SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Co-funded by the Erasmus+ Programme of the European Union

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

CU 36: Coordinating the AM Process (Pilot)

TOPIC 7: Product verification & Quality

David Wimpenny

FOR SAM PILOT ATTENDEES AND TRAINERS ONLY

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Introduction to Part verification & Quality

- Quality enables a user to characterize and determine which product is better than the other
- The quality level of products and services indicates not only their intended function and performance but also their perceived value and benefit to the customer
- In the AM industry, organizations are required to have a quality framework that addresses the new concerns specific to AM, in addition to adopting and committing to the approaches and expectations defined in quality management standards, such as ISO 9001:2015

Part verification & Quality criteria

The part quality requirements may be defined by;

- Requirements by customer
- Requirements by organization
- Requirements by statutory and regulatory bodies
- Contract / orders requirements

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Part verification & Quality

essential step not only to ensure that parts meets customer expectations but also as a critical aspect of process control

NASA Standard -MSFC-STD-3716

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Assessing AM parts can be challenging.....

- Complex geometry
- Poor / inconsistent surface finish
- Process and part orientation dependant material properties
- Part quality can depend on part orientation, build location (for example in PBF-LB flow of argon can affect part quality)
- Some defects are “unique” to AM

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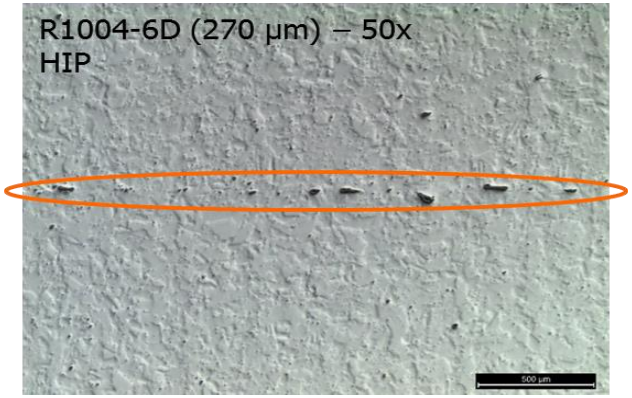
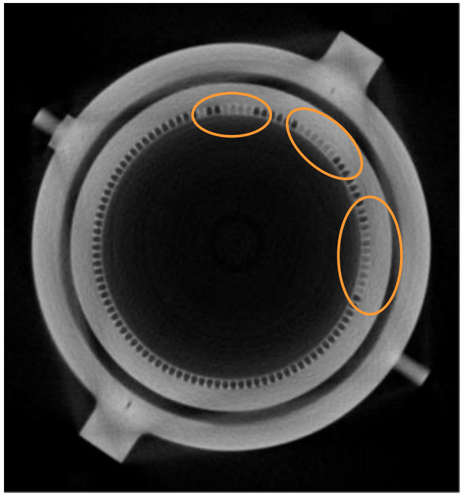
"Unique" AM Defects

- **Specific AM defects** – Layer defects (horizontal LOF), cross-layer defect (vertical LOF), unconsolidated powder and trapped powder

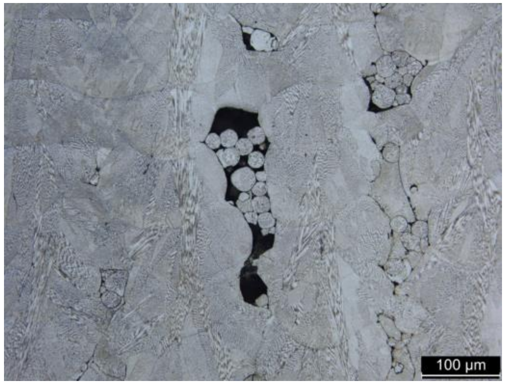


Layer defect (horizontal LOF)

Cross-layer defect (vertical LOF)



Trapped powder



Unconsolidated powder

Courtesy ISO/ASTM JG59 DTR 52905, 'Additive Manufacturing — Non-Destructive Testing and Evaluation — Standard Guideline for Defect Detection in Metallic Parts', Submitted for balloting.

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When to measure part quality ?

