To understand Additive Manufacturing from the perspective of the Powder

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CEO - LPW Technology Ltd

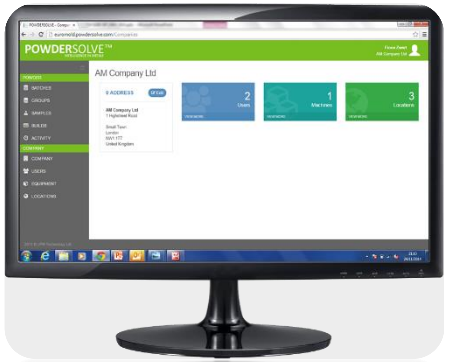
January 2017

Products and Services

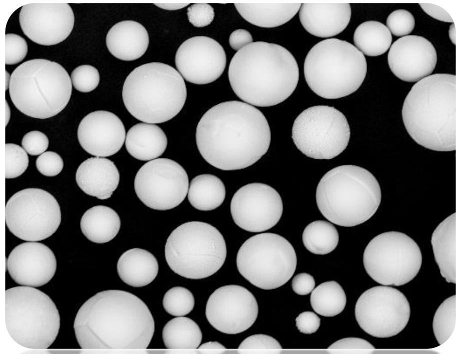
All focused on AM only

Metal Powders

Powder Management Software



Consultancy & Lab Testing Services



Powder Handling & Testing Equipment

LPW Development

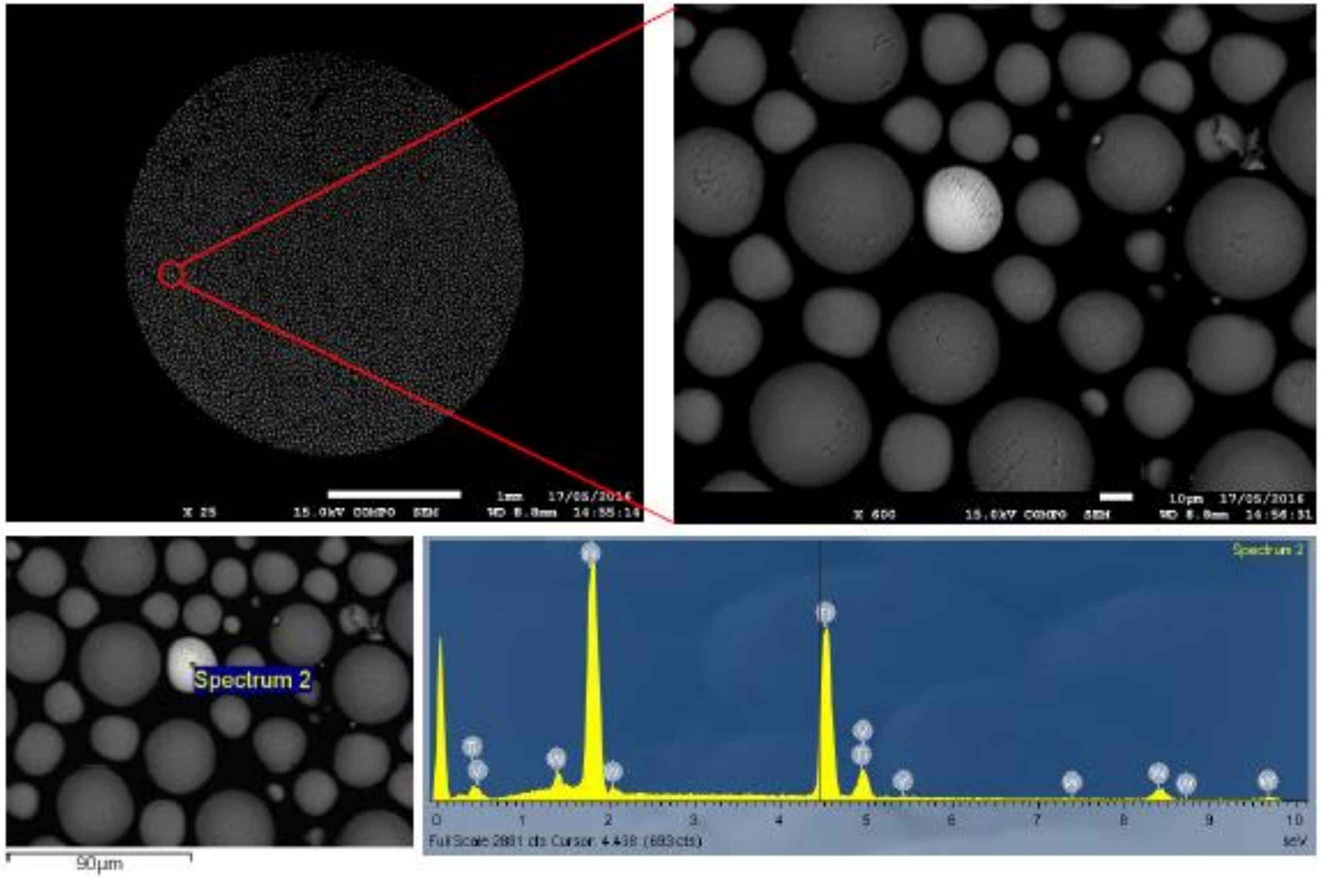
2007	2008	2013	2014	2015	2016	2017
Established	ISO 9001 certified	AS 9120 certified	£2M investment	Launch **POWDER**LIFE R&D program	LPW Germany	£20M investment
			LPW USA	Launch of **POWDER**SOLVE	LPW Italy	LPW UK move to dedicated 70k sqft facility
			LPW UK move to 20k sqft facility	**POWDER**TRACE	Plasma Spheroidisation	Launch of **POWDER**LIFE solution
			AS9100 & ISO 13485 certified		Launch of **POWDER**FLOW	LPW USA move to dedicated 12k sqft facility
					LPW R&D move to new facility	
					Queens Award for export	

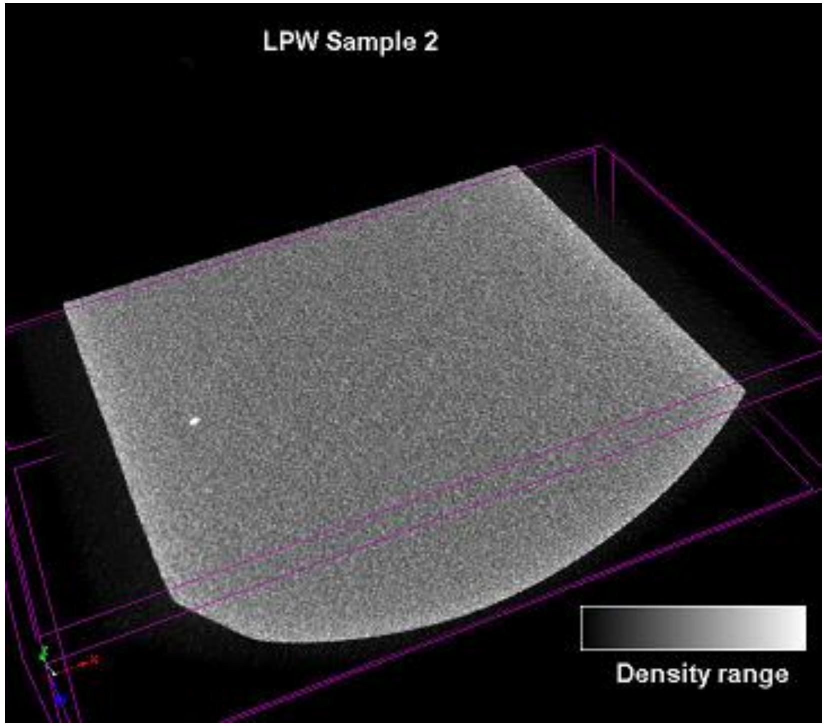
THE START — **EXPANSION** — **THE FUTURE…**

