UNIVERSITÀ DEGLI STUDI DI PADOVA

TE.SI. LABORATORY FOR PRECISION & MICRO MANUFACTURING

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Special Interest Group Meeting:
Quality Control for Additive Manufacturing
23 – 24 January, 2017

Session 1: state-of-the-art review

Dimensional metrology & NDT for additive manufacturing

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Precision manufacturing engineering group

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Outline

- Introduction
  - AM technical challenge areas
  - Challenges in quality assessment of AM parts
- Performance verification of AM machines
- Dimensional measurements for AM
  - Coordinate measuring machines (CMMs)
  - Optical measurements
  - X-ray computed tomography (CT)
- Non destructive testing (NDT) for AM

AM technical challenge areas

- Understanding of material properties
- Limited types of material suitable for AM
- Process understanding and performance
- Need for *in-situ* monitoring
- Surface finish of contoured surfaces
- Fabrication speed
- Lack of AM standards
- Data formats
- Need for qualification and certification of AM processes and parts
- Part accuracy
- Adequate measurement techniques

[NIST Measurement Science Roadmap for Metal-Based Additive Manufacturing 2013]
[Bourell et.al; Roadmap for Additive Manufacturing – Identifying the Future of Freeform Processing 2009]

AM technical challenge areas

- **Lack of standards and protocols**: Standards, protocols, and guidelines for all the aspects: from materials design and use to part build, inspection, and certification.

Part Quality, Consistency, and Conformance to Specifications	• Standards and guidelines for part conformance, qualification, and certification, including: ○ Geometric accuracy, material properties (spatial), defects, distortion, surface characteristics, and variation in these characteristics ○ Microstructure quantification, artifacts to test microstructure ○ Characterization of multi-material parts • Standardized measurement test pieces/specimens and lot-based testing standards • Standardized part validation tools • Post-process standards and specifications for parts (e.g., internal, surface roughness, measurements) • Standards for building (e.g., orientation) and repairing of parts ○ Round-robin testing for building and testing parts ○ Test protocols for materials testing and reporting of results ○ Repair protocols

[NIST Measurement Science Roadmap for Metal-Based Additive Manufacturing 2013]

- **Measurement and monitoring techniques and data**: Current technologies and techniques for measurement, monitoring and control are inadequate and can significantly impact part quality, functionality, and performance. New sensors, integrated models, and measurement methods will be needed to enable integration of materials and processing control and feedback.

Innovative metrology solutions are needed for AM

Challenges in quality assessment of AM parts

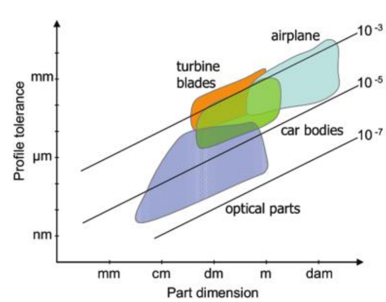
AM parts quality issues

- Complex freeform shaped parts
- High surface roughness
- Internal geometries and undercuts
- Voids and entrapped particles

Metrology challenges for AM

[Guo, Leo; Mech. Eng. 2013]

Typical applications for freeform surface



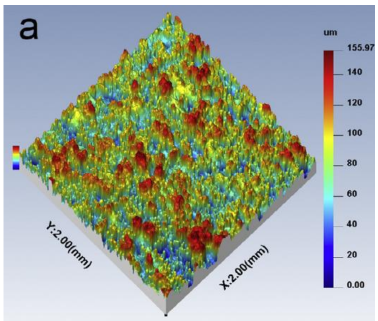
[Savio et al.; CIRP Annals 2007]

Challenges in quality assessment of AM parts

AM parts quality issues

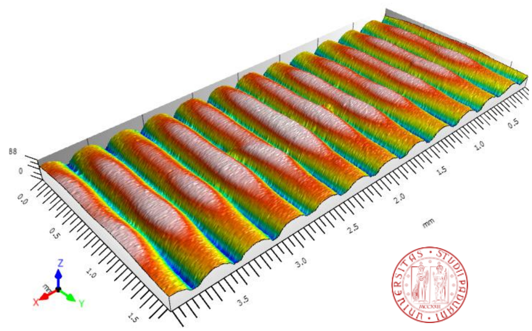
Complex freeform shaped parts | **High surface roughness** | Internal geometries and undercuts | Voids and entrapped particles

Metrology challenges for AM



[Townsend et al. – Precision Engineering 2016]

