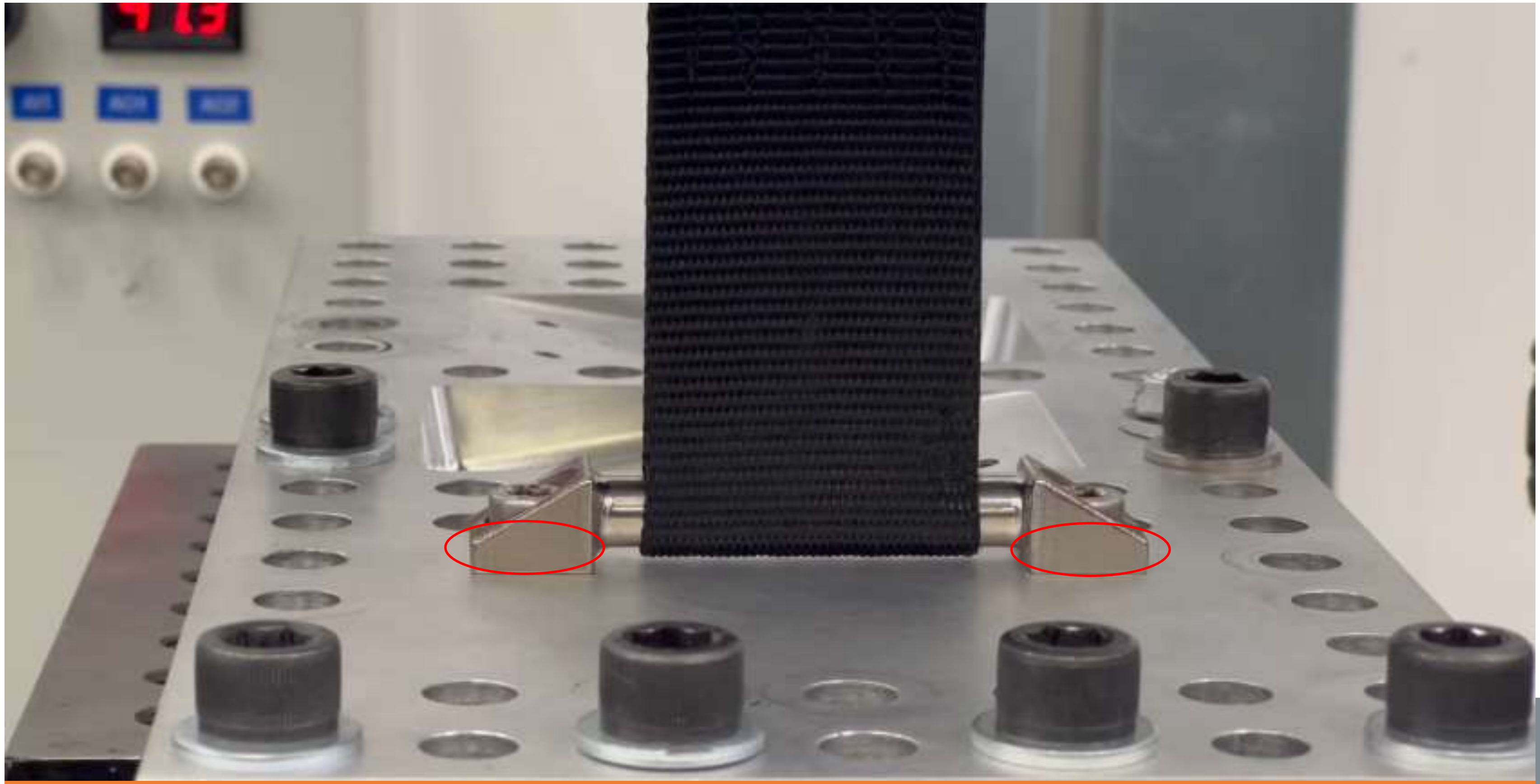




1.45 FoS on Yield

AM Ti 6AL-4V Seat belt anchorage verification

- Overload test to destruction
- Which will be highest
  - Belt capability
  - Bolt capability
  - Component capability



Concurrent bolt head failure at 225% of certification loadcase and belt torn

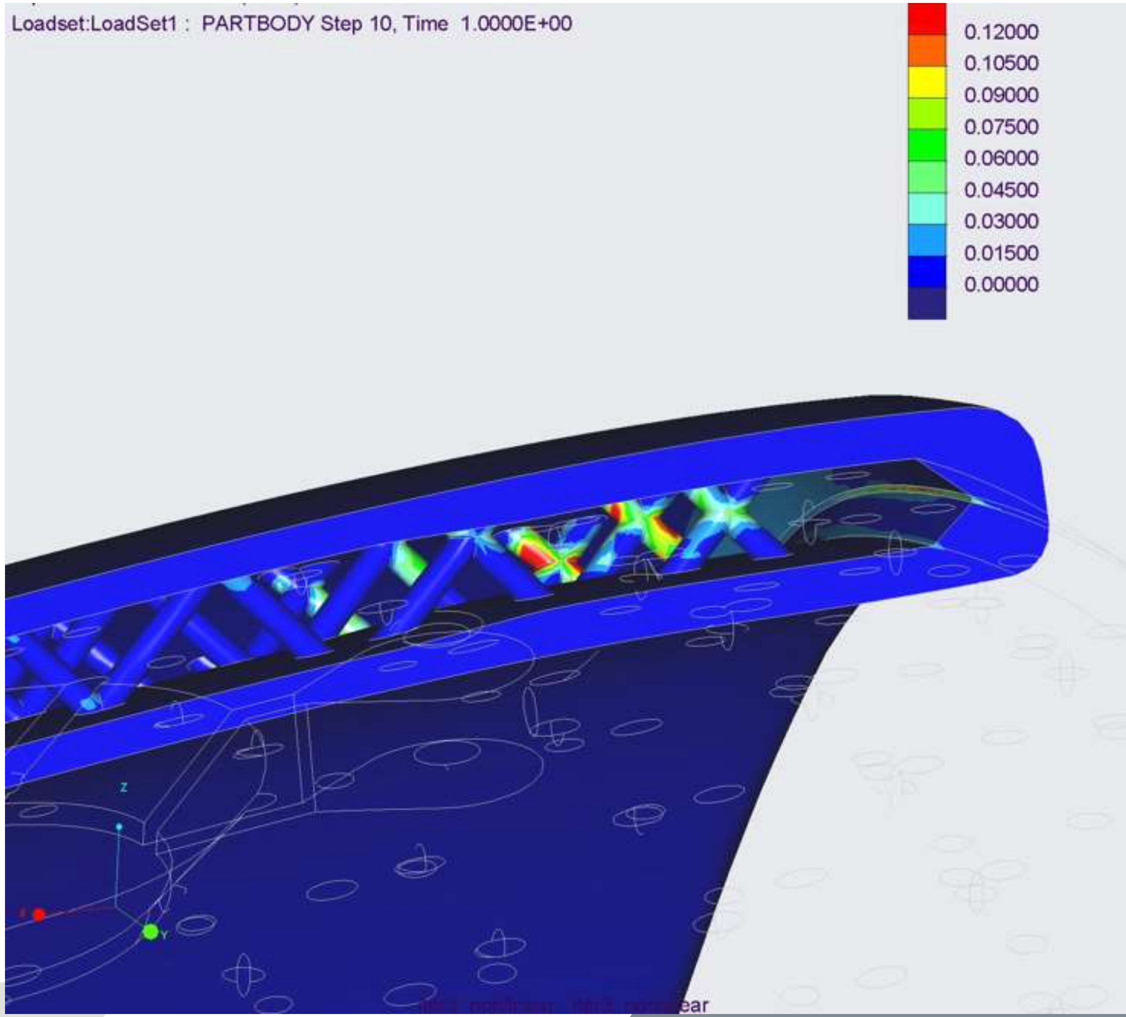
Demonstration of AM Titanium 6AL-4V ductility

- The component had previous endured the certification load in the vehicle test. No damage
- Been exposed to 33% overload on the rig test. No damage.
- The component has resisted 224% of certification load without failure. The component is visibly bent and clear to mechanics not for future use.
- The failure mode is desirably for the development of safety critical components.

KWSP

Beyond yield and progressive damage in different parts of the build

- The elongation values presented in the ASTM standard and the datasheet are for machined samples.
- The elongation to failure behaviour of the AM 6AL-4V in thin sections which are internal to the AM structure and surface features from build are not able to be dressed are lower than the bulk material.
- To get a predictive capability will require more modelling and test focus including the development of a failure model based on stress triaxiality.
- In particular the ability to model the sparse structures that give the efficiency to the design yet also cause the local stress raisers will challenging. The detailed features are currently too small to accurately model and get reliable damage progression.
- As previously stated, at KWSP safety structures are of paramount importance with respect to design and build integrity, so the design direction was verified by test.



Back at the test house with the AM 6AL – 4V Roll hoop

- Understanding the failure mechanisms of the materials and geometric structures to accommodate them unlocks the benefits of the AM process.
- Hollow structures with localized internal reinforcements has allowed this damage to propagate progressively from the contact point the remaining undamaged structure gives the foundations for further impact resistance.
- Multiple impacts or additional impact directions give further reassurance that safety is not compromised, and the certification standards are treated as a minimum.