Our Locations

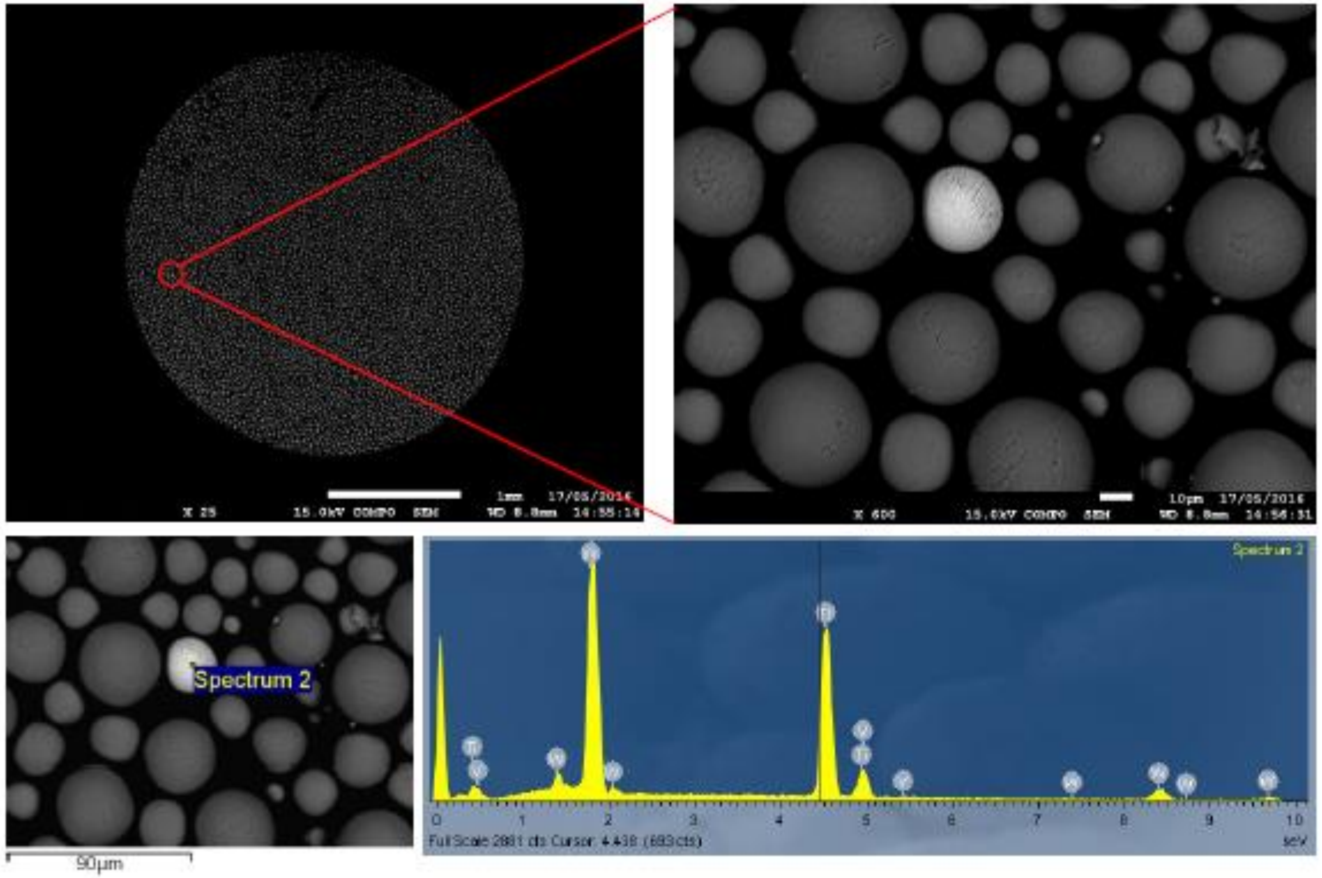
LPW Technology   LPW reseller

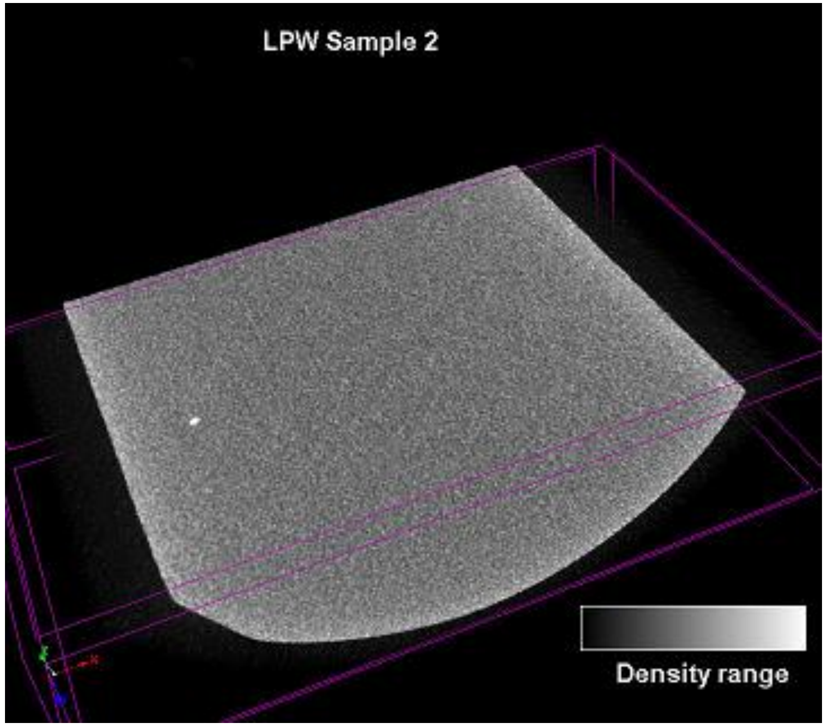
Contamination – Devil Particle





Contamination – Devil Particle





1kg AM Powder ≈ 2 Billion Particles ≈ 18 sqm surface area

PowderLife Strategy

"Creating novel solutions and products that enable our customers to ensure quality, traceability, and consistency of powder during re-use within the AM process"

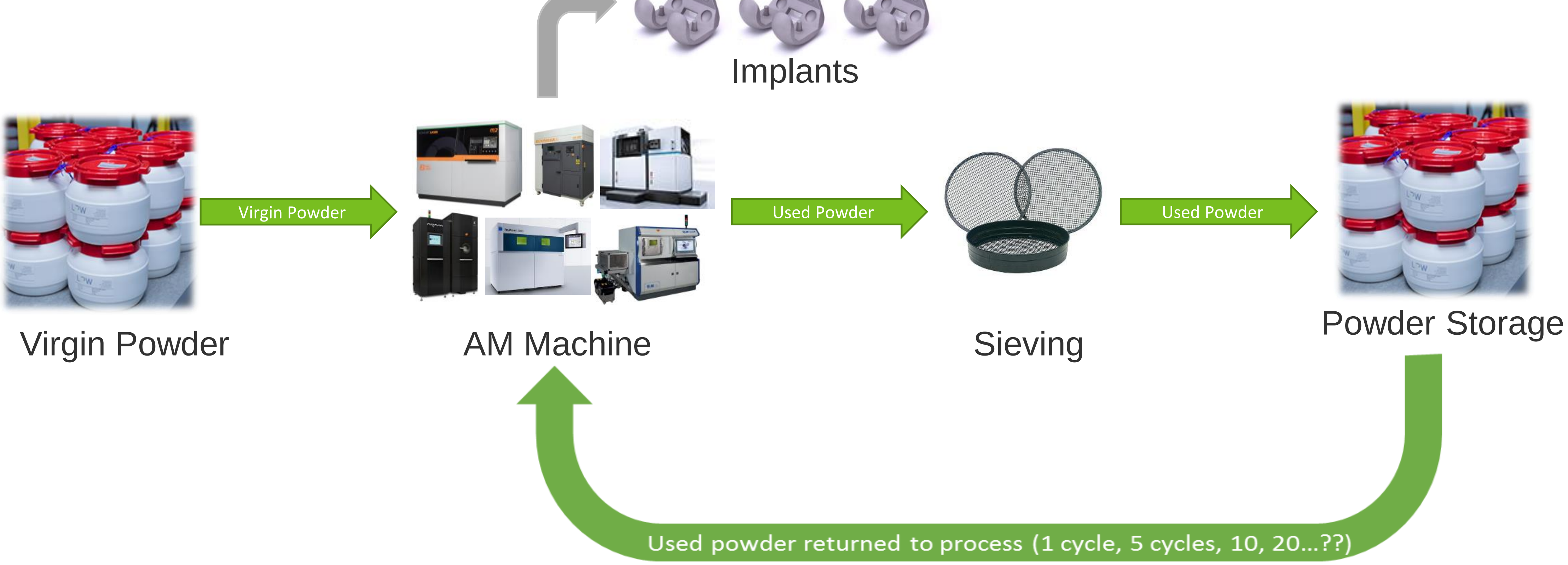
- Quality & Traceability
  - Application Teams → process mapping (powder handling & reuse methodologies)
  - **POWDER**SOLVE → fundamental backbone of all current and future TPM products & processes

- Contamination - control and measure "the devil particle"
  - Implement best practices powder handling & reuse methodologies
  - Reuse methodologies based on experimental data
  - Test certification focused on contamination & statistical confidence through repeated sampling

In-process Powder Control

Traditional AM Powder Cycle

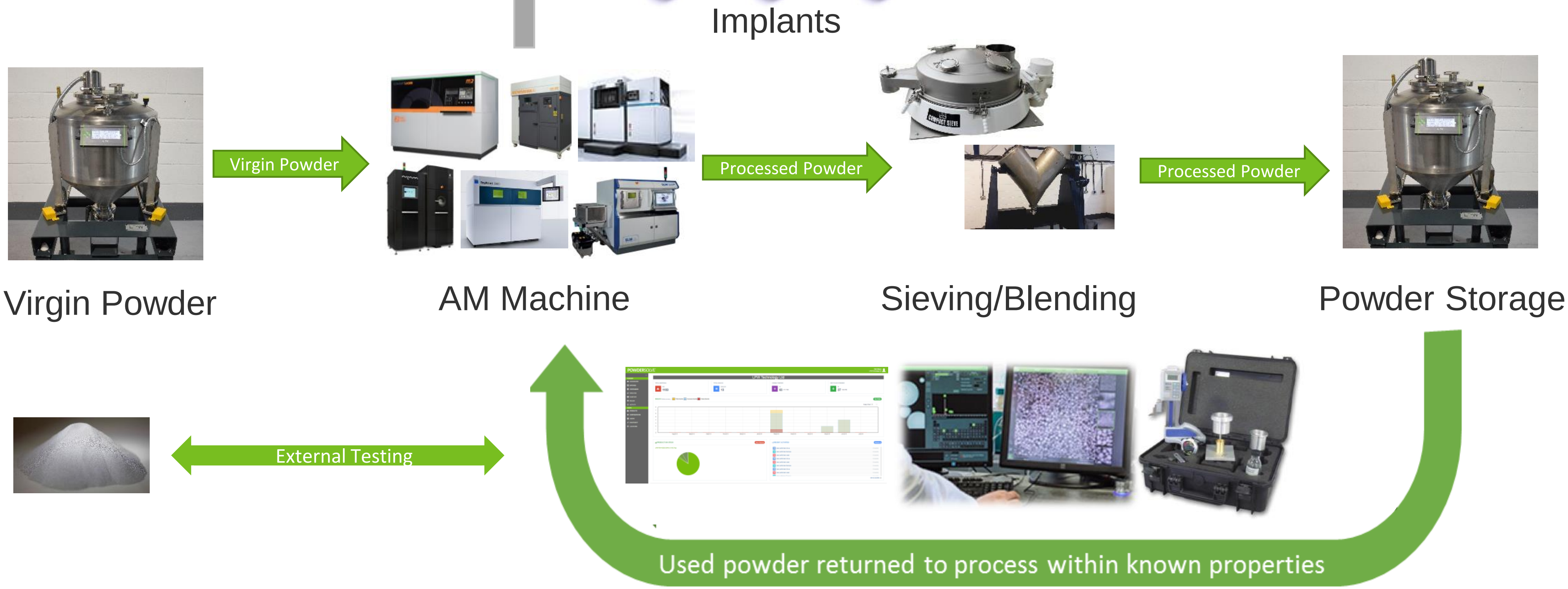
- Virgin powder and recycled powder used to manufacture
- Traceability of the powder lost after 1st build
- Impossible to operate an effective product recall system
- Component mechanical properties are not known as the powder degradation after repeat use is not monitored