Need to measure final part quality but should check

- After critical process steps
- During processing - increasingly in-process inspection methods are being employed to “measure as we make”
- Using this approach we can;
  - Avoid incurring costs in downstream processes
  - Enable replacement parts to be scheduled
  - Identify the source of problem and prevent it affecting future parts

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PBF-LB metal parts

Could measure;

- As built
- After stress relieving
- After base plate removal
- After support removal
- After heat treatment
- After finishing

But measuring introduces cost and delays – automated inspection methods will help to overcome this problem

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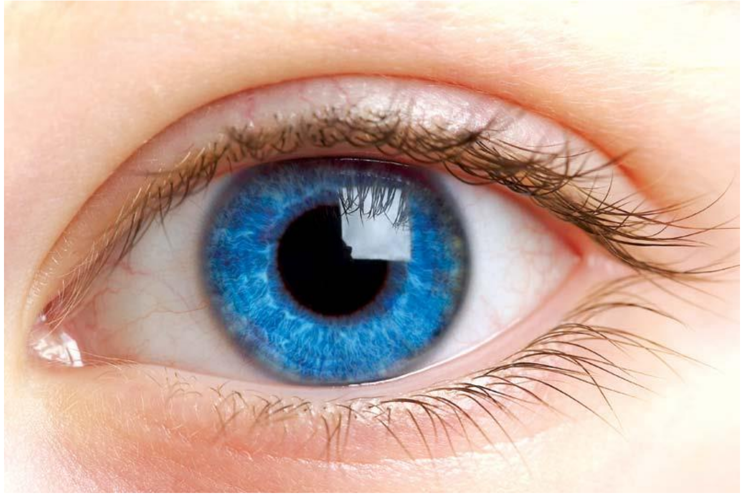
Inspection technique….?



- Widely available
- No capital investment
- No calibration
- Limited training
- Huge amount of data can be collected and processed very quickly

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Visual Assessment

- Distortion/swelling
- Delamination
- Poor surface finish
- Discolouration

6.2.12.2 As-Built Part Inspections

[AMR-41] Immediately upon build completion and removal from the powder bed, all parts shall receive, at minimum, full visual inspection for any indications of build anomalies prior to processes that may alter the as-built state of the part, such as bead or grit blasting, with all anomalies recorded in detail in the QMS.

[Rationale: Many indicators of L-PBF process quality are best evaluated prior to further part processing, including many indicators, such as coloration or support damage, that may be eliminated during further part processing.]

Build anomalies include, but are not limited to, witness lines on the part surface (see definition), unusual discoloration, laminar defects such as cracks or tears, separation of part from support structures, and geometric distortion.

At this time, the L-PBF machine should receive an inspection for any anomalies. Any damage or nicks in the edge of the recoater blade should be noted.

High quality photographs to document the as-built part inspection process is recommended, particularly unusual observations or anomalies.

NASA Standard
-MSFC-STD-3716

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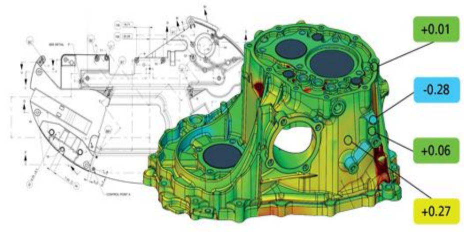
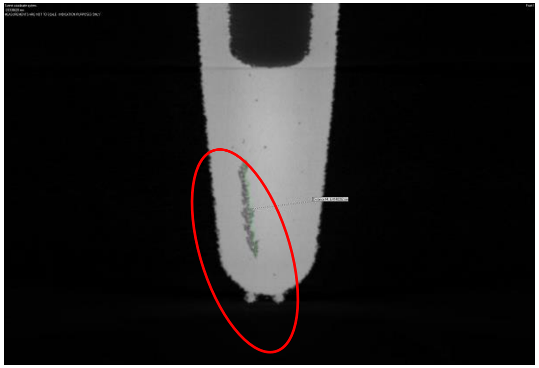
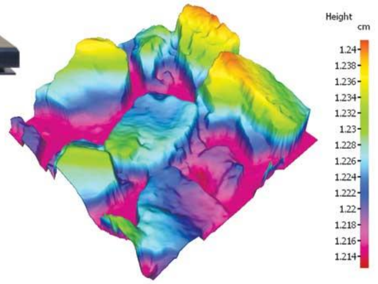
Final part quality assessment

- **Part accuracy** - hand held measurement tools, CMM +touch trigger probe (TTP) but increasingly using optical techniques (such as photogrammetry / structured light / laser strip)



- **Surface finish** – optical measurement of area (Sa,SZ) rather than linear profile lines
- **Integrity** - NDT (eg Xray CT)





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Assessing part integrity by Non Destructive Testing (NDT)