Dispelling the myths

- How will we ever deal with the anisotropy of the AM materials?
  - In many cases conventional materials also exhibit anisotropy.
  - We are happy to analsye and predict the performance of composites and the difference in 0 and 90 directions is massive in comparison.

- The material properties are hugely different build to build, how will we ever prove it is strong enough?
  - Process control and a sound manufacturing partner for AM has given consistency to the products deployed at KWSP.
  - Chasing a headline figure for material properties rather than the guaranteed minimums is a route to the undesirable variability.

- Isn't it better we just machine them from solid?
  - For properties alone the AM Ti 6AL-4V the minimum Strength values are higher than for the wrought product.
  - For Scalmalloy the figures are very close to the benchmark 7075 T6
  - The opportunities for geometric complexity gives significant structural opportunities from AM components and takes the efficiency of these AM structures to another level.

Some final thoughts

Firstly thank you to KWSP and DMC for the collaboration on the various projects we have been engaged.

I look forward to continuing this journey as we together improve both the structural and manufacturing simulations.

At KWSP we support the engineering of new structures to accommodate the attributes of AM materials whilst respecting the need to provide verification of the modelling approach and validation of the component performance.

If there is a particular application you would like to discuss, please reach out to us.

THANK YOU

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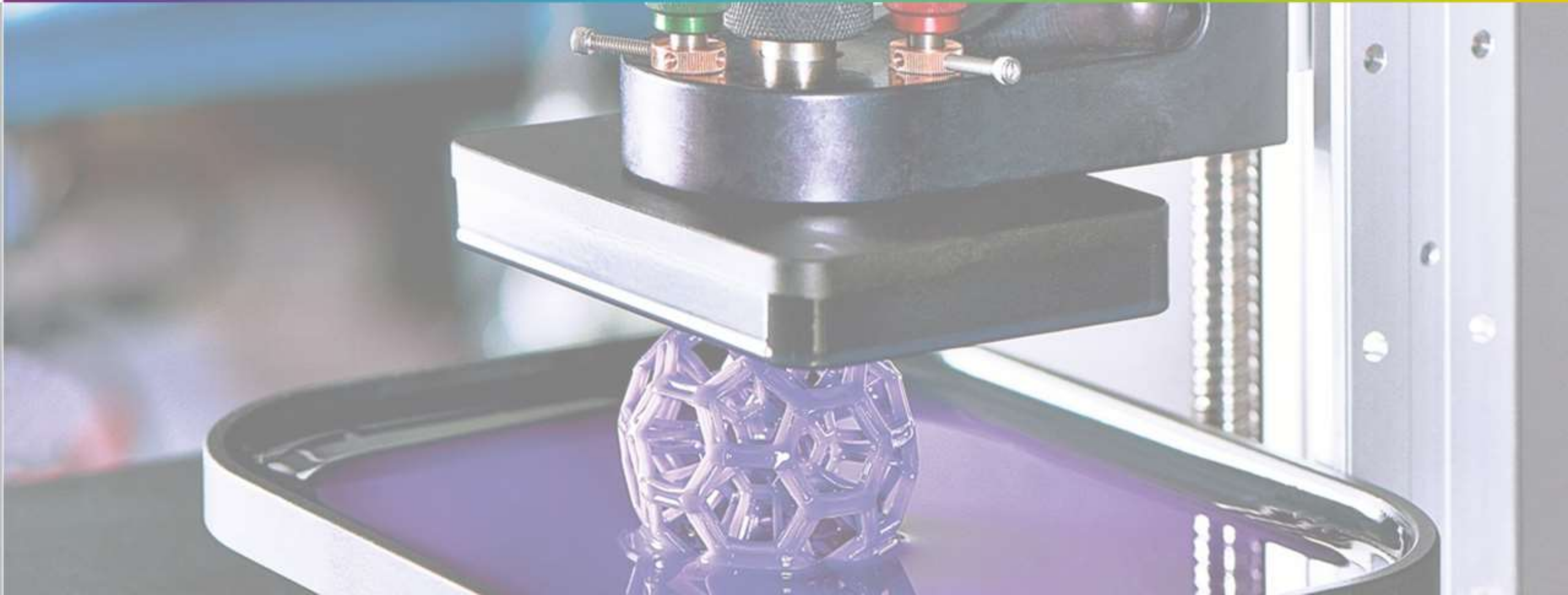
SILVERSTONE TECHNOLOGY CLUSTER

DIGITAL & ADVANCED MANUFACTURING
ADVANCES IN ADDITIVE MATERIALS



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PBF-LB Capability Development in High Strength Aluminium Alloys

Joseph Chamberlin
Advanced Research Engineer

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What is the Manufacturing Technology Centre?


Aerospace


Defence & Security


Construction


Space


Infrastructure


Food & Drink


Healthcare


Power & Energy

TRANSFORMATION TEAM	DIGITAL ENGINEERING	ADVANCED PRODUCTION SYSTEMS	COMPONENT MANUFACTURING TECHNOLOGY
BUSINESS TRANSFORMATION	MODELLING & SIMULATION	AUTOMATION, MECHATRONICS AND ELECTRONICS MANUFACTURING	ADDITIVE MANUFACTURING
DIGITAL TRANSFORMATION	METROLOGY & NDT	DESIGN & BUILD	LASER PROCESSING
TECHNOLOGY TRANSFORMATION	INFORMATICS		ADVANCED MATERIALS PROCESSING

Home of…

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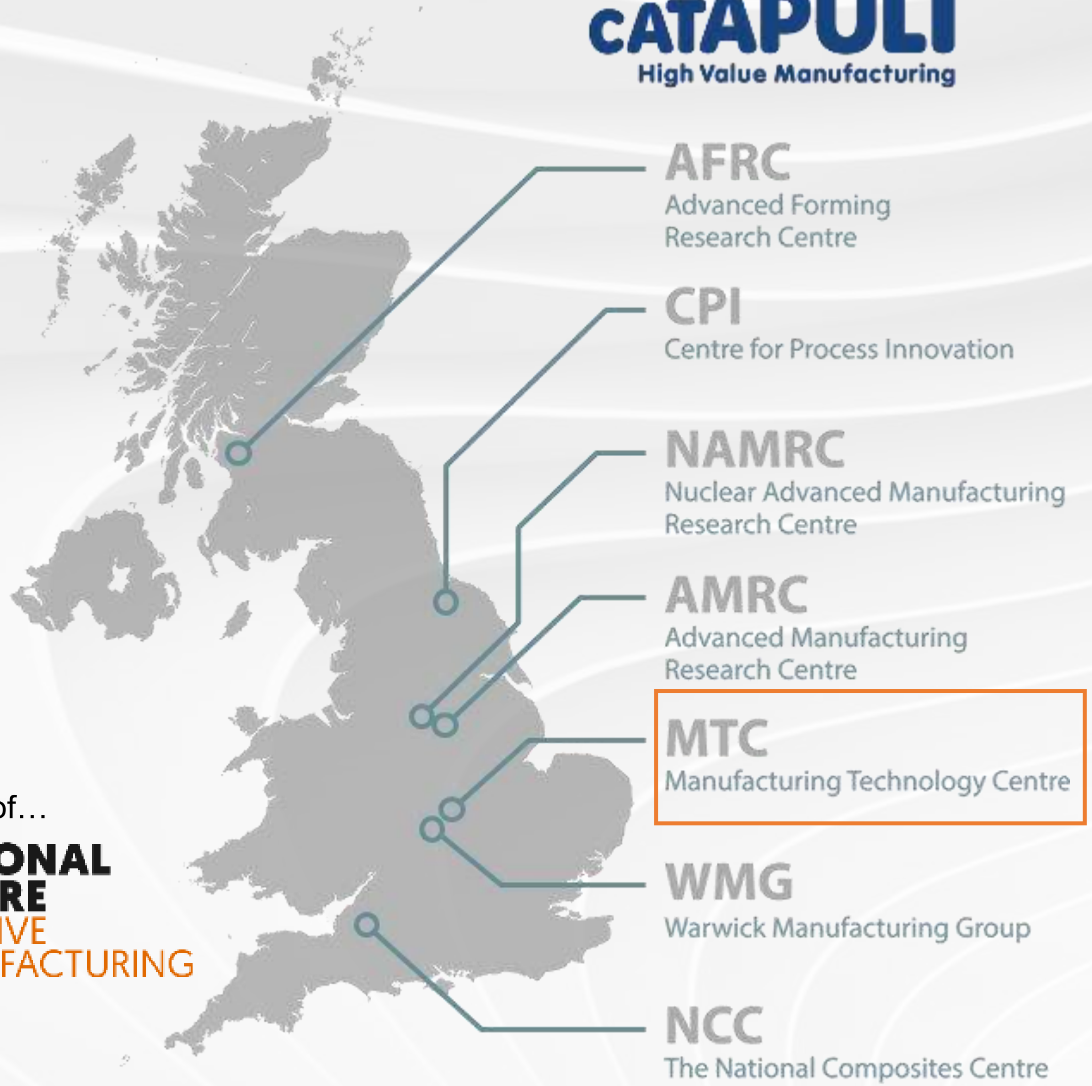

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What is NCAM?