In-process Powder Control

Traditional AM Powder Cycle

- The blending of virgin and used powders are controlled
- Full traceability of all raw materials is maintained – possible to implement an effective product recall in the event of a rejected component
- Mechanical propertied can be determined as powder degradation is monitored



Impact of In-process Powder Control

Cost Savings

- Requirement for 450,000 components over 25 years
- 15 builds per powder batch
- 10 component per build
- 15 builds per machine per month

Single powder batch
300Kg @ £300/Kg
Total £90,000

→

15 Builds producing components with a total weight of 225Kg

→

75Kg of Powder is out of specification and unusable powder (Scrap)
Total value of Scrap £22,500

Impact of In-process Powder Control

Manufacture of production components

CURRENT COST

• 15 builds per month on one machine	Input £90K	Scrap £22.5K
• Monthly requirements for 10 machines	Input £900K	Scrap £225K
• Annual powder requirements for 10 machines	Input £10.8M	Scrap £2.7M
• Powder required for the complete project life cycle	Input £270M	Scrap £67.5M

Impact of In-process Powder Control

Manufacture of production components

- Increase powder usage by 1 build per batch
  - Total powder requirements reduce by £16.8M
  - Scrap powder reduced by £4.21M

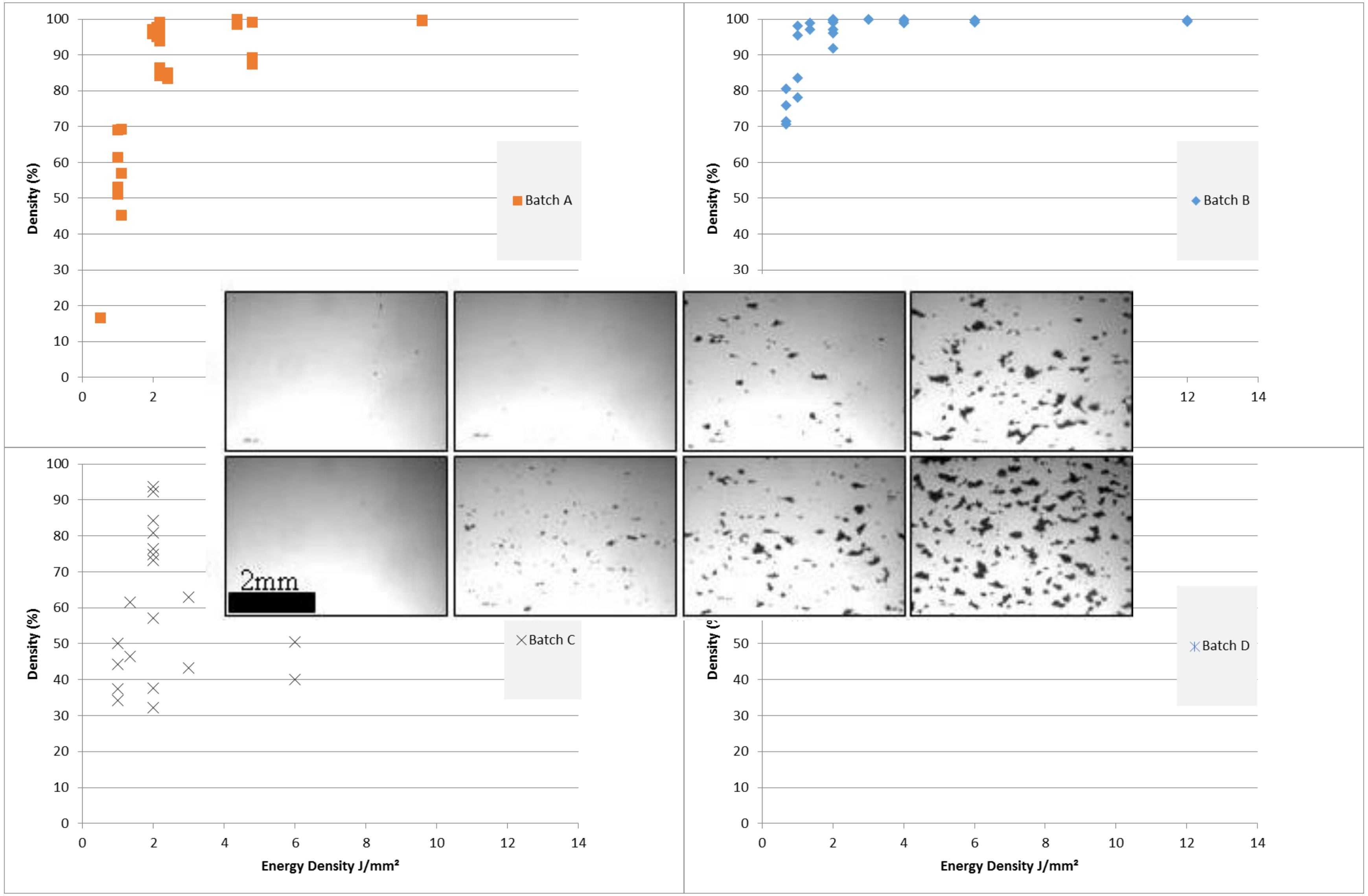
- Impact on component costs during lifetime of project
  - Initial cost per part £600
  - Increase powder usage £562.5 (6% cost reduction)

Case Study – AM Processing Window and Supplier Evaluation

Importance of powder specifications

Case Study – AM Processing Window and Supplier Evaluation

Importance of powder specification



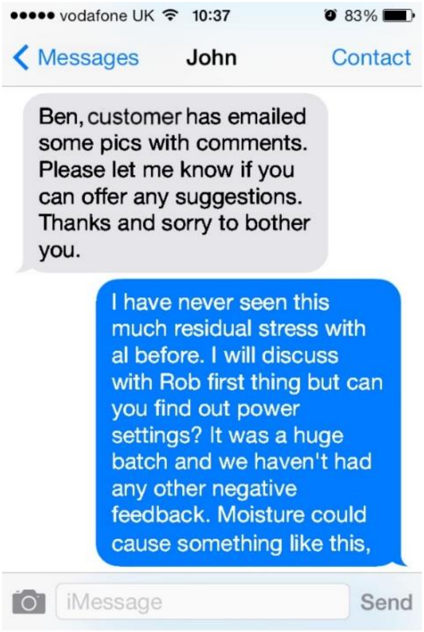
- Supply chain stability – dual atomisation source for all core products
- Powder batches with 15-45micron size range
- Variable scatter and success in AM build quality
- Caution! Energy Density!!

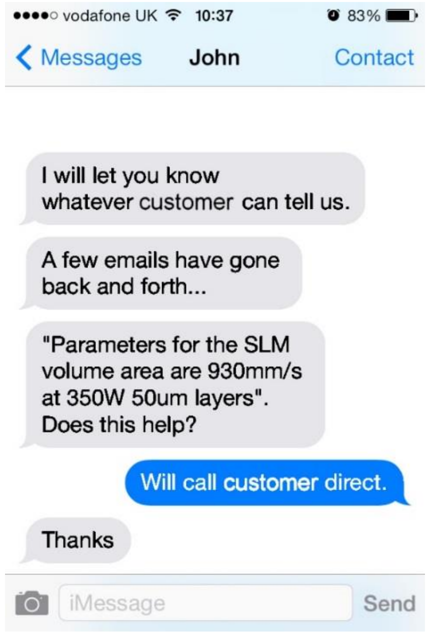
Case Study – The Devil Particle

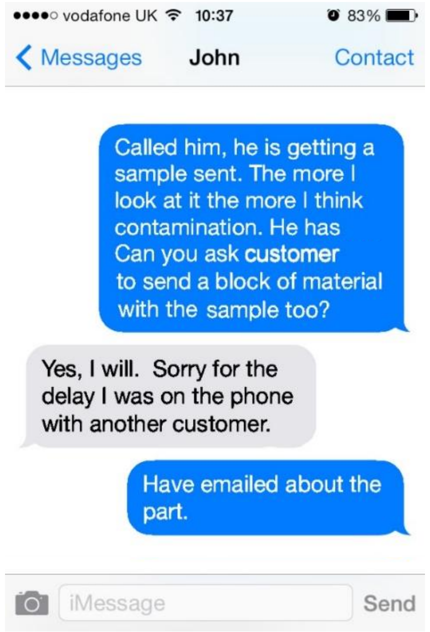
Aluminium Contamination

Monday 25th August - Problem

- Customer informs that their aluminium products have failed and suspect problem with the powder
- Text messages show Ben and John making a start on resolving the issue put forward by the customer