Mainly for reference but please READ

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X-ray Imaging

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NDT Technique	Physical Phenomena	Fundamentals	Applications
Radiographic Testing	Electromagnetic radiation (ionizing)	Requires the incidence and penetration of radiation energy on and through an inspected material, which is absorbed homogeneously by the material, except in the regions where thickness, density variations or defects arise. The radiation that passes through material impinges an image in a sensing medium revealing the defects.	Detect deep or embedded defects (virtually no limits); Poor sensibility for defects perpendicular to the radiation direction; Poor sensibility for small defects compared to the sample dimension; Not suitable for on-line inspection. Human health concerns.
X-ray Backscatter	Electromagnetic radiation (ionizing)	Backscatter X-ray detects the radiation that reflects from the target as opposed to conventional X-rays.	Detect deep or embedded defects (virtually no limits); It can operate even if only one side of the target is available; Inspecting times can be unacceptably long.
Computed Tomography	Electromagnetic radiation (ionizing)	Method of forming reliable three-dimensional (3D) representations of an object by taking many x-ray images around an axis of rotation and using algorithms to reconstruct a 3D model.	Detect deep or embedded defects (virtually no limits); Not suitable for online inspections. Time-consuming and size limitations.

ADMIRE

TÉCNICO LISBOA

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Ultrasound

NDT Technique	Physical Phenomena	Fundamentals	Applications
Conventional Pulse-echo Ultrasonic Testing	Mechanical vibration	A beam of high-frequency sound waves is introduced into a material, travel through it and are reflected at interfaces or defects. The reflected sound is analyzed to identify the presence and location of defects.	Can be used for flaw detection, location and measurement; It cannot be used for high-temperature inspection (typically > 300 °C); Surface treatment dependent. Not adequate for locally non-planar surfaces.
Phased Array Testing	Mechanical vibration	PA systems utilize multi-element probes, which are individually excited under computer control. By exciting each element in a controlled manner, a focused beam of ultrasound can be generated. Software enables the beam to be steered. Two and three-dimensional views can be generated.	Can be used for flaw detection, location and measurement; Fast inspection times; Able to penetrate thick sections; Cannot work at high temperatures; Requires coupling; May require several probes.
Immersion Ultrasonic Testing	Mechanical vibration	Immersion or water-column (squirt) US techniques allow a more efficient coupling between the US probe and the inspected material. It facilitates the automation of the inspection process providing C-scan images of the test pieces.	Improved probability of detection of the smallest defects; More accurate sizing and location of subsurface flaws; Good results independents of the geometry complexity; Cannot be used on-line and under high temperature; Requires immersion of the part.
Electromagnetic Acoustic Transducer (EMAT)	Mechanical vibration and Electromagnetic induction	This inspection method uses an electromagnetic acoustic (EMA) way of ultrasound excitation and reception.	Can be used for flaw detection, location and dimensional measurements. Contactless and couplant independent but requires proximity; Suitable for high temperatures; Geometry constrained. Low sensibility for small defects.
Laser Ultrasonic Testing	Thermal expansion and optical measurement	A laser pulse is directed to the surface, heating it and inducing an ultrasonic pulse that propagates into the sample. This ultrasonic pulse may interact with a defect and then returns to the surface. A separate laser receiver detects the displacement that is generated when the pulse reaches the surface.	Can be used for flaw detection, location and measurement; Capable of detecting very small flaws (virtually no limits); Contactless and couplant independent; Can be used on complex geometries, curved or difficult to access areas; Can be used at very high temperatures.

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Electromagnetic

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NDT Technique	Physical Phenomena	Fundamentals	Applications
		when the pulse reaches the surface.	
Potential Drop	Electrical current	Measurement of the potential drop by an increase in the electric resistant between two measurement electrodes in a presence of a discontinuity.	Very good at estimating surface cracks depth; Penetration depth of few mm; Surface roughness reduces the accuracy of the sized cracks. Can be used at high temperature.
Eddy Currents	Electromagnetic induction	A coil (probe) is excited with an alternating electrical current, producing an alternating magnetic field around a conductive test piece. Eddy currents are induced in the materials, but defects cause a change in eddy current, corresponding to a change in the impedance coil, allowing the identification of the defects.	Can be used for surface and subsurface flaw detection; Penetration depth of few mm (1/2 mm); Very sensitive to small defects. Contactless but requires proximity; Limited to conductivity materials.
Magnetic Particle Testing	Magnetic field	The inspected material is magnetized. The presence of a surface or subsurface defect allows the magnetic flux to leak. Then magnetic (ferrous) particles are applied on material surface and attracted to the flux leak zone, indicating the presence of a defect.	Limited to ferromagnetic materials; Can detect subsurface defects. Not adequate for online inspection.