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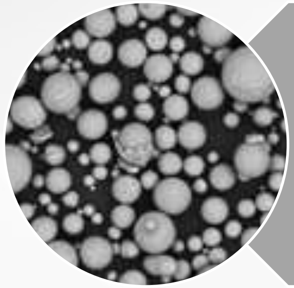
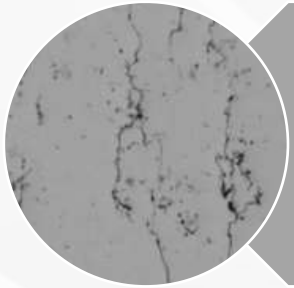
Opportunities for High Strength Al in AM

Challenges for High Strength Al in AM



Can the alloys be produced as high-quality spherical powders with good processability?



Can the alloys be printed at high speeds without defects and with consistently good properties?

Can the alloys be easily post-processed to achieve the desired properties?

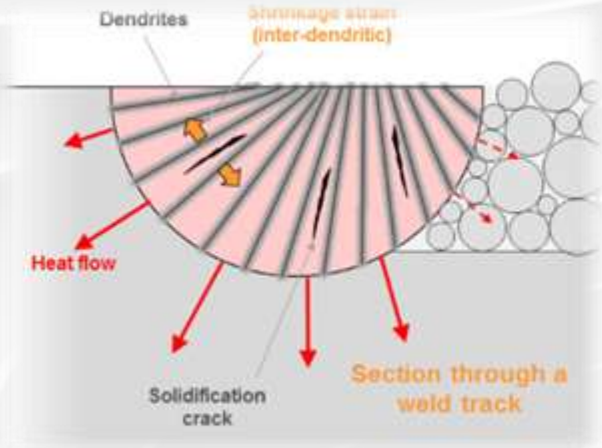


Image: Renishaw

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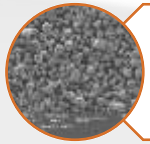
Current Material Development Work

Material 1: GM 7xxx	Material 2: ECKART A20X	Material 3: Constellium Aheadd® CP1	ESA Benchmarking
Al Zn Mg Cu Zr	Mixed metal composite with TiB_2 particles	98% purity aluminium based on Al-Zr-Fe structure	Bencmarking study to assess novel Al alloys for space applications
20-63 µm Gas atomised	Gives very high strength (420 MPa yield)	Gives high conductivity while maintaining strength	Materials include A20X, ScanCromAlMo, 7S & 5T
Bulk parameter development & microstructure analysis	Excellent high temperature and fatigue performance	Streamlined post-processing and finishing	Includes bulk parameter development & testing

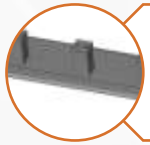


1. Powder characterisation

2. Bulk parameter development

3. Surface parameter development

4. Mechanical property benchmarking



5. Feature property benchmarking

6. Manufacture parts

Allows us to go from this…

…to this

7xxx Material Development

Aim

- To create a novel 7xxx series aluminium chemistry and to investigate its's performance in PBF-LB, with trials to alter grain structure, reduce crack susceptibility and to gain an understanding in solidification behavior.

Objectives

- Alloy Chemistry Identification and Characterisation.
- Density DoE Build.
- Crack Mitigation Trials via Parameter Manipulation.
- EBSD Assessments.
- In-situ PBF-LB System with Synchrotron X-Ray and Infrared Measurement Capability to assess Vapour Cavity, Melt Pool Depth, Temperature Gradient (G), and Solidification Rate (R).

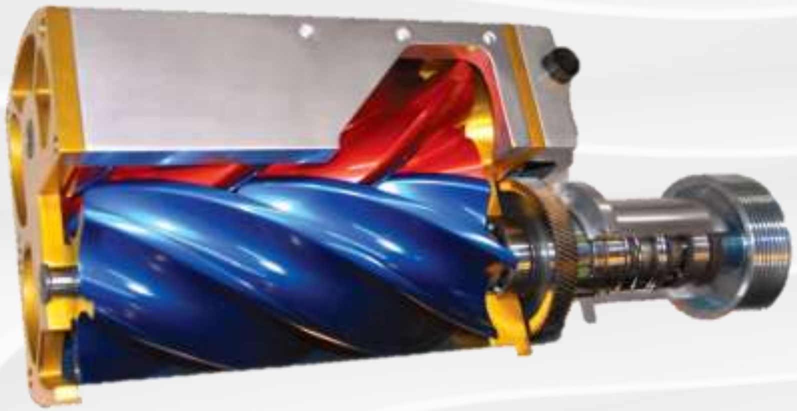
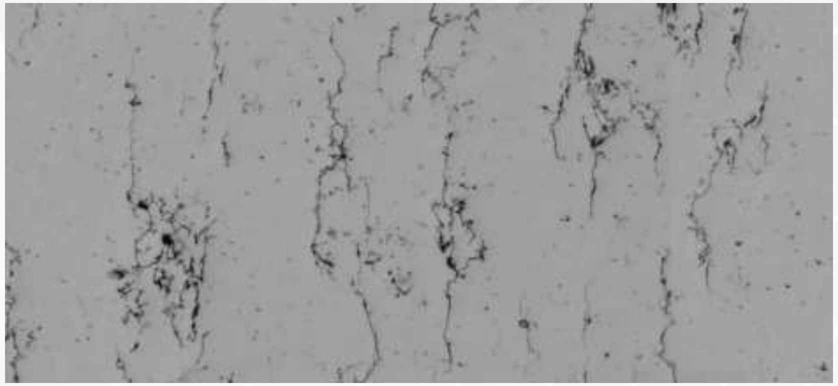


Image: Race Care Network



7xxx Material Development

Chemistry Identification

- Vickers micro-hardness testing of cast 20g Al12ZnMg ingots (T6 condition) resulted in an average hardness of 211±5 VHN indicating a yield strength of >600 MPa.
- For comparison, 7075 in the T6 condition has a hardness of 182 VHN, corresponding to an ultimate tensile strength of 573 MPa.

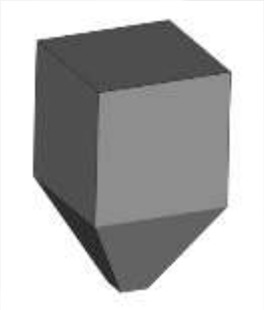
	Composition (wt.%)								Scheil Liquidus (ºC)	Scheil Solidus (ºC)	Freezing Range (ºC)	CSC*dT
Alloy	**Al**	**Zn**	**Mg**	**Cu**	**Cr**	**Zr**	**Si**	**CSC**				
7075	Bal.	5.5	2.5	1.6	0.23	0	0	0.28	634	326	308	86.2
Al12ZnMg Ideal	**Bal.**	**12**	**3.5**	**<0.5**	**0**	**0.2**	**0**	**0.30**	**622**	**446**	**176**	**52.8**
AlSi10Mg	Bal.	0	0.35	0	0	0	10	0.34	594	559	35	11.9

7xxx Material Development

Specimen Manufacture

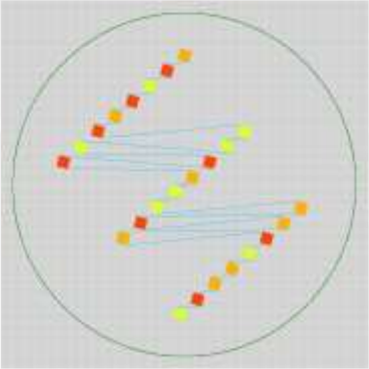
- A Trumpf Truprint 3000 system was used with the gas atomised powder to create 10 x 10 x 17.5 mm pyramidal specimens.
- Parts were manufactured under a continuous argon flow across at 1.8 m/s to achieve <1000 ppm of oxygen in the build environment.
- A constant layer thickness of 30 µm, preheating temperature of 200°C and spot size of 100 µm was used throughout this study.