Case Study – Aluminium Contamination

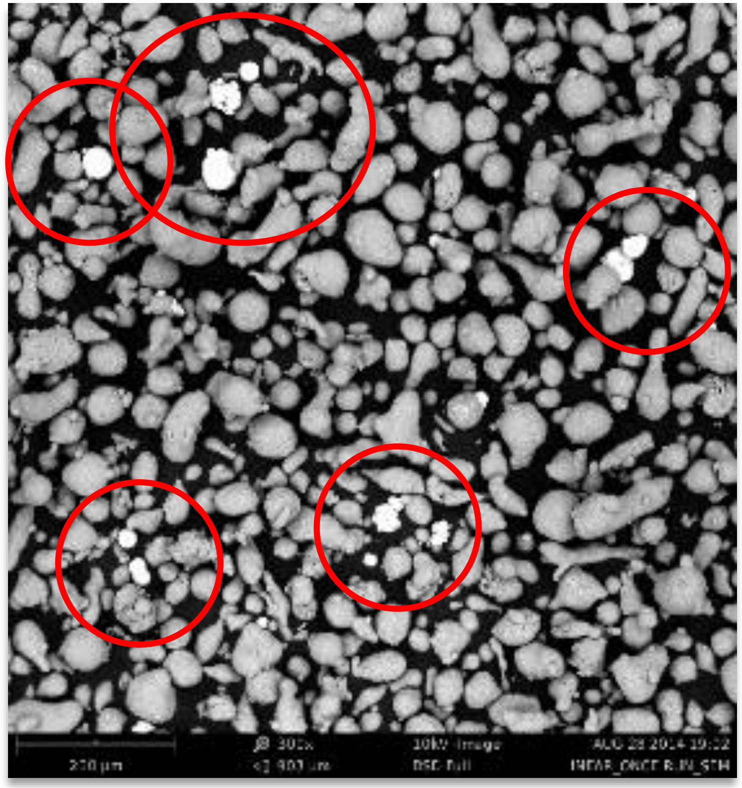
Tuesday 26th August - Problem

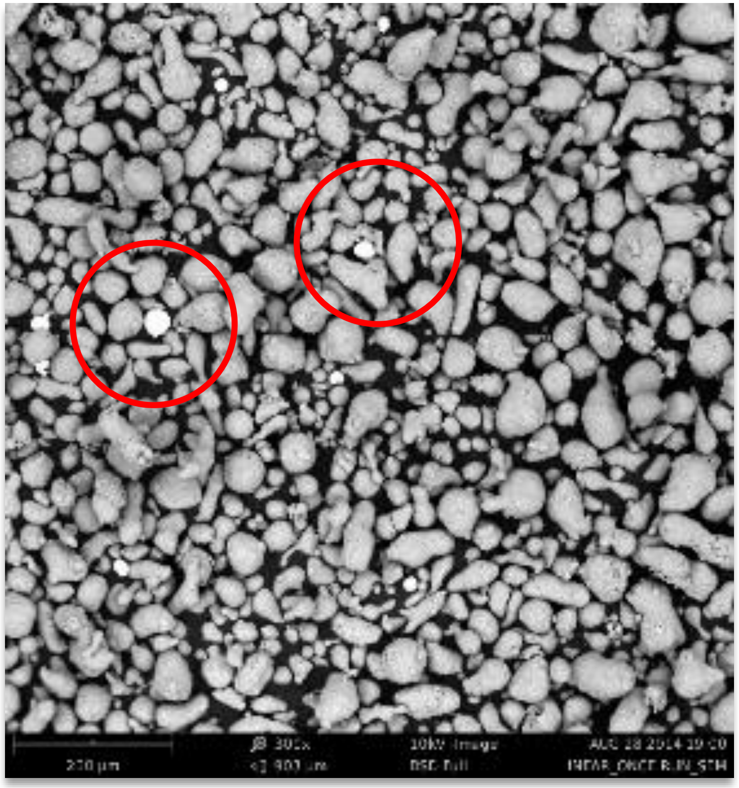
- Failed aluminium parts

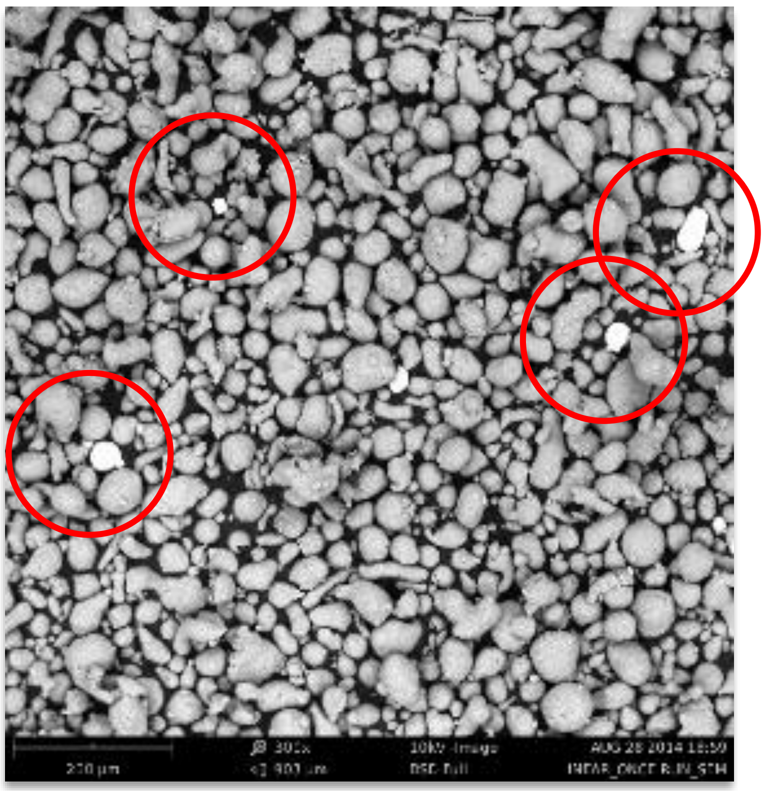
Case Study – Aluminium Contamination

Thursday 28th August - Testing

- Powder samples from failed build
- This confirms that there is some degree of contamination but is not conclusive that this level of contamination can cause cracking

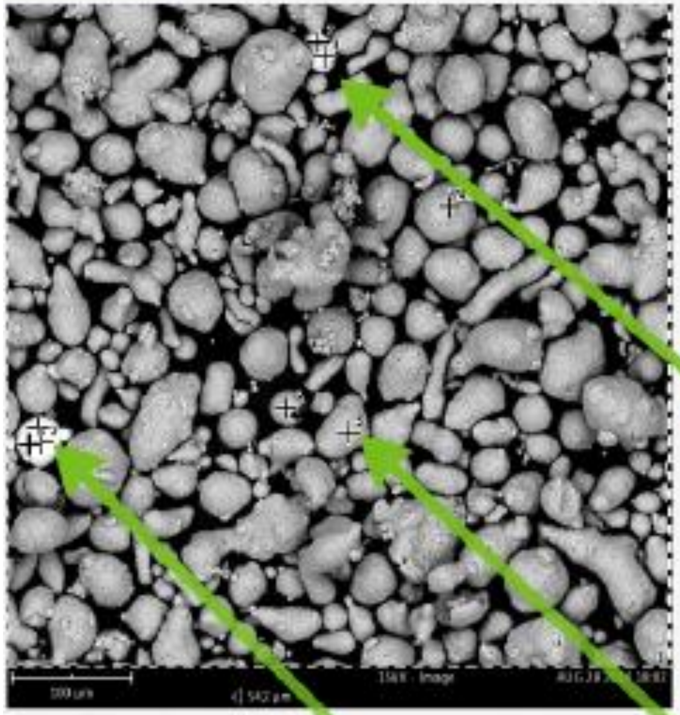




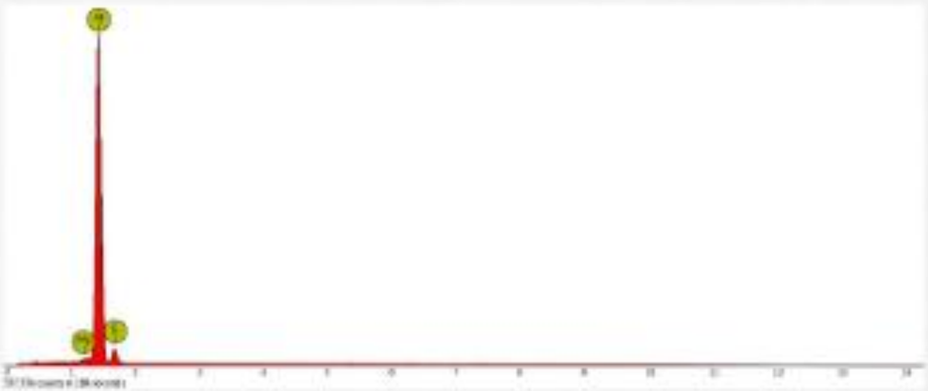


Case Study – Aluminium Contamination

Thursday 28th August - Testing



OVERALL AREA

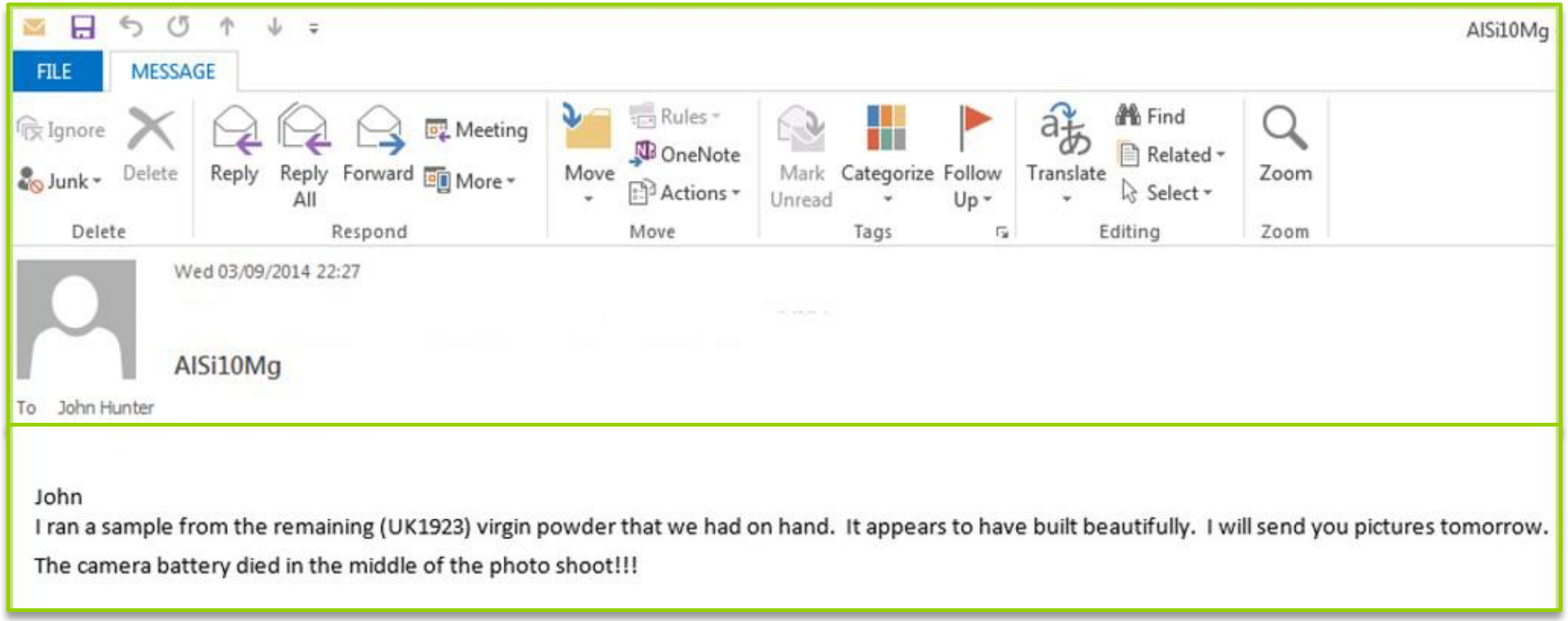


- Powder samples from the failed build.
- SEM-EDX chemical analysis shows Inconel625 contamination within the Aluminum powder samples.
- This confirms the assumption of failing parts due to contamination.