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Thermography

NDT Technique	Physical Phenomena	Fundamentals	Applications
Infrared Thermography	Electromagnetic radiation	Infrared thermography aims at the detection of subsurface features, owing to temperature differences (DT) observed on the investigated surface during monitoring by an infrared camera.	Can detect subsurface defects; Risk-free (no radiation); Suitable for online monitoring; Requires heated working material; Large areas can be scanned fast.
Laser Thermography	Electromagnetic radiation	A high-power laser source is used for external heat delivery and the energy will diffuse in the specimens' surface making discontinuities detectable with the analysis of the temperature distribution near the laser spot.	Can detect subsurface defects; Suitable for online monitoring; Contactless and requiring no surface finishing;
Vibro Thermography	Electromagnetic radiation and mechanical vibrations	An ultrasonic transducer generates elastic waves within the test specimen. These waves will interact with the irregularities present in the object and due to the friction, energy will be dissipated in heat form and later detected by an IR camera.	Can detect subsurface defects; Requires contact; Very short measurement time (seconds). Difficult to apply in heated surfaces.
Eddy Current Thermography	Electromagnetic induction and radiation	Use of induced EC to heat the sample and defect detection is based on the changes of the induced eddy currents flows revealed by thermal visualization captured by an infrared camera.	Can detect subsurface defects. May require time to deposit enough energy in the material; Suitable for online monitoring.

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Other

NDT Technique	Physical Phenomena	Fundamentals	Applications
Penetrant Testing	Capillary action	Components are wetted with a fluorescent penetrant and penetrant soak into a surface defect. The penetrant excess is removed, and a developer is applied to the surface, drawing penetrant from defects out, forming a visible indication of the defect.	Cannot detect interior defects; Cannot be implemented on-line; It is time-consuming (> 20 min).
Acoustic Emission	Mechanical vibration	Elastic waves that are emitted in a medium due to crack can be captured by suitable piezoelectric sensors on the surface of a specimen.	Can be used for flaw detection and location; Perfect for parts in operation; Not suitable for post-manufacture inspection (prior to service). Not adequate for online inspection.

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Measurement of quality "by proxy"

- Witness samples produced alongside/joined to components
- Can be subjected to destructive testing including;
  - Metallurgical assessment – microstructure / density
  - Mechanical properties
  - Chemical composition (including interstitial contamination)
  - Other properties

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In process measurements

- As well as in-process monitoring of KPVs the development of in-process inspection methods can be used to assess the accuracy and integrity of parts
- As well as providing timely information it enables a directly link between KPVs and potential defects to be investigated
- Systems under development include Ultrasonic and eddy current NDT heads for DED to identify potential defects in-situ

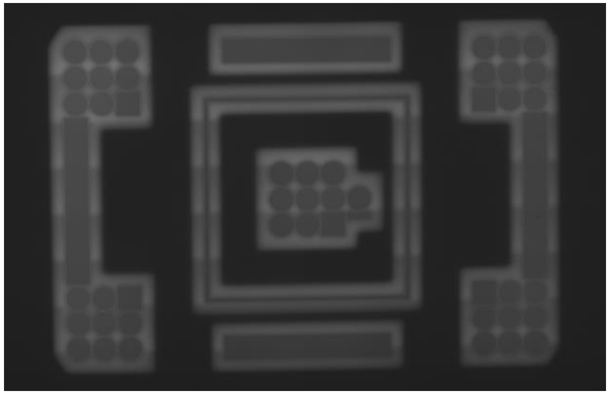

Image of a layer obtained using the near-infrared thermal imaging camera on the Arcam Q20 at MTC

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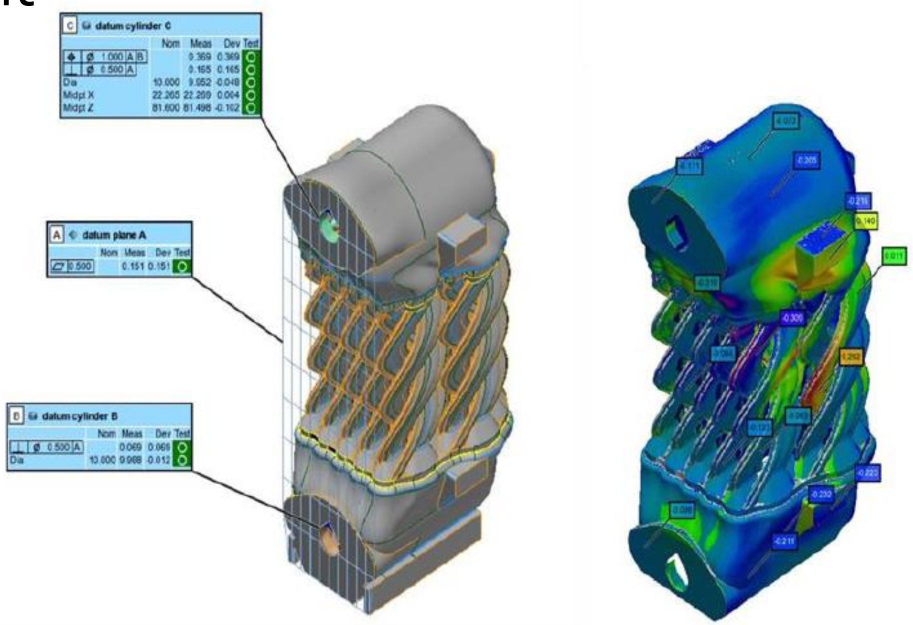
Product verification