SLM texture



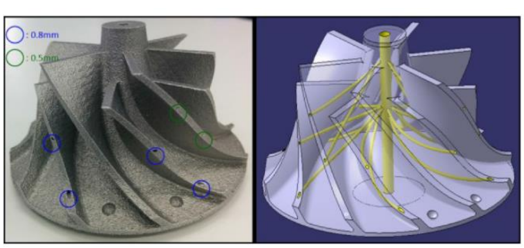
FDM texture

Challenges in quality assessment of AM parts

AM parts quality issues

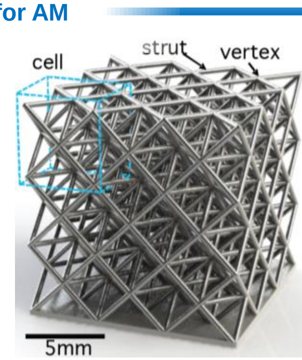
Complex freeform shaped parts | High surface roughness | **Internal geometries and undercuts** | Voids and entrapped particles

Metrology challenges for AM



EBM part with internal channels

[Villaraga-Gomez et al; ASPE 2016]



Octet test part

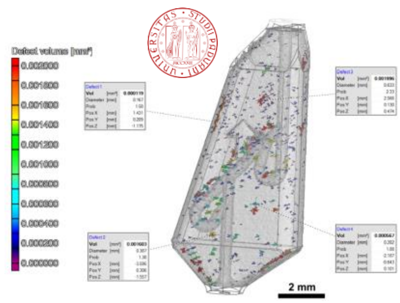
[Martz et al; ASPE 2014]

Challenges in quality assessment of AM parts

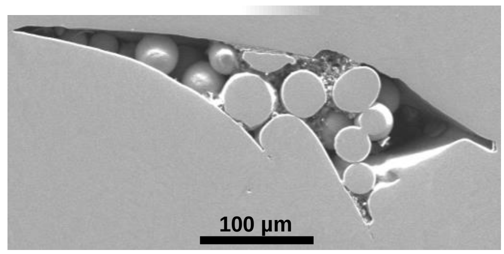
AM parts quality issues

Complex freeform shaped parts | High surface roughness | Internal geometries and undercuts | Voids and entrapped particles

Metrology challenges for AM



Ti6Al4V SLM micro-valve

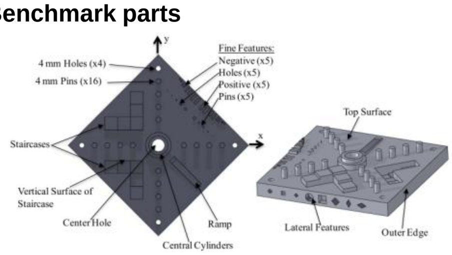


[Hermanek, Zanini, Carmignato, Savio; ASPE 2016]

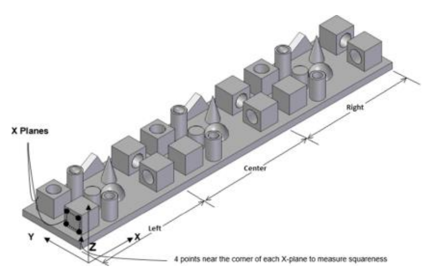
SEM image of a pore
with entrapped unmelted powder

Performance verification of AM machines

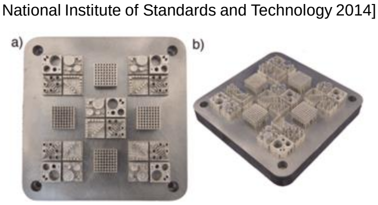
Benchmark parts



[Moylan et al; Journal of Research of the
National Institute of Standards and Technology 2014]



[Fahad and Hopkinson; Int. J. Adv. Manuf. Technol. 2016]



[Teeter et al.; Journal of Engineering in Medicine 2014]

[Uhlmann et al.; ASPE 2015]

Performance verification of AM machines

Requirements for benchmark parts design

- Large enough to test the performance of the system over the entire platform
- Substantial number of small, medium, and large features
- Presence of both holes and protruding features
- Fast building enabled
- Reduced material quantity required
- Many features of a "real" part (e.g., thin walls, flat surfaces, holes, etc.).
- Simple geometrical shapes, allowing perfect definition and easy control of the geometry
- No post-treatment or manual intervention required
- Repeatability measurements allowed
- Easy to be measured

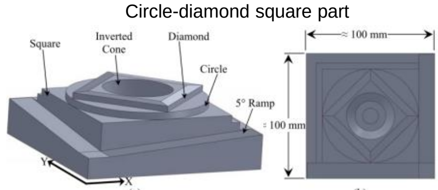
[National Institute of Standards and Technology 2014] [Fahad and Hopkinson; Int. J. Adv. Manuf. Technol. 2016]

[Teeter et al.; Journal of Engineering in Medicine 2014] [Uhlmann et al.; ASPE 2015]