Case Study – Aluminium Contamination

Wednesday 3rd September - Solution

- Testing confirms powder was contaminated
- Using the virgin powder for the product gave a product that was "built beautifully"



Wed 03/09/2014 22:27

AlSi10Mg

To John Hunter

John

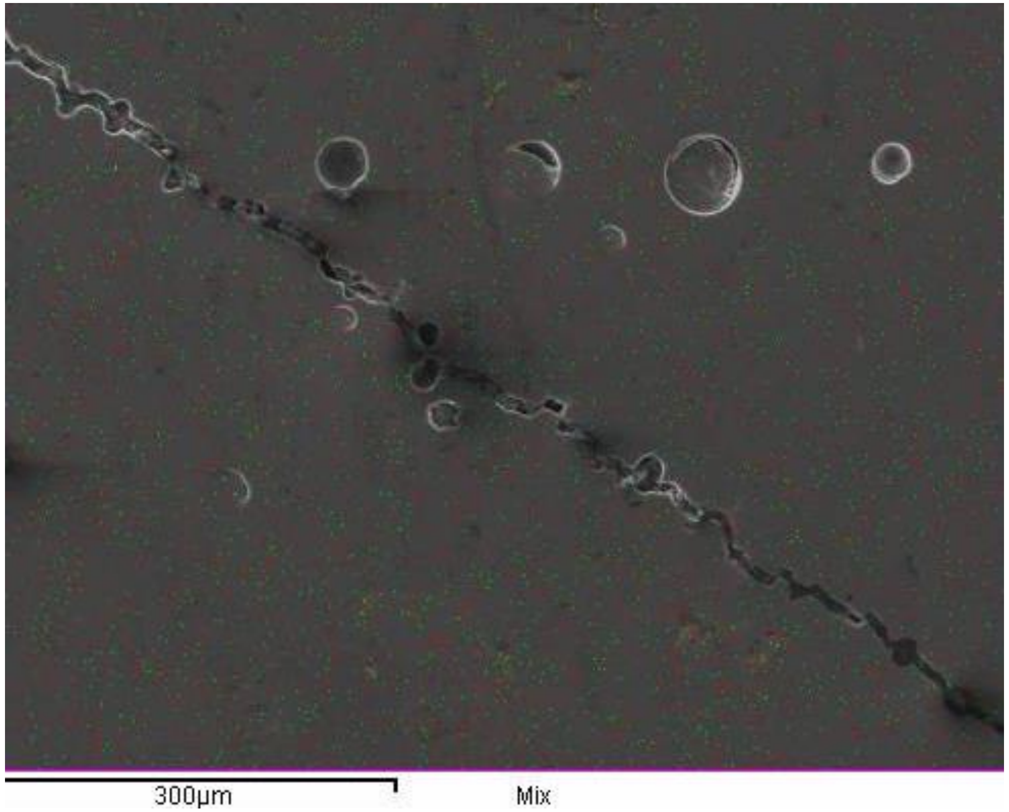
I ran a sample from the remaining (UK1923) virgin powder that we had on hand. It appears to have built beautifully. I will send you pictures tomorrow.

The camera battery died in the middle of the photo shoot!!!

Case Study – Aluminium Contamination

Validation

Element	Weight%	Atomic%
Al	81.93	85.51
Si	10.93	10.96
Cr	1.72	0.93
Ni	5.42	2.60
Totals	100.00	100.00

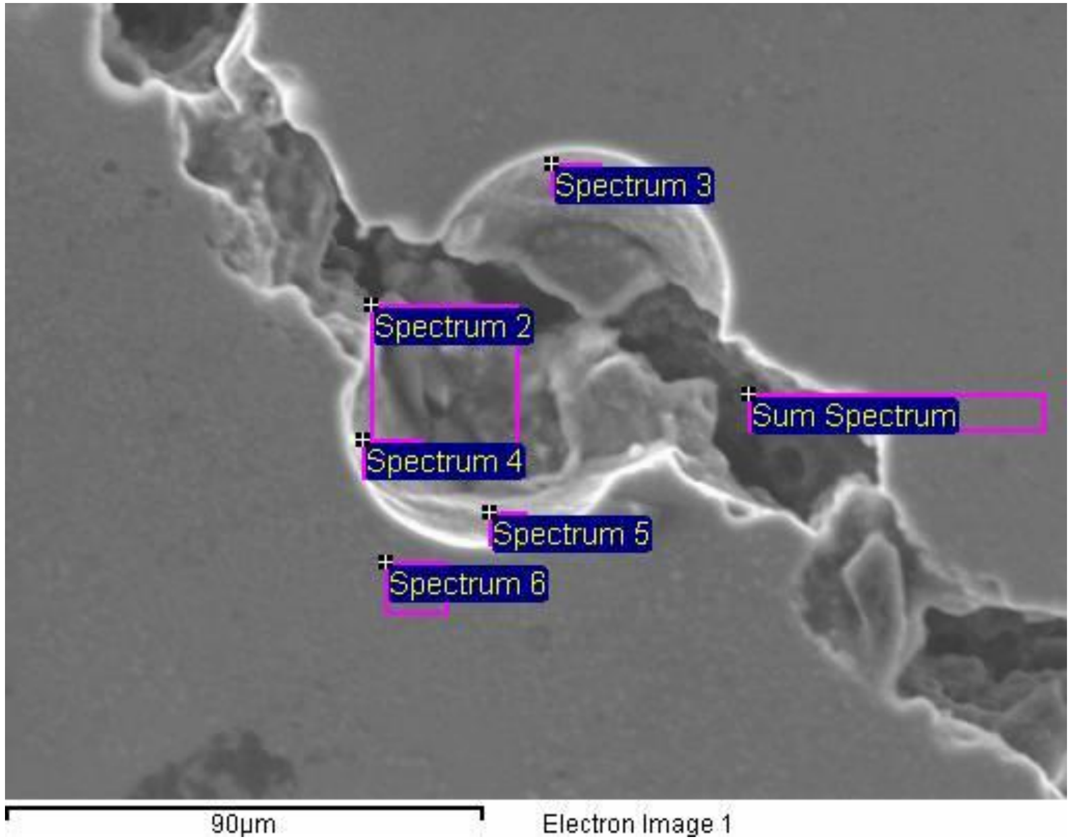


Nickel homogeneously spread in the aluminium matrix

Case Study – Aluminium Contamination

Validation

Spectrum	Al wt%	Si wt%	Cr wt%	Ni wt%	Total
SumSpectrum	79.55	12.63	1.79	6.03	100.00
Spectrum 2	48.05	5.37	6.30	40.28	100.00
Spectrum 3	58.87	8.61	4.38	28.14	100.00
Spectrum 4	58.30	11.22	3.31	27.16	100.00
Spectrum 5	76.13	16.04	2.27	5.57	100.00
Spectrum 6	81.56	10.24	1.98	6.22	100.00



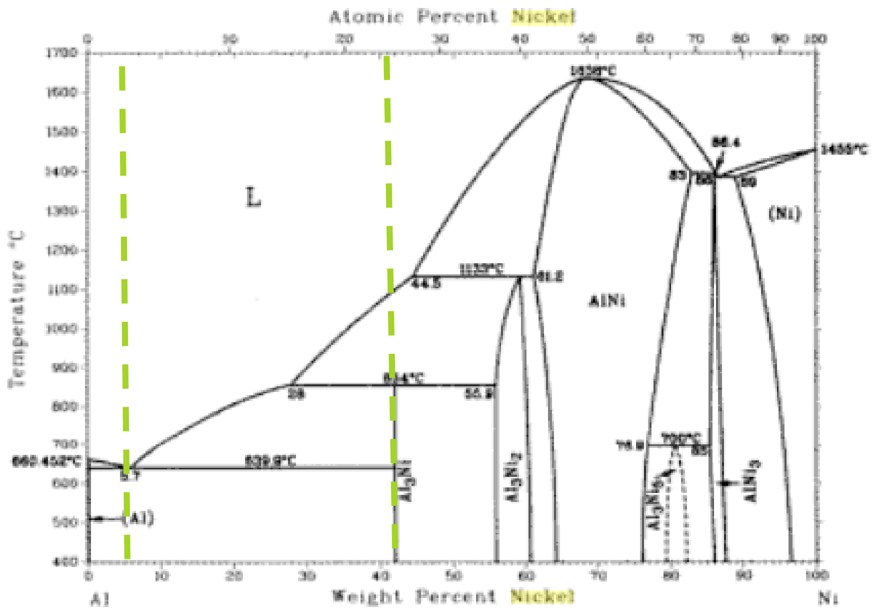
- At some points nickel content is relatively high
- Phase diagram would suggest high volume percent of brittle intermetallic phases in the Al matrix
- Nickel content could be even higher at some points, but due to the crack Al noise could be measured from different planes

Case Study – Aluminium Contamination

Solution - Physical Metallurgy: AL – NI Binary Diagram

- Ni solubility in Al is limited to 0.24 wt%
  - Not contributing to matrix strengthening
- Over solubility limit Ni starts to appear as an insoluble intermetallic ($NiAl_3$) increasing the strength
  - Usually up to 4 wt% Ni is used
- $NiAl_3$ volume percent increases with Ni content
- In the hypoeutectic (<5.7 wt%) Ni starts to appear as interdendritic α Al – $NiAl_3$ eutectic
- In the hypereutectic (>5.7 wt%) Ni appears as large NiAl3particles which are detrimental for ductility
- Over ~ 42 % more brittle intermetallic phases are starting to appear in the Al matrix
- The most brittle are the AlNi (61-83 wt%) and $NiAl_3$ (85-87 wt%)
  - Also known as nickel aluminides – potential for high temperature structural applications, but with almost 0% ductility