Case study – KHUB-AM-0005 planning for product verification
Heat exchanger produced by Metal PBF-L
(you have been supplied with this report)

Product verification is important aspect of manufacturing, used to ensure product meets required design specifications and therefore performs as intended.



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Planning for Product Verification

- Should start at the design concept and process planning stages
- Has significant impact on product quality, manufacturing process and cost
- Final inspection of product at the end of manufacturing process is most common method of verifying product quality

BUT

- Components which are complex or require multiple manufacturing operations it may be better to verify as manufacturing progresses to;
    - Avoid incurring cost /time for downstream process
    - Take time corrective action (such as rebuild)
    - Identify the cause of the problem (for example geometrical inaccuracy)
    - Enable access to features (for example assembled/welded parts)

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Strategy for Product Verification

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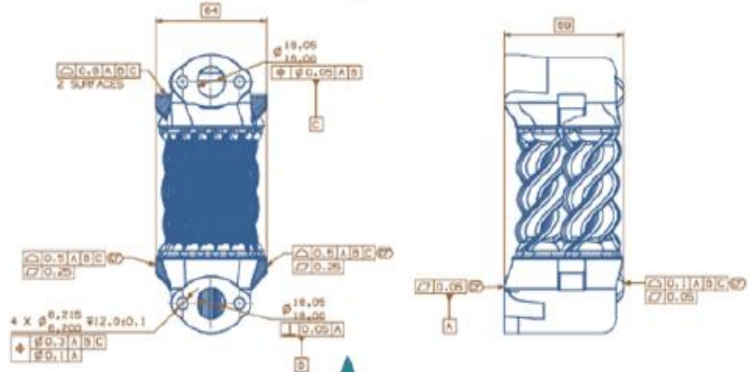
Documents relating to product verification against key product lifecycle steps

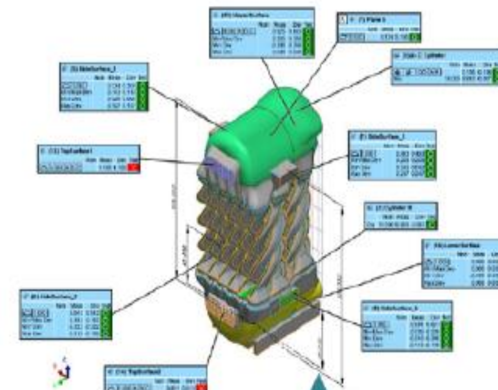
- Functionality statements

Functional requirement	Interpretation	Characteristic type
The component must not interfere with surrounding parts at maximum material condition.	Bounding envelope / maximum material condition.	Form
The interfaces must achieve a strong connection and a good seal.	Threaded flange interface. Control datum features.	Fit
The component must achieve the minimum heat transfer characteristics within its operating volume and conditions.	Heat transfer of xx. Surface area of xx.	Function
The component must achieve the desired hydraulic performace at operating conditions through its life.	Pressure drop vs flow characteristic curve at operating envelope.	Function
Component integrity must be maintained through its life at nominal conditions and at worst operating conditions for a short period.	Operating conditions for xx hours and/or xx heat/cool cycles. Max temperature/pressure for xx hrs. Surface finish of xx worst case for fatigue.	Function

- Drawings



- Inspection programs
- Inspection reports & data



Functionality definition → Process design → Part definition → Inspection planning → Inspection execution

Functional requirements	Verification routes					
	Dimensional	NDT	Condition of supply control	Manufacturing process control	Functional test	In-service history
The component must not interfere with surrounding parts at maximum material condition.						
The interfaces must achieve a strong connection and a good seal.						
The component must achieve the minimum heat transfer characteristics within its operating volume and conditions.						
The component must achieve the desired hydraulic performace at operating conditions through its life.						
Component integrity must be maintained through its life at nominal conditions and at worst operating conditions for a short period.						