Image courtesy of Trumpf Ltd



10 x 10 x 17.5 mm

Pyramidal Specimens



Build File in TruTops

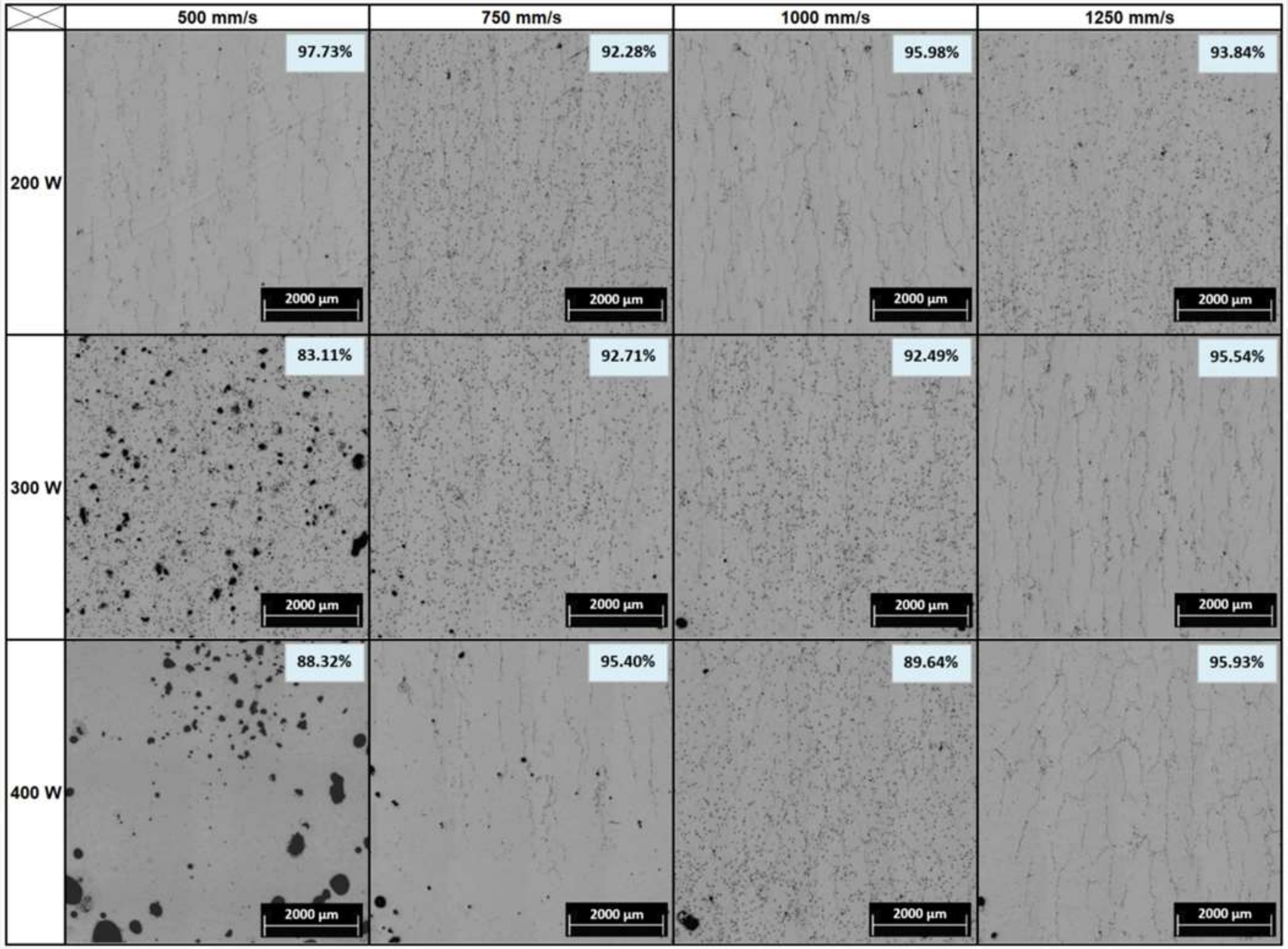
Print Viewer

7xxx Material Development

Specimen Manufacture

- There were four main types of defects observed across the specimens:
  - Solidification Cracking
  - Keyhole Porosity
  - Fine Gas Porosity.
  - Lack of Fusion.

- Keyhole porosity was observed in the higher powers (300 W and 400 W) and across the full speed range with the most severe at the lowest scan speed (500 mm/s).

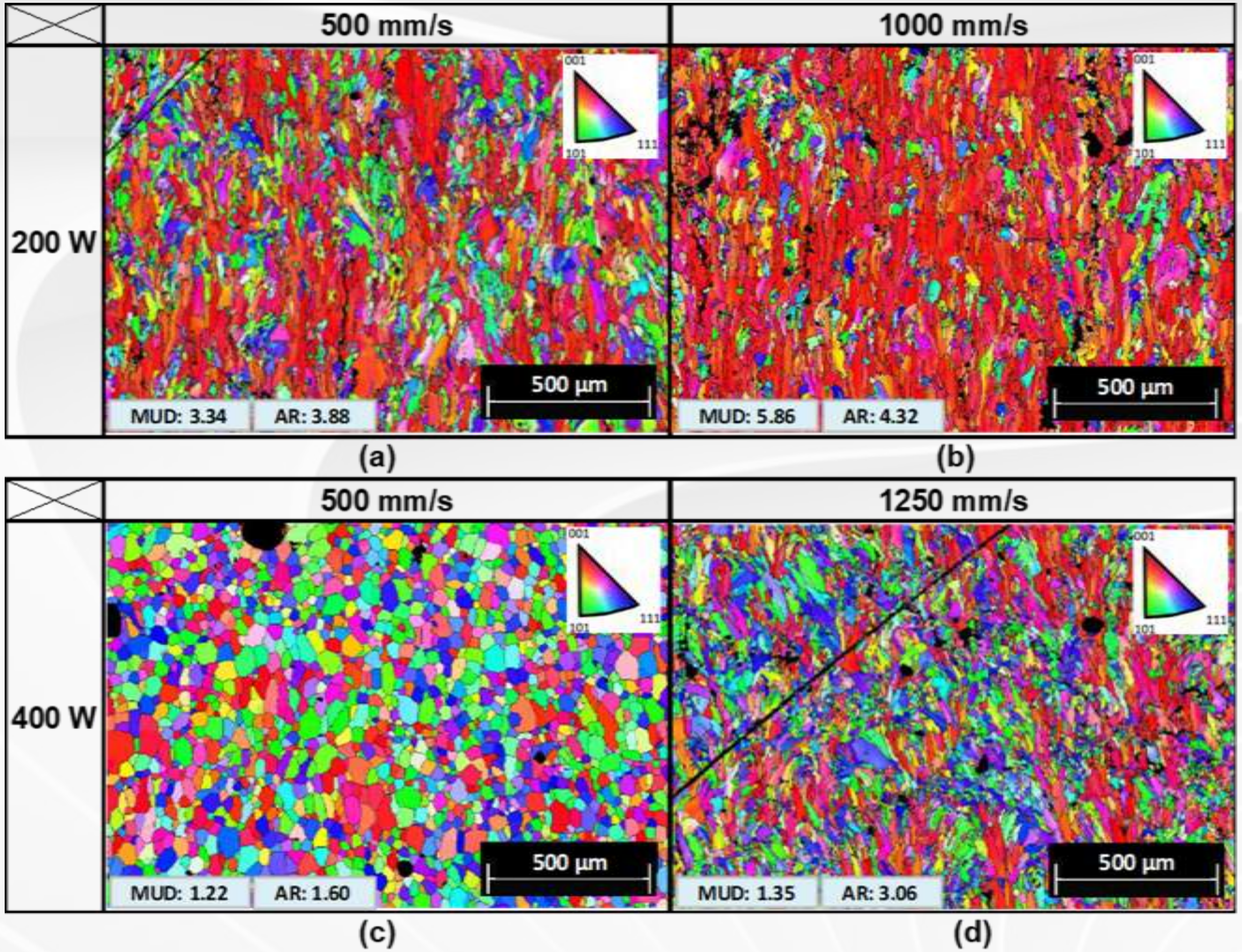


7xxx Material Development

EBSD Analysis

- The amount of texturing can be quantified and compared using the maximum intensity of the pole figures known as the multiple of uniform density (MUD).
  - MUD of 1 corresponds to randomly oriented grains
  - MUD >1 is indicative of texture.

- The specimens manufactured at 400 W are less textured than those manufactured at 200 W and an equiaxed grain morphology was achieved in the lower region of specimen C (400 W, 500 mm/s).