Al-Ni



P. Nash, M.F. Singleton, and J.L. Murray, 1991

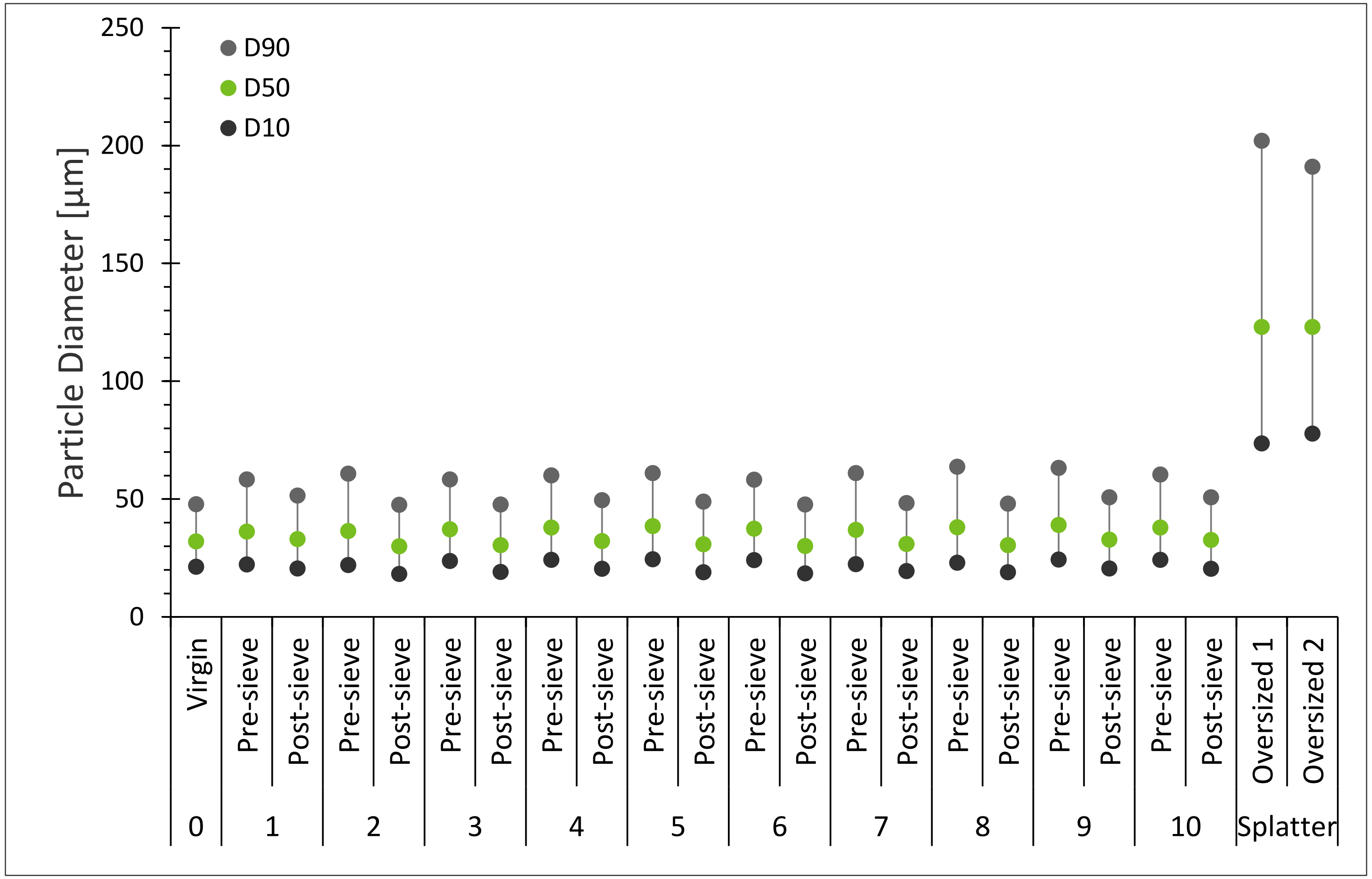
Phase	Composition, wt% Ni	Pearson symbol	Space group
(Al)	0 to 0.24	$cF4$	$Fm\bar{3}m$
Al_3Ni	42	$oP16$	$Pnma$
Al_3Ni_2	55.9 to 60.7	$hP5$	$P\bar{3}m1$
AlNi	61 to 83.0	$cP2$	$Pm\bar{3}m$
Al_3Ni_5	79 to ~82	...	$Cmmm$
$AlNi_3$	85 to 87	$cP4$	$Pm\bar{3}m$
(Ni)	89.0 to 100	$cF4$	$Fm\bar{3}m$

Degradation of Ti-6Al-4V Powder in Powder Bed Fusion

Can you re-use powder which has been through AM process?

Degradation of Ti-6Al-4V Powder

Particle Size Distribution

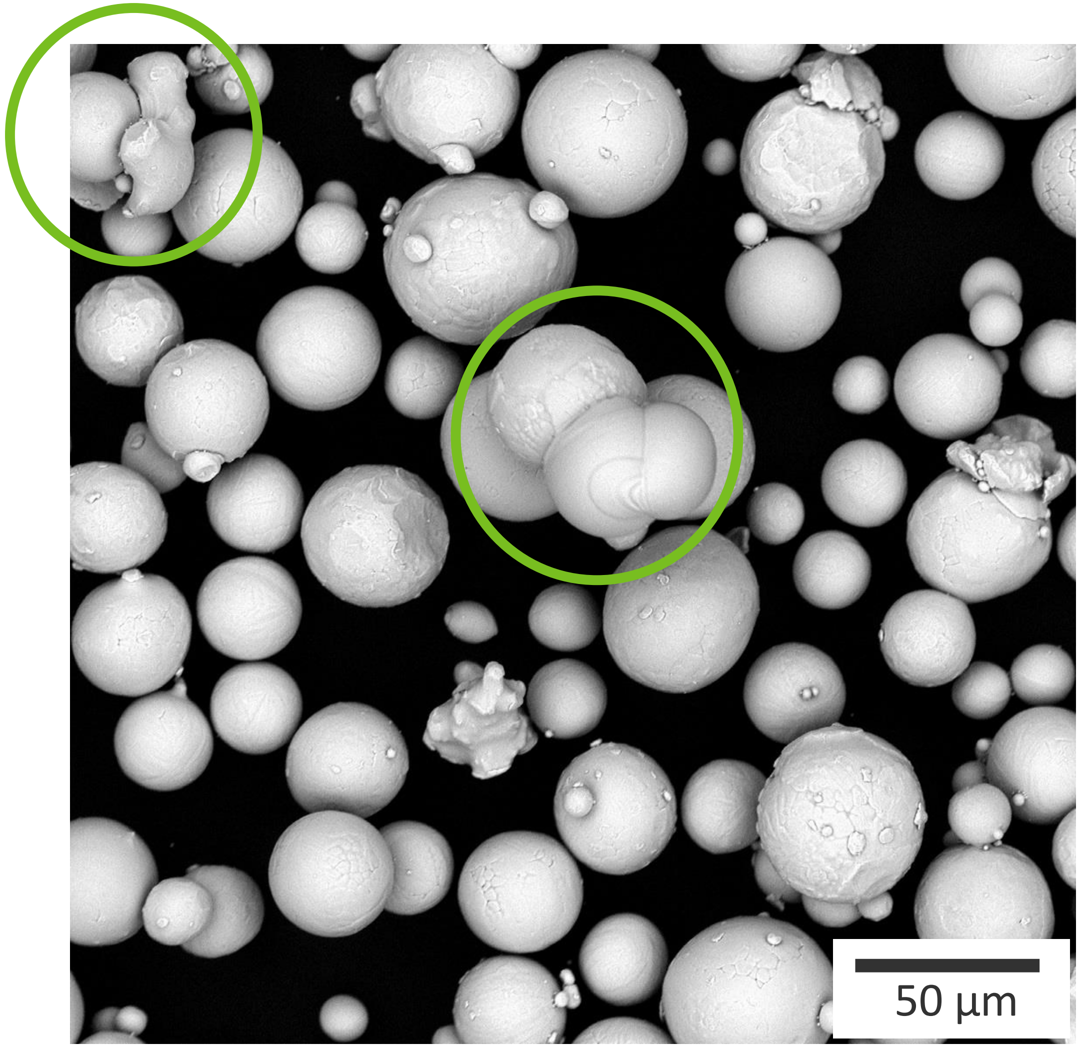


- Range of powder sizes
- Particle size and distribution tends to increase after a build
  - Sieving brings size and range closer to virgin
- Oversized particles have the largest diameter and have the largest range