- Verification matrices

Feature	Drawing ref	Sheet/grid ref	System type	Point strategy	Reporting strategy	Feature construction	Comments
1	[⏥ 0.05] ►-[A] 2 SURFACES	1-E12	CMM with scanning tactile probe	Scan around each large hole. 2 scans total.	Report 1 flatness value.	Least squares fit for plane. Treat as continuous feature.	Primary datum feature
2	Ø16.05/16.00 ►-[B]	1-D10	CMM with scanning tactile probe	2 scans at 1/3 and 2/3 depths.	Report 1 diameter. Report 1 roundness for info.	Least squares fit.	Secondary datum feature
3	[⊥ 0.05 A] ►-[D]	1-D10	CMM with scanning tactile probe	Measured above.	Report 1 perpendicularity.	Software mode set to ASME Y14.5	Secondary datum feature
4	Ø16.05/16.00 ►-[C]	1-H10	CMM with scanning tactile probe	1 scan at middle depth.	Report 1 diameter. Report 1 roundness for info.	Least squares fit.	Tertiary datum feature
5	[⌖ Ø0.05 A B] ►-[C]	1-H10	CMM with scanning tactile probe	Measured above.	Report 1 position.	Software mode set to ASME Y14.5	Tertiary datum feature
6-9	4xØ6.215/6.200	1-D6	CMM with scanning tactile probe	1 scan at middle depth.	Report diameter values. Hole at 6 o'clock is no. 1 then number holes clockwise.	Least squares fit.	

- Inspection plans

Functionality statements

Recommended that document with the following minimum information is created:

1. **Functional requirements**: high level qualitative statements of the intended part function;
2. **Interpretation**: high level quantitative expressions of how the functional requirements will be translated into specifications;
3. **Characteristic type:** whether the functional requirement relates to form, fit or function;
4. **Criticality:** an assessment of relative criticality or importance

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Some of the functional requirements for heat exchanger…

Functional requirement	Interpretation	Characteristic type	Criticality
The component must not interfere with surrounding parts at maximum material condition.	Bounding envelope / maximum material condition.	Form	
The interfaces must achieve a strong connection and a good seal.	Use threaded flange interface. Make mating surfaces datum features.	Fit	Critical
The component must achieve the minimum heat transfer characteristics within its operating volume and conditions.	Minimum heat transfer coefficient. Minimum surface area.	Function	Critical
The component must achieve the desired hydraulic performance at operating conditions through its life.	Pressure drop vs flow characteristic curve at operating envelope.	Function	Critical

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Verification matrix

Describes how to assess if each requirements is met;

- Dimensional inspection e.g. measuring a feature using manual gauging;
- Condition of supply checks, e.g. ensuring a valid and traceable CoC (certificate of conformity) has been provided, as the supplier might be responsible for carrying out the inspection;
- Manufacturing process controls, e.g. ensuring the process is stable or capable, or locking and using correct versions of programs;
- Functional testing;
- Leveraging data, e.g. from in-service history or on-going statistical analysis.
- An assessment of how adequate each method would be, This can be as simple as stating whether the requirement would be fully or partially met, or a more advanced assessment could include the RPN score (risk priority number) from a DFMEA (design failure mode and effect Analysis).

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Legend:

Manual gauging / visual	CMM	Data	Insufficient
3D Structured Light	Focus variation	Process	Partially sufficient
X-Ray CT	Testing	Other	Sufficient

Verification matrix for heat exchanger

Functional requirements	Possible verification routes					
	Dimensional	NDT	Condition of supply	Manufacturing	Functional test	In-service history
The component must not interfere with surrounding parts a[…] conditi[…]	Measure linear dimensions or […]			Prove process is capable.	Go/nogo fixture. Assembly success/failure.	
The inte[…] a strong[…] good s[…]		[…]heck […]mage. […]e of […]ealant.	Verify screws / inserts are in spec.	Torque settings locked. Calibrated wrenches.	Leak test. Fatigue / vibration test.	
The co[…] the min[…] charact[…] operating volume and conditions.	[…] a surface.	[…]surface […]. […] Sa of internal & external surfaces.	Verify powder is in spec.	Process proved stable. KPVs controlled.	Power test.	Use proven part family design elements.
The component must achieve the desired hydraulic performace at operating conditions through its life.				Process proved stable. KPVs controlled.	Pressure test.	Use proven part family design elements.
Component integrity must be maintained through its life at nominal conditions and at worst operating conditions for a short period.						
The component's internal surfaces must have antifouling properties to avoid performance degradation.						
The component's external surfaces must be self-cleaning to avoid performance degradation.						
The component should be designed in such a way as to not trap powder as this can damage the hydraulic system.	Measure profile of surface (external features).	Scan part for presence of powder.		CAD interrogation tools. Machine cleaning / maintenance schedule.	Part contamination test.	
The component must be corrosion resistant.		Presence of corrosion.	Material spec.		Accelerated corrosion test.	

different colours represent the different methods, and the icons represent whether a requirement is fully or partially met.