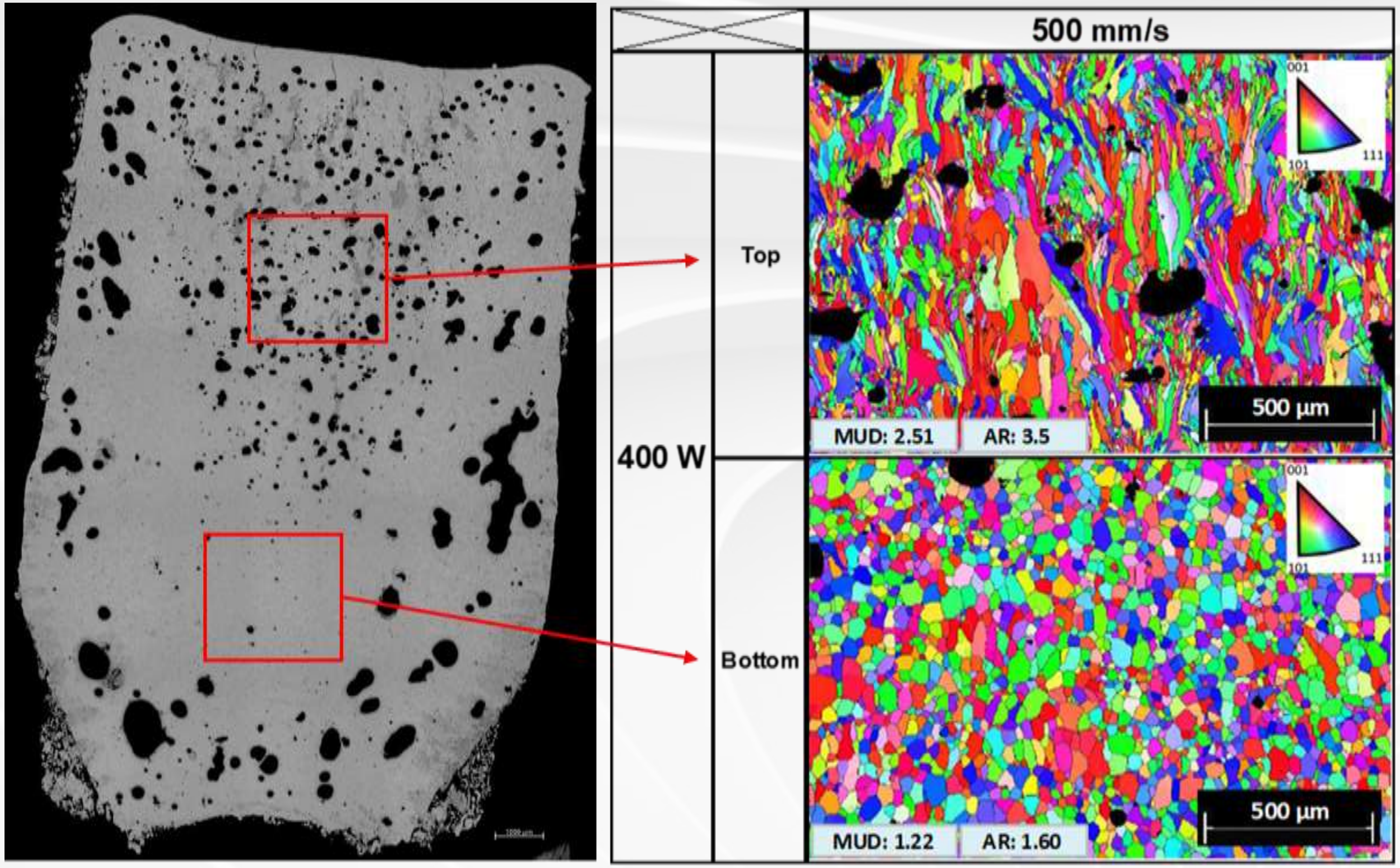


7xxx Material Development

EBSD Analysis

- Further EBSD analysis of specimen C (400 W and 500 mm/s) found that the grain morphology changed from equiaxed in the lower region to columnar in the upper region.

- The texture in the upper area increased to a MUD of 2.51 (from 1.22) with an aspect ratio of 3.5 (from 1.6). The equiaxed region, featured no cracking.



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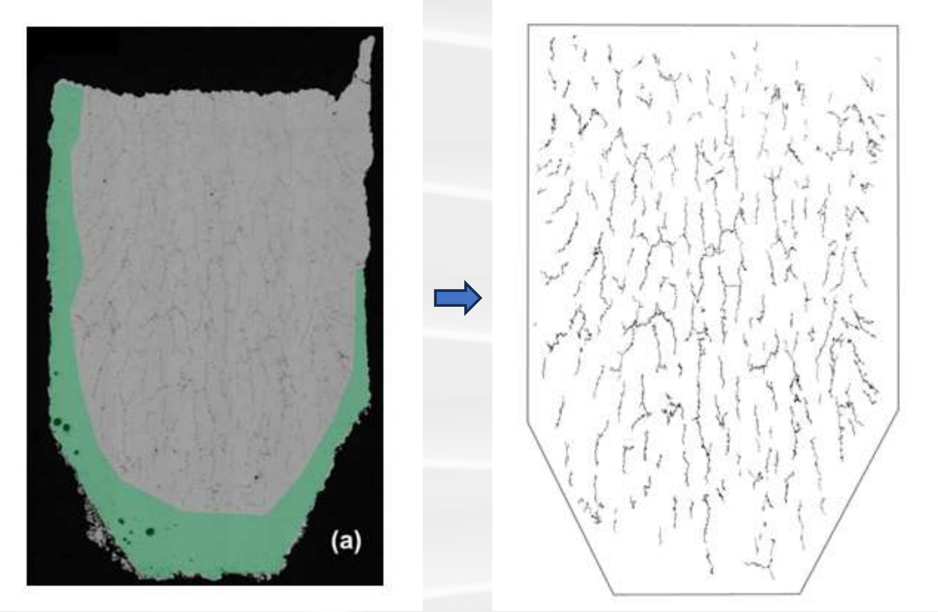
7xxx Material Development

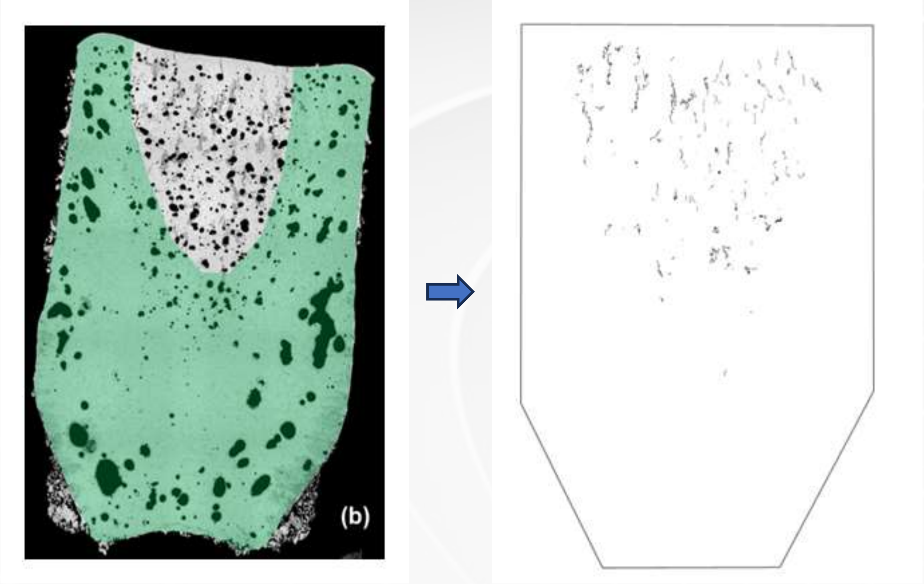
Crack Analysis

- Lower energy density specimens had large crack networks with less keyhole pores.
- Higher energy density specimens had small crack networks with large keyhole pores.
- Parameter changes have some effect on porosity and cracking but did not eliminate hot cracking.
- Emphasises the importance of alloy design and chemistry.

Low Energy Density Specimen



High Energy Density Specimen



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A20X Material Development

Aim

- To develop a set of parameters that achieve density and suitably high mechanical properties to build electrification demonstrator geometries.

Objectives

- Powder Characterisation.
- Density DoE Build.
- Surface Development.
- Mechanical Testing Build (Tensile/Fatigue)
- Feature Trial
- Motor Case/Shaft Demonstrator Builds.

YIELD STRENGTH

AlSi10Mg – 238 MPa

A20X Powder – 440 MPa

ULTIMATE TENSILE STRENGTH

AlSi10Mg – 306 MPa

A20X Powder – 511 MPa

ELONGATION

AlSi10Mg – 11%

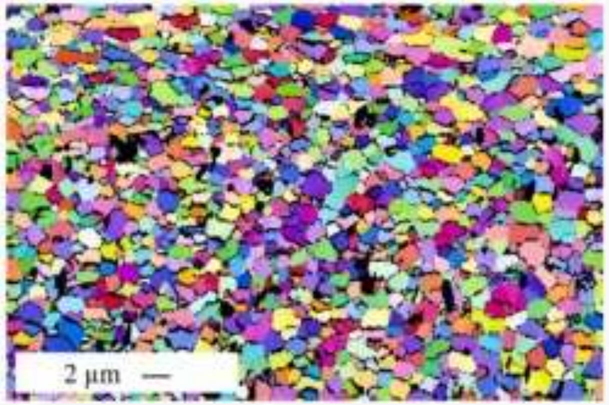
A20X Powder – 13%

A20X Material Development

Material Summary

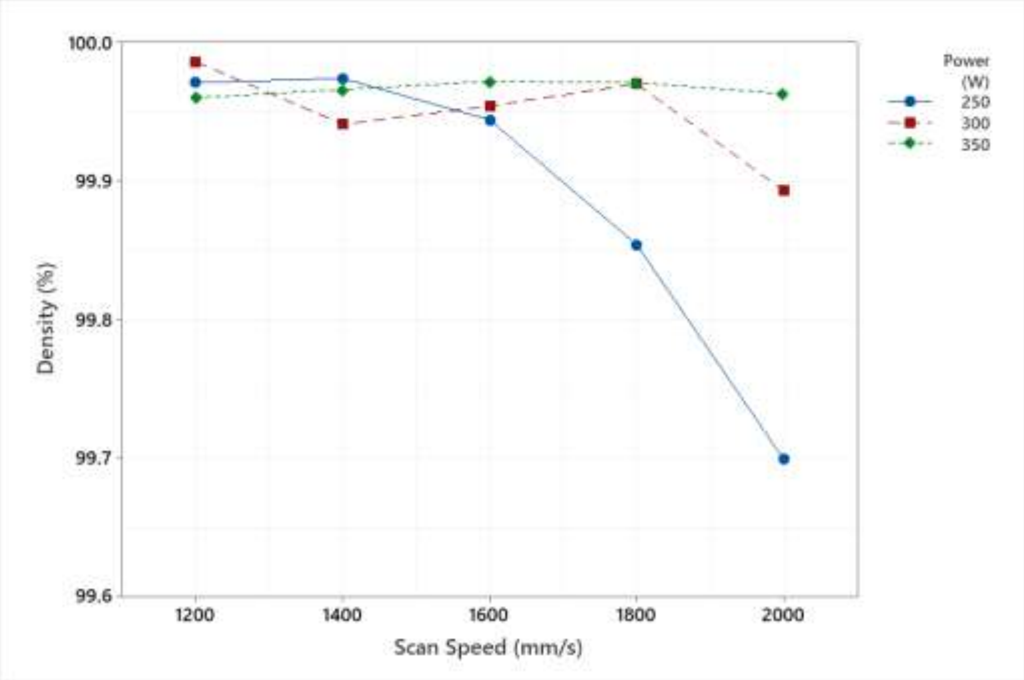
- ➢ Ultimate Tensile Strength up to 511 MPa.
- ➢ Yield Strength up to 440 MPa.
- ➢ Elongation at fracture up to 13%.
- ➢ Aerospace-approved.
- ➢ Excellent high-temperature strength performance.
- ➢ Fatigue properties comparable to 7xxx alloys.
- ➢ Processability comparable to AlSi10Mg.
- ➢ Fully equiaxed microstructure.