Performance verification of AM machines

Parts used for different manufacturing technologies

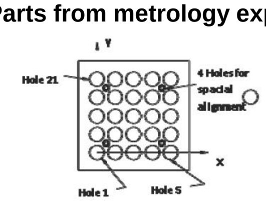
Circle-diamond square part



[Cooke, Soons; 21st Annual Solid Freeform Fabrication Symposium: An Additive Manufacturing Conference 2010]

[Möhring H.C. et al; CIRP Procedia (28) 2015]

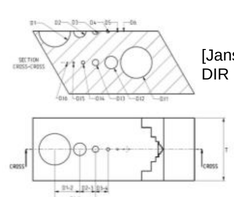
Parts from metrology experience



[Hansen H.N. et al; ASPE 2014]

Parts with internal features

[Kim F. H. et al; ASPE 2016]



[Jansson A. et al; DIR 2015]

Coordinate Measuring Machines (CMMs)

- Measurement of external geometries
- Measurement of internal geometries (destructively)

Contact CMMs

- Contact CMMs can measure form with high accuracy
- Limited number of measured points on an object's surface.
- Relatively slow (not ideal for in-line inspection)

Optical CMMs

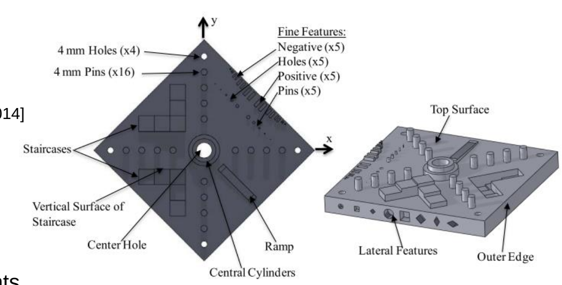
- Non-contact probing systems based on optical principles (i.e. like autofocus, triangulation and conoscopic holograpy) allows non-contact and faster acquisition of a larger number of points
- Optical CMMs are less accurate than contact CMM

[Savio E et al.; CIRP Annals 2007]

Coordinate Measuring Machines (CMMs)

Contact CMMs

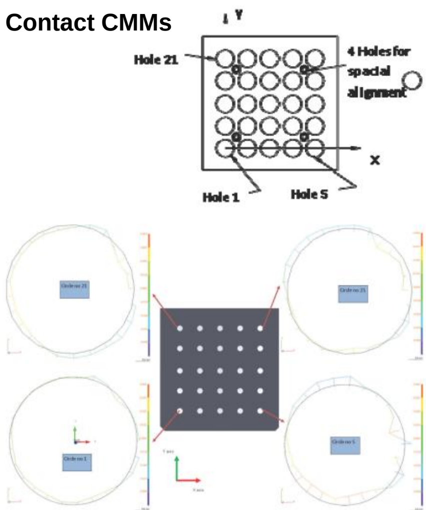
[Moylan et al.; Journal of Research of the National Institute of Standards and Technology 2014]



- Flatness of the top surface: 12 points
- Cylindricity of the center hole: 3 levels with 8 points each
- Pins and holes: 6 points, 3 mm from the top of the feature
- Height of each stair step: 1 point
- Straightness measurements: 1 line segment with at least 15 points distributed over at least 80 % of the feature's length
- Parallelism and perpendicularity: at least 10 points, also distributed over a line at least 80 % of the length of the feature

Coordinate Measuring Machines (CMMs)

Contact CMMs



- Hole plate produced by FDM technology
- Application of a calibration artefact for CMMs
- Developed to create a connection with the traditional calibration method of CMMs
- The design of the hole plate has been used to measure its geometry with acceptable accuracy using standard CMMs

Roundness measurement
(25 points for each hole)

[Hansen H.N. et al; ASPE 2014]

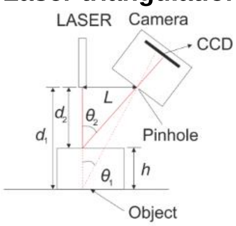
Optical measurements

- The two main types of optical form measurement systems which can be the most useful for industrial AM are those currently used in conventional manufacturing industry, namely, **laser triangulation (LT)** and **structured light projection (SL)**.
- LT and SL are **active systems**, i.e. they recreate a 3D model of the object's form by detecting the modulation of projected illumination caused by the object's shape.
- SNR improves on parts featuring optically rough surfaces, since smooth surfaces (e.g. obtained by subtractive manufacturing) can produce specular reflectance.
- However, the roughness remains a measurement challenge on the accuracy of the final result, especially when it is too fine to resolve.