- Select verification routes from the matrix based on minimising risk, or maximising the component's functionality, within the given cost and practicality constraints.
- For the heat exchanger example, we can see that, as a minimum, functional testing, X-ray computed tomography, and 3D structured light methods should be used to verify the component. It is notable that verification in this case will be heavily reliant on functional testing.

Part definition and inspection planning

- Part definition refers to the creation of drawings and GD&T (geometric dimension & tolerancing) , following from the definition of the general geometry.
- For a single component the following drawings could be created:
  - Stage drawing for the component in as-built condition;
  - Stage drawing following the removal of support structures;
  - Stage drawing for the post-heat treated condition;
  - Stage drawing following surface processing (e.g. polishing);
  - Stage drawing(s) for the machining operations;
  - Part drawing for the component in its finished-machined condition;
  - Inspection drawings;
  - Drawings for any machining and inspection fixtures;
  - Drawing for any nested parts on the build plate.

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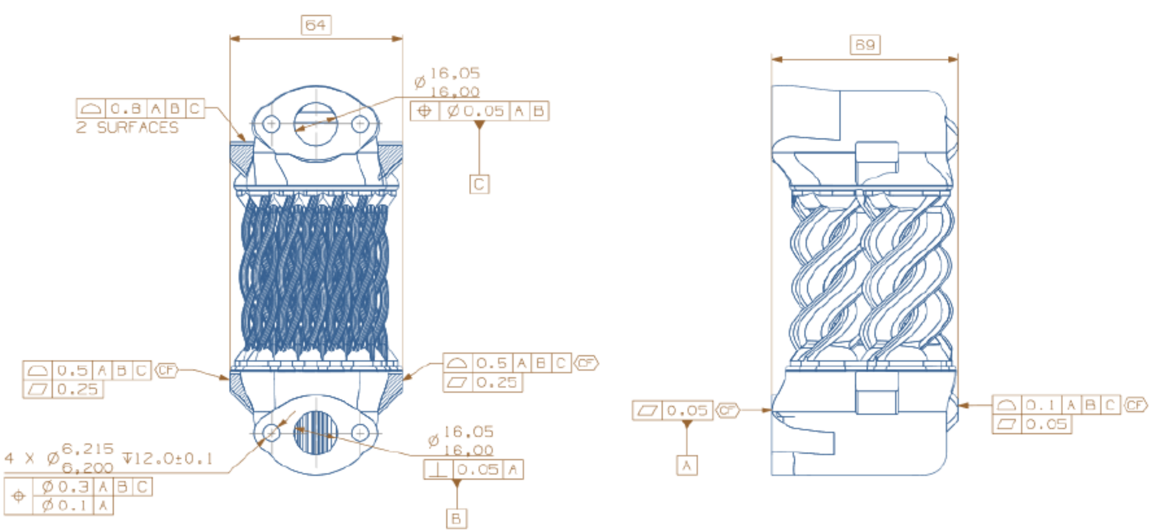
generating full set of drawings is advisable as it will help highlight issues early, for example any potential issues with datum transfers and tolerance stack ups.

Downside is multiple drawings will have to be updated when changes are made to the design or the process.

For this reason an c
definition practices
towards the use of
CAD.

Technical drawing for the heat exchanger with Geometric Dimensions and Tolerances



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Inspection planning

creating the overall strategy for the inspection of every feature or requirement in the drawing (such as drawing notes or referenced specifications)

The inspection plan should include the following information:

- Part number;
- Drawing name and version;
- Feature description and feature grid reference or number;
- Inspection system to be used;
- Measurement strategy to be used;
- Feature construction strategy or algorithm to be used;
- Feature reporting strategy.