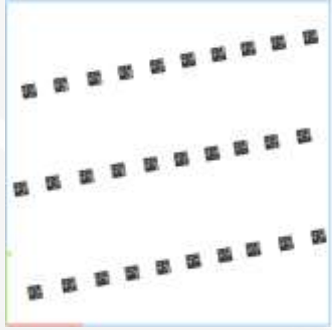
Image: ECKART



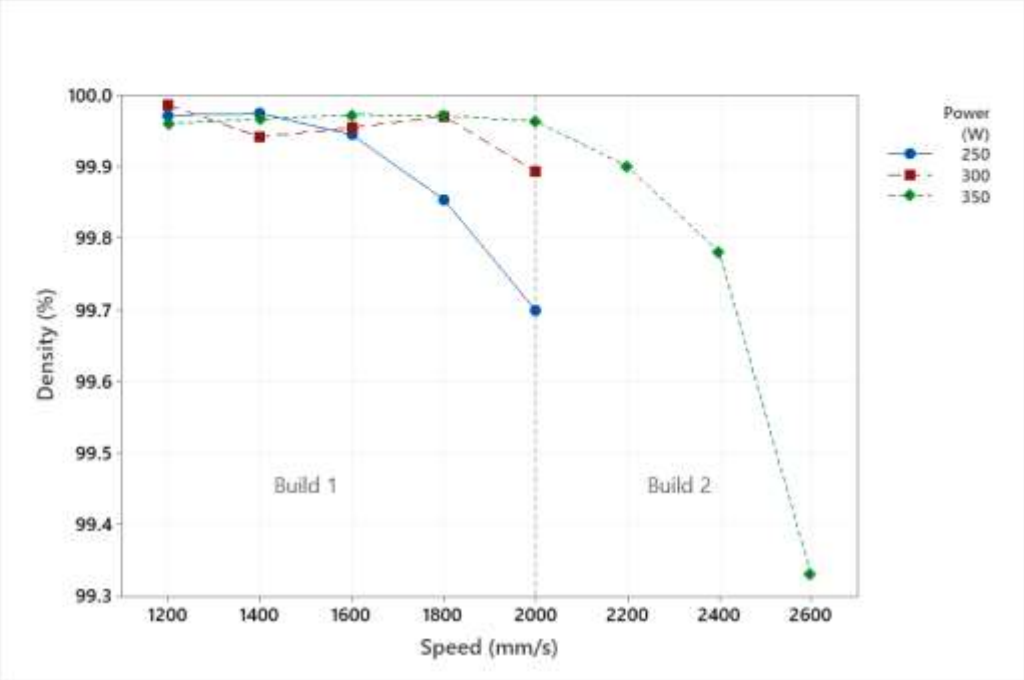
A20X Material Development

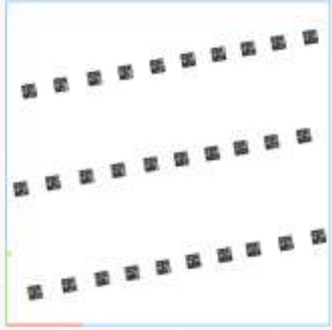
Build 1





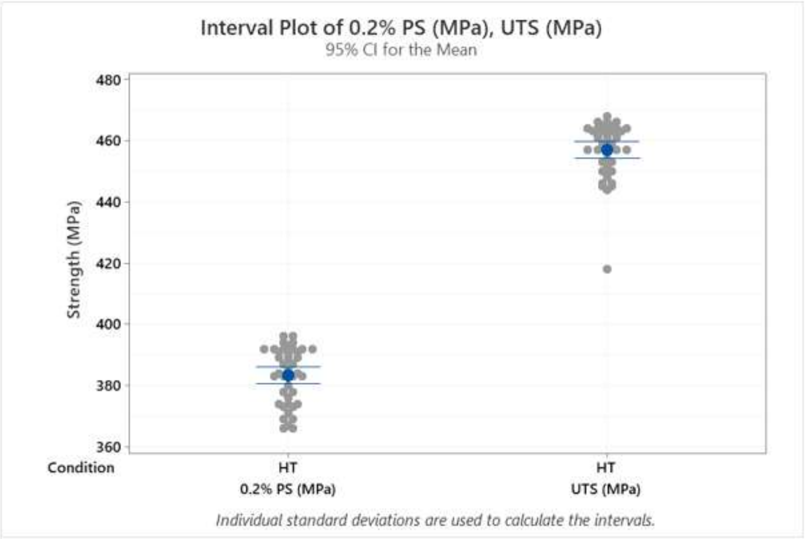
Build 2

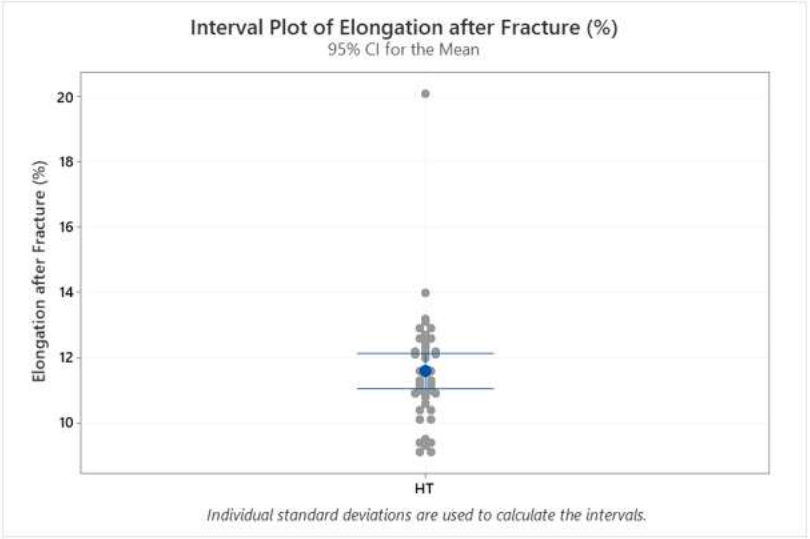


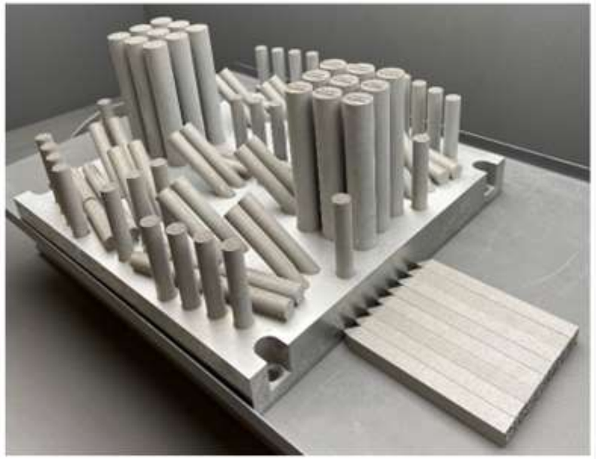


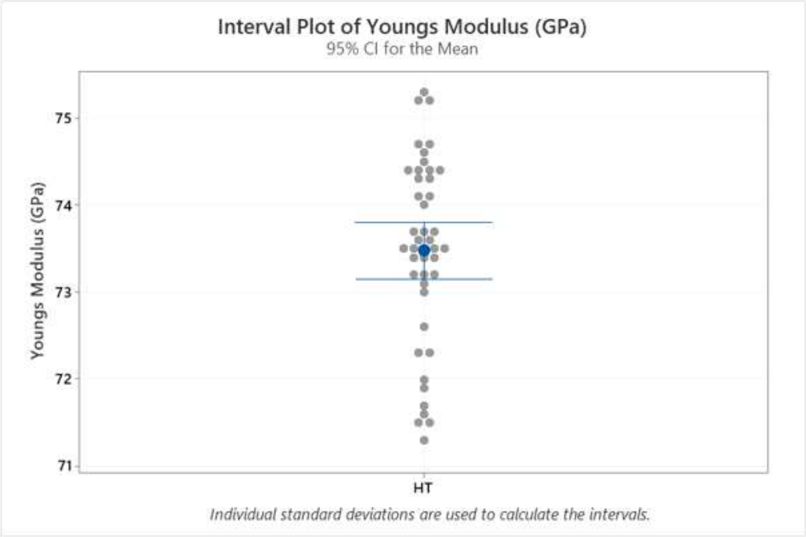
A20X Material Development

- Mean HT UTS = 457 MPa
- Mean HT 0.2% PS = 383.5 MPa
- Mean HT Young's Modulus = 73.5 GPa
- Mean HT Elongation = 11.6%