Degradation of Ti-6Al-4V Powder

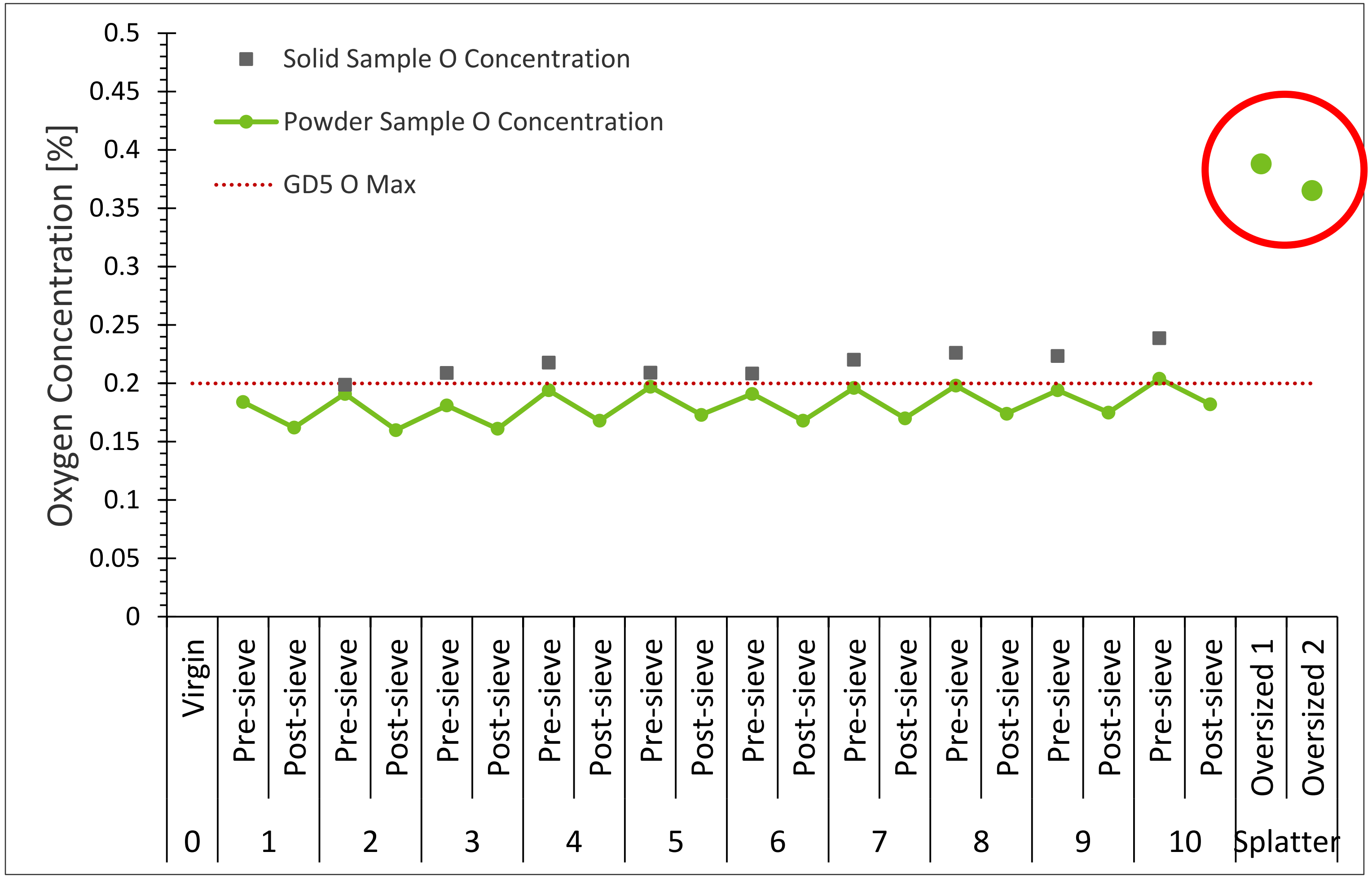
Powder Shape

- Oversized irregular particles and agglomerates from Spatter



Degradation of Ti-6Al-4V Powder

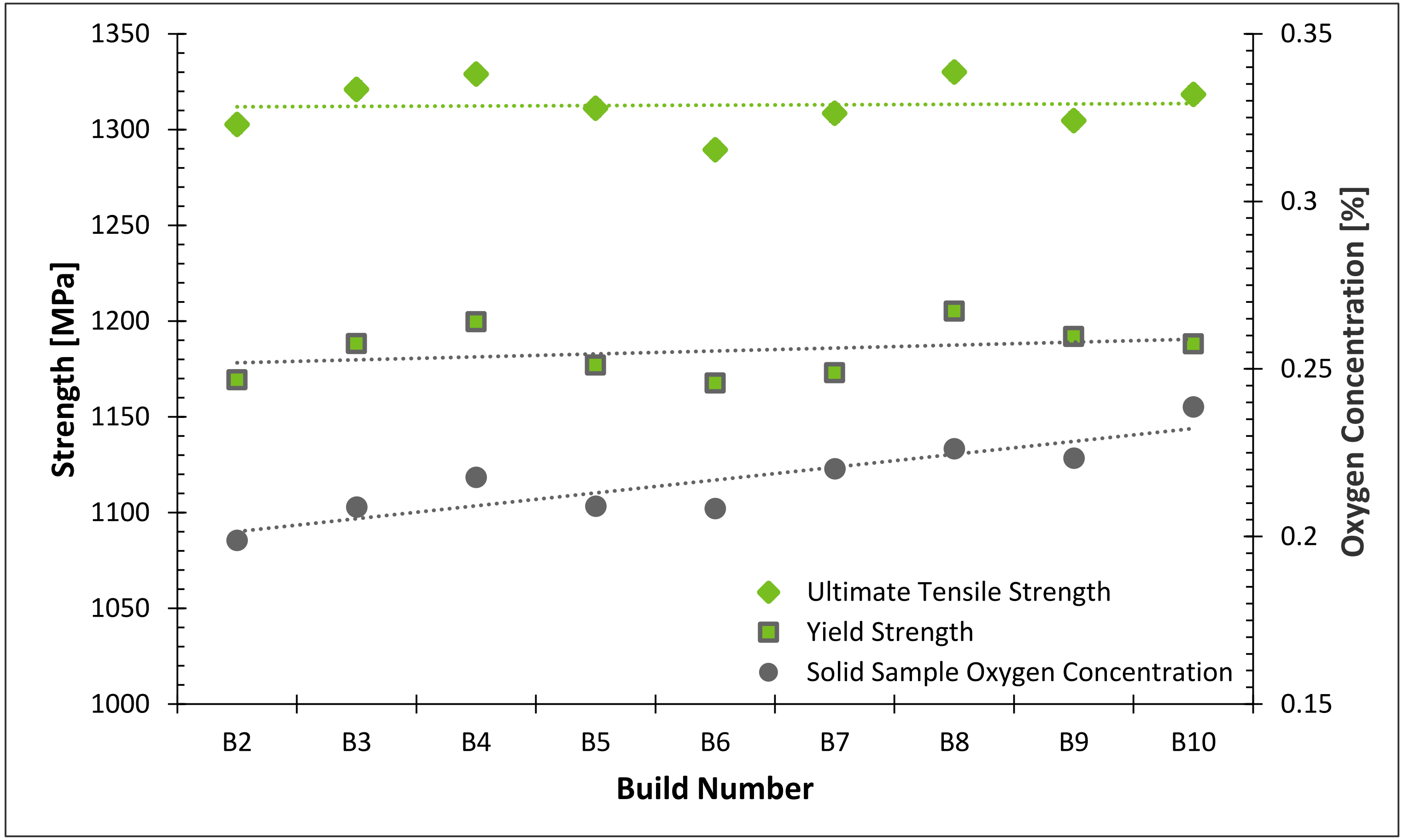
Powder Chemistry - Oxygen



- Oxygen content has an influence on the final part's mechanical properties
- Oxygen increase after first build
- Sieving out large particles significantly decreases oxygen content
- General increase with more builds
- Remains Grade 5 specification until build 10
- Oversized particles have largest oxygen content
- Oxygen content in solid sample slightly higher than powder

Degradation of Ti-6Al-4V Powder

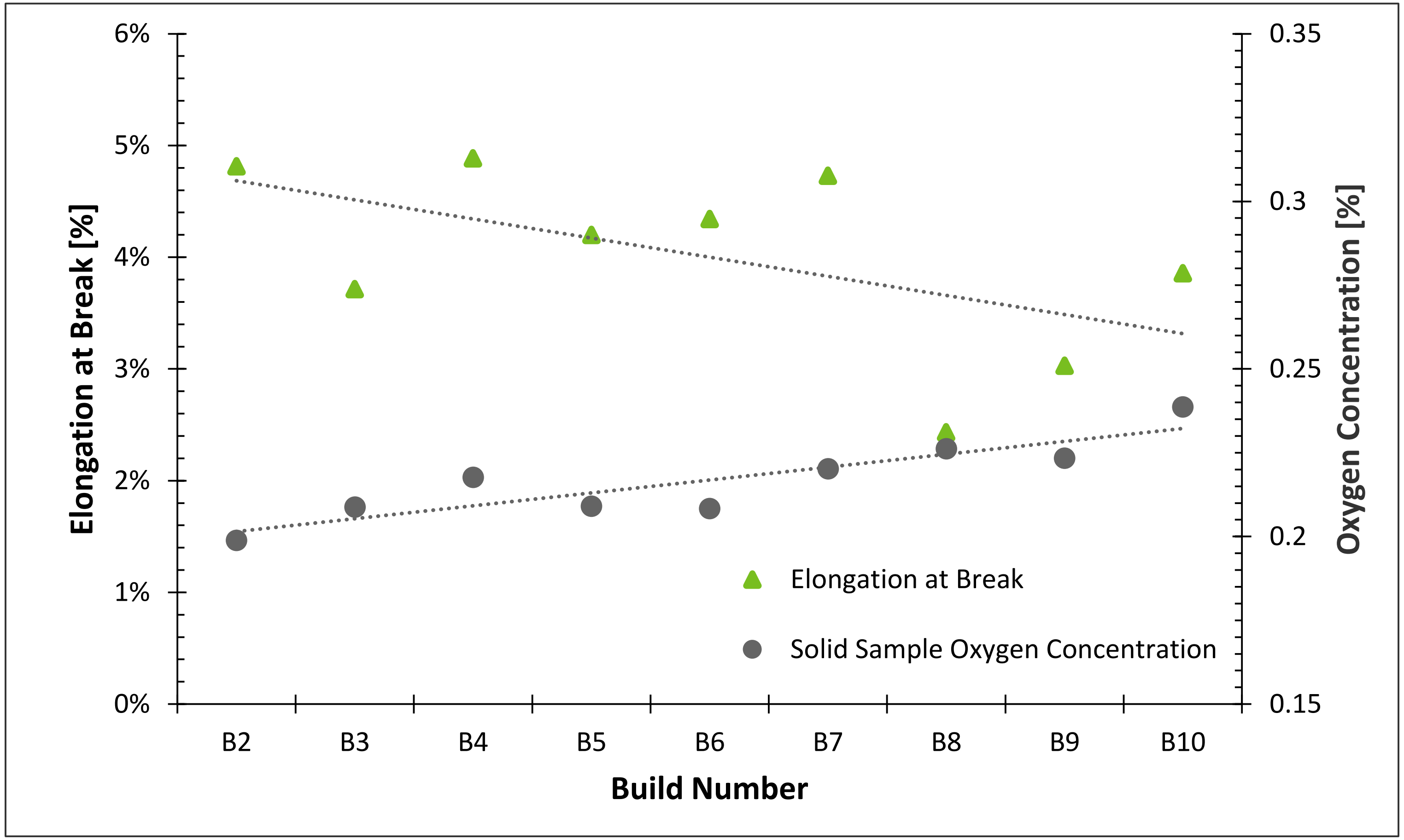
Mechanical Properties - Strength



- As-build part strength properties stay relatively unchanged from Build 1 to Build 10
- Yield strength and ultimate tensile strength heavily correlated with oxygen content