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Part of the inspection plan for the heat exchanger

Document:	12352-INSP-PRT-V1.1						
Description	Dimensional inspection plan for DRAMA heat exchanger test case in as-built condition						
Created by:	E.Chatzivagiannis	Date:	21/03/2019				
Drawing ref.	12352-PRT-101-V1.0						
Feature	Drawing ref.	Sheet/grid ref.	System type	Point strategy	Reporting strategy	Feature construction strategy	Comments
1	[FLAT|0.05]<CF> (2 SURFACES) [A]	1-E12	CMM with scanning tactile probe	Scan around each large hole. 2 scans total.	Report 1 flatness value.	Least squares fit for plane. Treat as continuous feature.	Primary datum feature
2	DIA16.05/16.00 [B]	1-D10	CMM with scanning tactile probe	2 scans at 1/3 and 2/3 depths.	Report 1 diameter. Report 1 roundness for info.	Least squares fit.	Secondary datum feature
3	[PURP|0.05|A] [B]	1-D10	CMM with scanning tactile probe	Measured above.	Report 1 perpendicularity.	Software default strategy, using evaluation as per ASME 14.5.	Secondary datum feature
4	DIA16.05/16.00 [C]	1-H10	CMM with scanning tactile probe	1 scan at middle depth.	Report 1 diameter. Report 1 roundness for info.	Least squares fit.	Tertiary datum feature
5	[POSN|DIA0.05|A|B] [C]	1-H10	CMM with scanning tactile probe	Measured above.	Report 1 position.	Software default strategy, using evaluation as per ASME 14.5.	Tertiary datum feature
6,7,8,9	4xDIA6.215/6.200	1-D6	CMM with scanning tactile probe	1 scan at middle depth.	Report diameter values. Hole at 5 o'clock is no.1 then number holes clockwise.	Least squares fit.	
10,11,12,13	4xDPTH12.0+/-0.1	1-D6	CMM with scanning tactile probe	TBD by inspector.	Report 4 depths. Numbering as above.	TBD by inspector.	
14,15,16,17	[CPOS|DIA0.3|A|B|C]	1-D6	CMM with scanning tactile probe	Measured above.	Report 4 positions to upper FCF.	Software default strategy, using evaluation as per ASME 14.5.	Part of composite positional tolerance
18,19,20,21	[CPOS|DIA0.1|A]	1-D6	CMM with scanning tactile probe	Measured above.	Report 4 positions to lower FCF.	Software default strategy, using evaluation as per ASME 14.5.	Part of composite positional tolerance
22	[SPRF|0.5|A|B|C]<CF>	1-E6	CMM with scanning tactile probe	Scan a square loop on each pad. 2 scans total.	Report 1 profile value. Report 1 max dev value for info. Report 1 min dev for info. Report 1 min zone value for info.	Least squares fit. Treat as continuous feature.	
23	[FLTN|0.25]<CF>	1-E6	CMM with scanning tactile probe	Measured above.	Report 1 flatness value.	Least squares fit. Treat as continuous feature.	
24	[SPRF|0.5|A|B|C]<CF>	1-E11	CMM with scanning tactile probe	Scan a square loop on each pad. 2 scans total.	Report 1 profile value. Report 1 max dev value for info. Report 1 min dev for info. Report 1 min zone value for info.	Least squares fit. Treat as continuous feature.	
25	[FLTN|0.25]<CF>	1-E11	CMM with scanning tactile probe	Measured above.	Report 1 flatness value.	Least squares fit for plane. Treat as continuous feature.	
26,27	[SPRF|0.8|A|B|C] (2 SURFACES)	1-H7	CMM with scanning tactile probe	Scan a loop on each pad.	Report 2 profile values.	Least squares fit. Do no treat as continuous feature.	
28,29	2xDIA6.215/6.200	1-H23	CMM with scanning tactile probe	1 scan at middle depth.	Report 2 diameter values. Bottom hole is no.1 top is no.2.	Least squares fit.	

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Grouping Inspection Requirements

Multiple inspection plan documents will need to be created for the different manufacturing operations. It might be preferable to group inspection requirements of a single inspection operation (example above) or it might be preferable to separate out the requirements for different systems (example below which separates out the XCT inspection requirements).

Inspection plan that groups inspection requirements for multiple inspections.

Document:	12352-NDT-PRT-V1.0				
Description	Integrity requirements for DRAMA heat exchanger test case in finished machined condition				
Created by:	E.Chatzivagiannis	Date:	03/05/2018		
Drawing ref.	12352-PRT-101-V1.0				
No.	Defect type	Acceptance criteria			
1	Cracks (internal and external)	None allowed			
2	External surface pores	50µm² maximum pore size		Maximum of 5 pores per 50mmx50mm area	
3	External witness marks, weld tracks	Allowed as long as they are removed by maching and finishing, and as long as surface finish requirements are met			
4	Internal porosity - core	25µm² maximum pore section area		5µm maximum pore length	100µm³ maximum pore volume
5	Internal porosity - solid areas	400µm² maximum pore section area			
6	Inclusions	None allowed			
7	Unconsolidated powder / lack of fusion	None allowed			

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Questions ?
& Thank you

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