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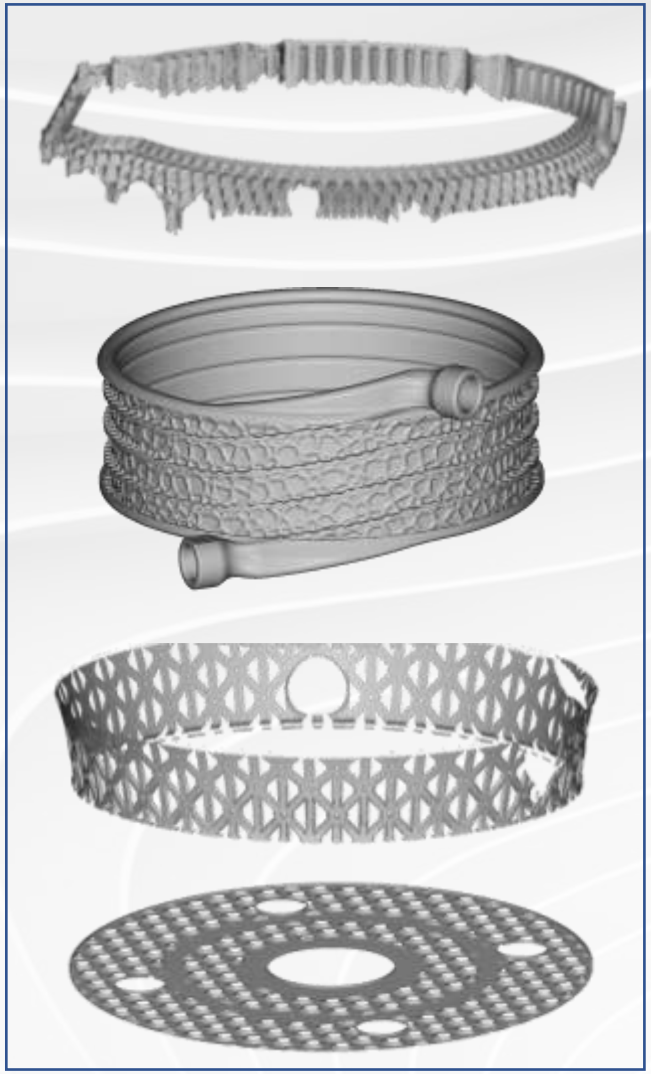
A20X Material Development

Original Motor

Optimisation informed geometry (Designed in Siemens NX)



Lattice, surface texture and automated design tools (Designed in nTopology)

Outcome

- 65% mass reduction
- 27% increase in cooling area
- 14 components consolidated to one

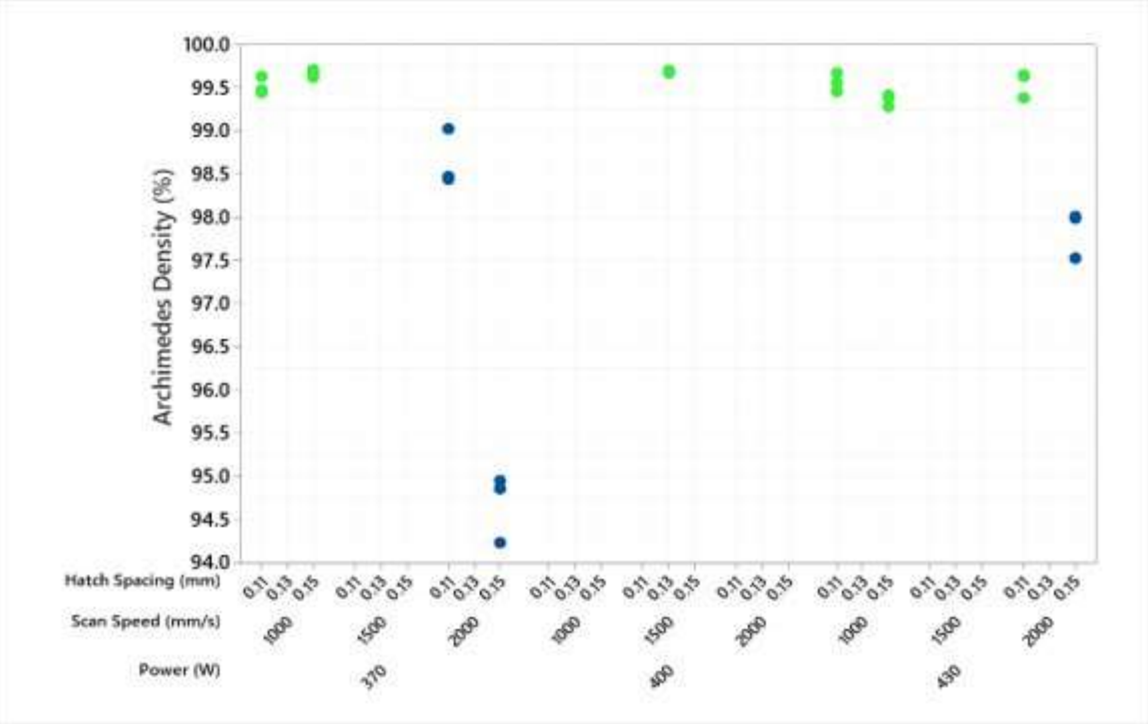
CP1 Material Development

- Constellium Aheadd CP1 is a AlZrFe (8xxx) alloy with a strong combination of strength, ductility and conductivity.
- It utilises a simple post build, single hold temperature heat treatment with no quench for better geometric control.
- It is expected to be robust within the PBF-LB environment, the melt pool is expected to be stable and there are no volatile elements such as Zn or Mg.
- Constellium suggest:
  - CP1 can achieve high productivity and higher print speeds than Al-Si alloys with lower residual stress.
  - Initial data shows excellent corrosion resistance and surface finishing properties.

Images: Constellium

CP1 Material Development

- Build 1 assessed bulk density
- Full factorial DoE with 2 levels, using supplier parameters as mid-point.
- 6 parameter sets resulted in mean AD over 99.3% (highest is 99.7%)
- AD results validated optically.