Degradation of Ti-6Al-4V Powder

Mechanical Properties - Ductility



- Ductility has decreasing trend with build number
- Ductility in AM influenced by:
  - Porosity
  - Impurity content
- Ductility has is heavily correlated to oxygen content in present study

Degradation of Ti-6Al-4V Powder

Summary

- Powder is effected from reuse
  - Oxygen and Nitrogen content increase
  - Powder became more spherical (aspect ratio increased)
- Powder is effected by post-process sieving
  - Removes large agglomerates that are high in oxygen and nitrogen
- Porosity in built part increases when using recycled powder
- Variation in mechanical strength with reuse
  - High correlation with oxygen content
- Ductility degrades with reuse
  - High correlation with oxygen content
  - Increased porosity could be contributing factor

Concluding remarks

- Three case studies presented
  - Importance of **Powder Specification**

    Variability between suppliers

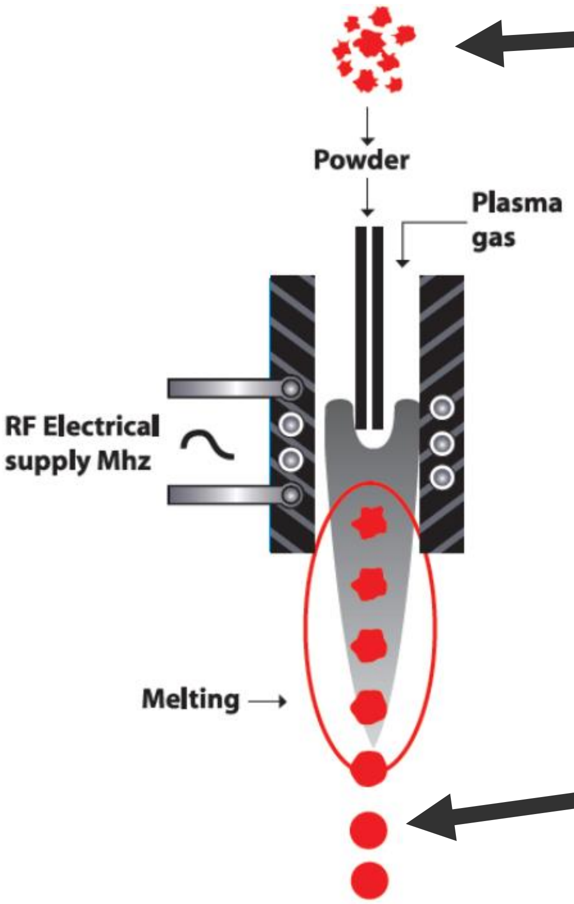
  - **Contamination** can be catastrophic

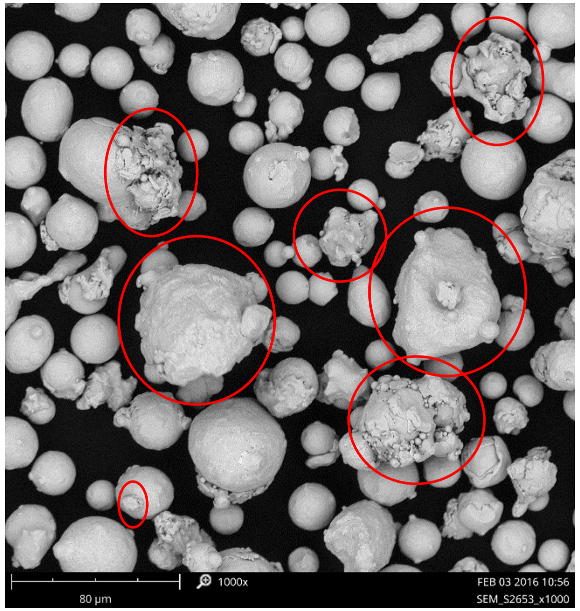
    Measures to detect and mitigate must be employed

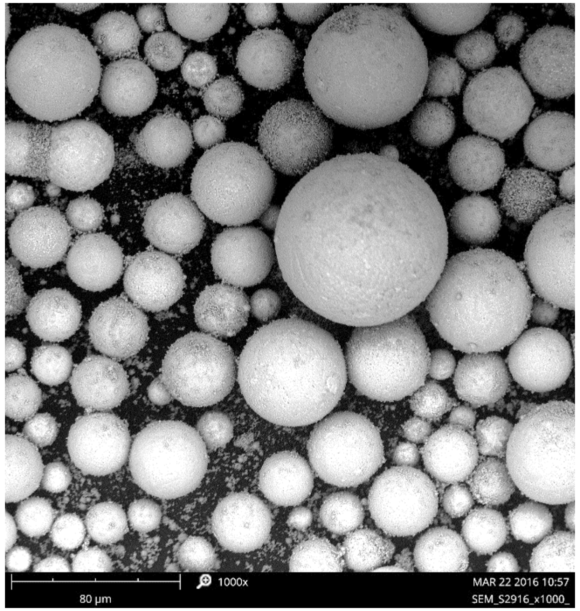
  - Powder changes (**Degradation**) with repeated use

    Critical to high-end applications and must be managed and understood to ensure traceability is maintained

LPW- 247LC Plasma Spheroidisation







As-Atomised feedstock

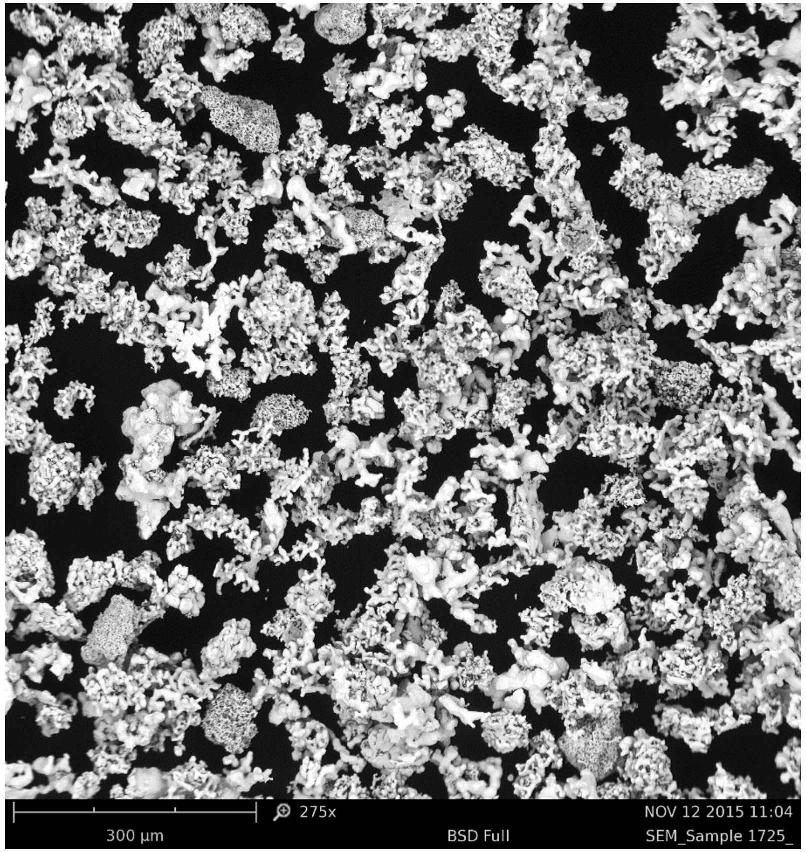
- Poor flow
- High surface area
- High O & N content

Plasma Spheroidised

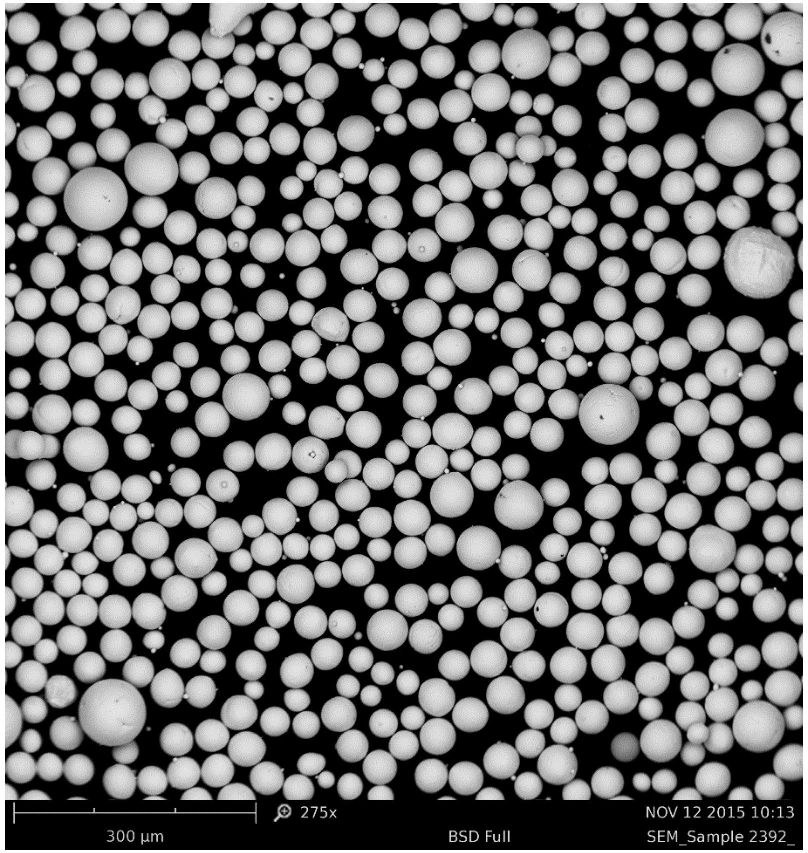
- Enhanced flow
- Reduced surface area
- Removal of organic contamination
- Lower O & N content

Tantalum (15-45 µm) Plasma Spheroidisation

As- received feedstock



Plasma Spheroidised



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