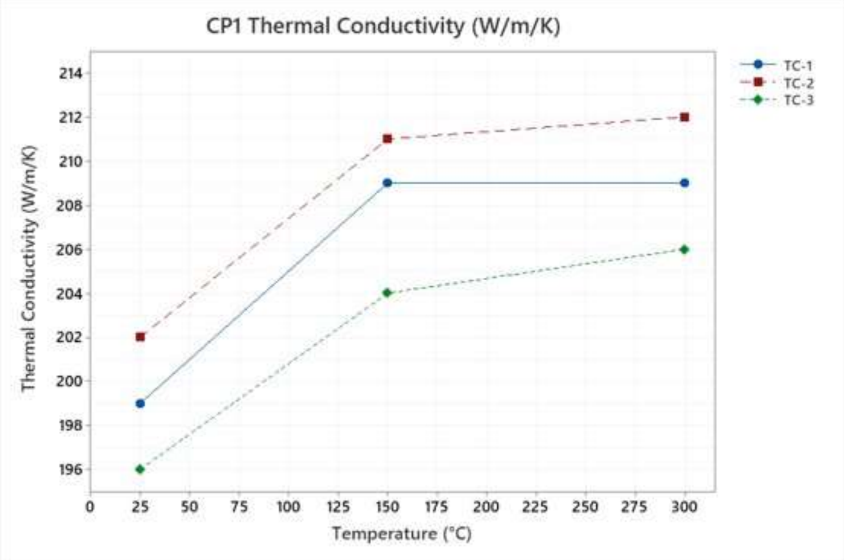


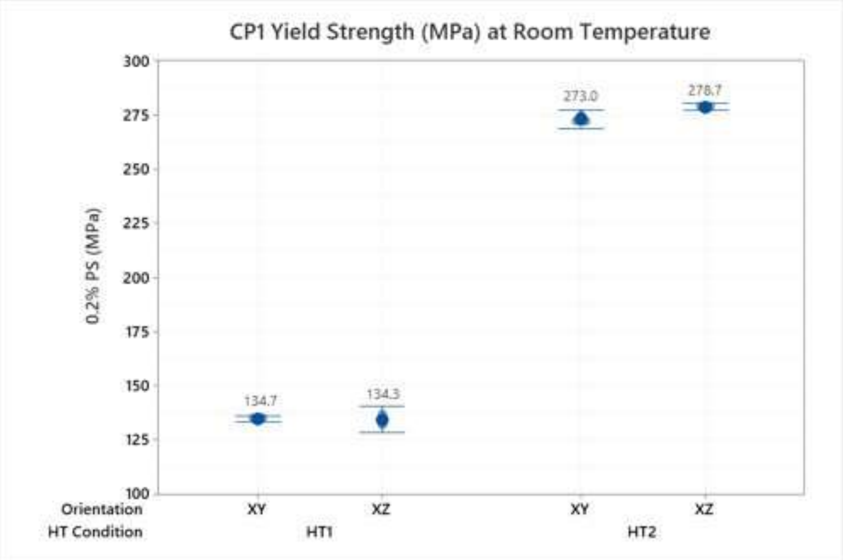
CP1 Material Development

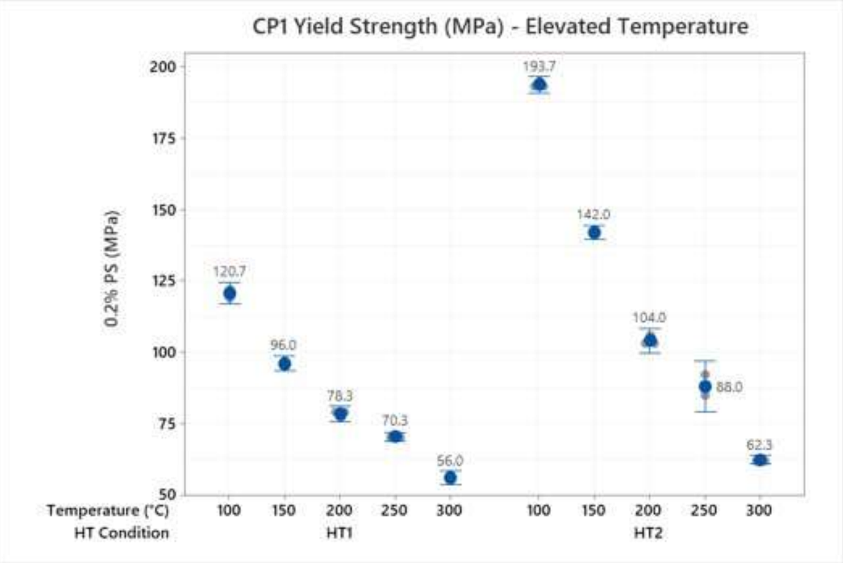
- Thermal conductivity calculated as the product of Archimedes density, specific heat and thermal diffusivity.

- Tensile data at room temperature and elevated temperature.

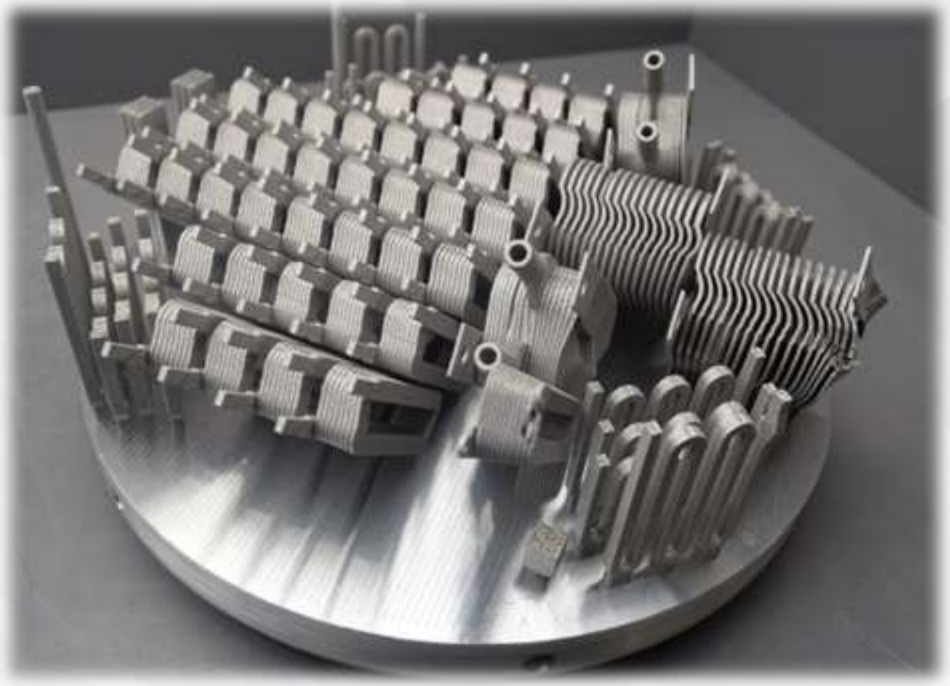
- Heat treatment 1 tailored to high conductivity.
- Heat Treatment 2 is a trade off between conductivity and strength.







CP1 Material Development

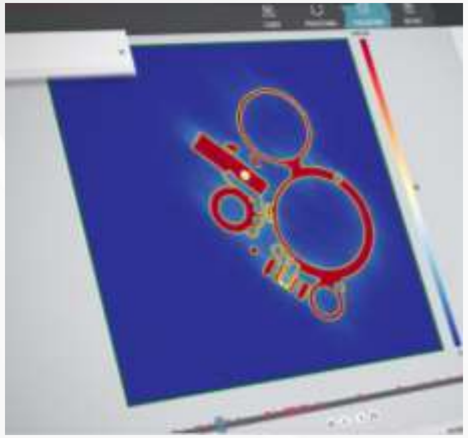


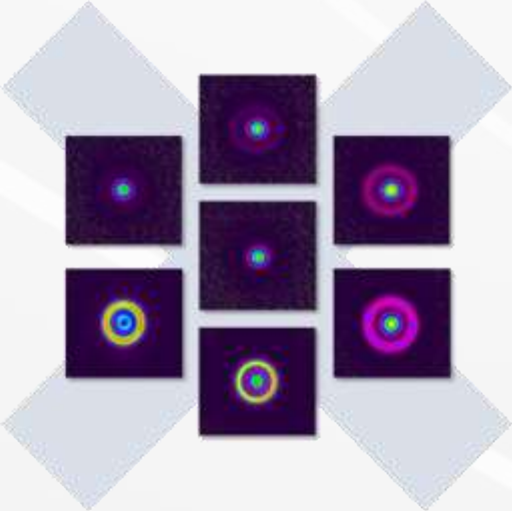
Motor Windings Build

Assembled Stator Pack

NATIONAL CENTRE ADDITIVE MANUFACTURING

Going Forward: SOTA Capability





State-of-the-art equipment allows us to:

- Improve part properties of exotic materials
- Increase build productivity
- Rapidly change between materials
- Improve atmospheric controls
- Monitor build performance during the build

nLIGHT

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Manufacturing Technology Centre

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Thankyou

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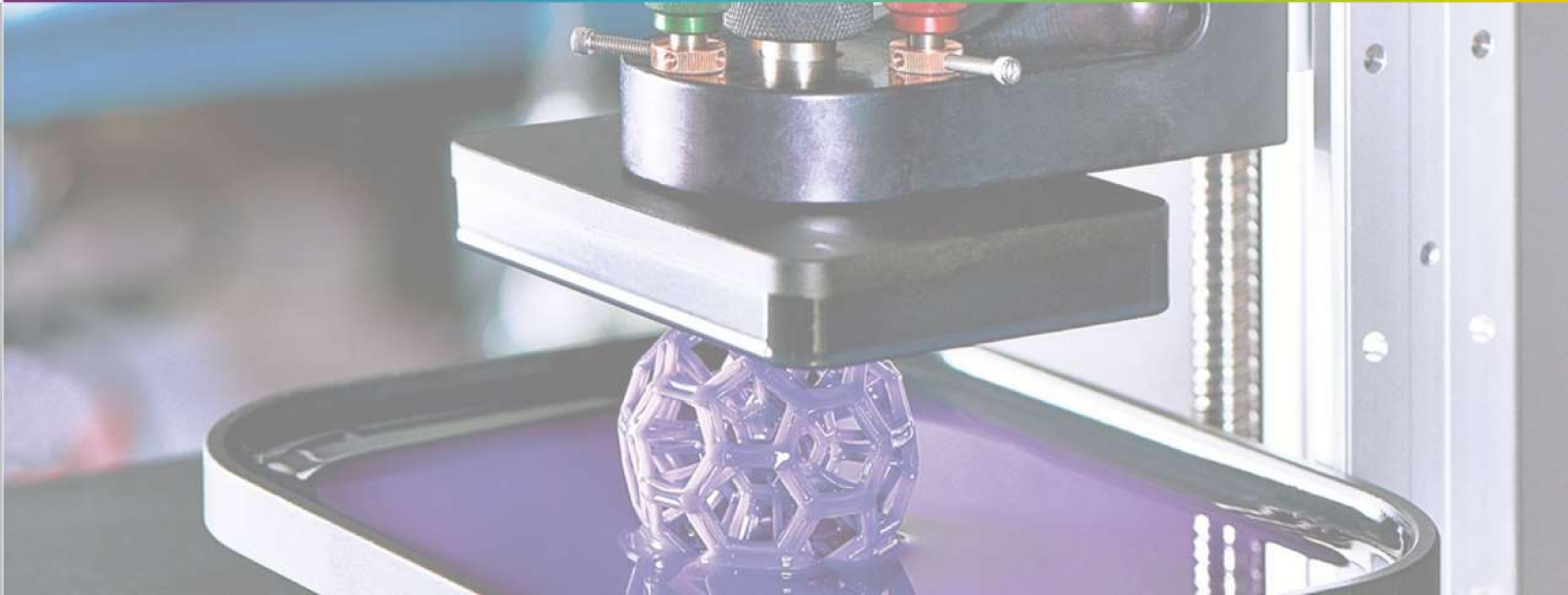
CATAPULT High Value Manufacturing

SILVERSTONE TECHNOLOGY CLUSTER

DIGITAL & ADVANCED MANUFACTURING
ADVANCES IN ADDITIVE MATERIALS



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YOUR FEEDACK IS IMPORTANT TO US