[Stavroulakis P I, Leach R K et al.; Review of Scientific Instruments 2016]

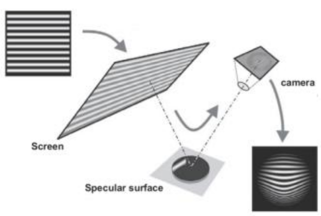
Laser triangulation

[Stavroulakis P I, Leach R K et al.; Review of Scientific Instruments 2016]



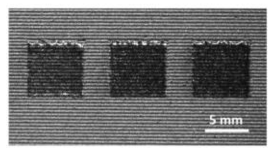
- Laser triangulation systems project a laser spot or a line onto the part.
- The spot or line is scanned across the object by deflecting the beam using a mirror. At each mirror position, triangulation is performed to calculate the height of the scanned points.
- The most fundamental source of measurement uncertainty in laser triangulation is the roughness of the surface.

Structured light projection technique



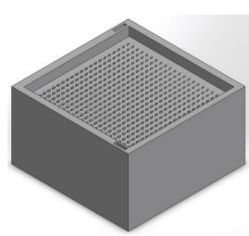
[Savio et al.; CIRP Annals 2007]

Sinusoidal fringe projection is the most promise: high speed, pixel-level resolution, highest accuracy

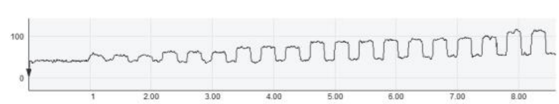


[Zhang et al.; ASPE 2016]

Other optical measurements



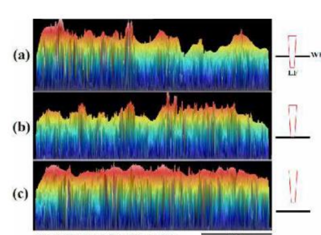
Focus variation principle (Alicona)



[Thompson M. K. et al; ICAD 2015]

Confocal profilometry (Sensofar) to measure the height of AM thin-walls.

[Khademzadeh S. et al; iCAT 2014]



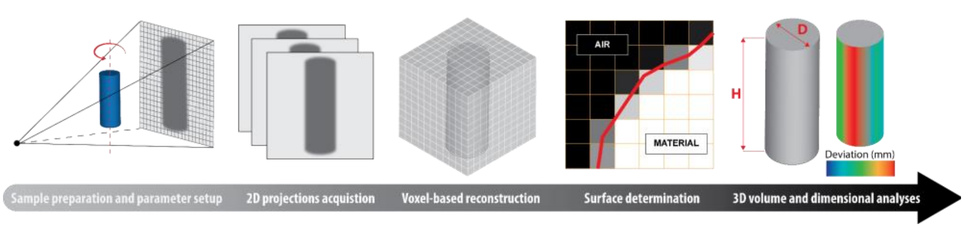
Non-Cartesian measuring instruments

Equator™
Non-Cartesian digital gauge.

- Unaffected by thermal variations in the production environment
- Located directly on the production line
- Pass/fail criteria based on an AM 'gold standard', validated using a CMM

[http://www.renishaw.com/en/equator-gauging-system—12595]

X-ray computed tomography



- Holistic three-dimensional reconstruction of the scanned object
- High surface digitalization
- **Non-destructive** and **non-contact** measurement of external and internal geometries, features and micro-features
- Traceability still challenging

X-ray computed tomography

- Quality control and dimensional metrology:

AM → CT → Report ✓

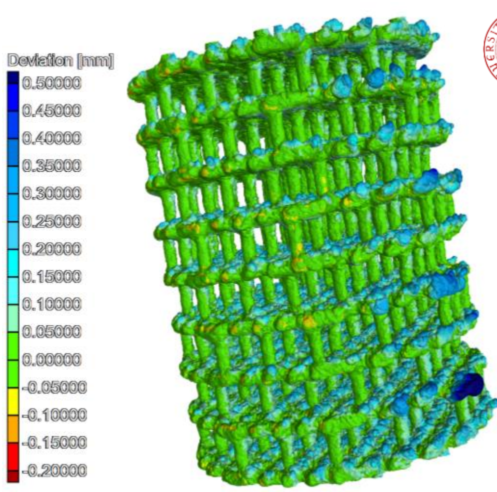
- Product development and process optimization:

AM → CT → AM

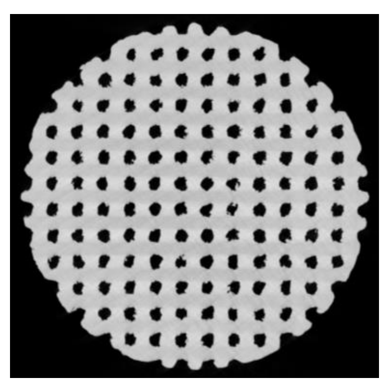
- Reverse engineering for rapid prototyping:

Object → CT → AM

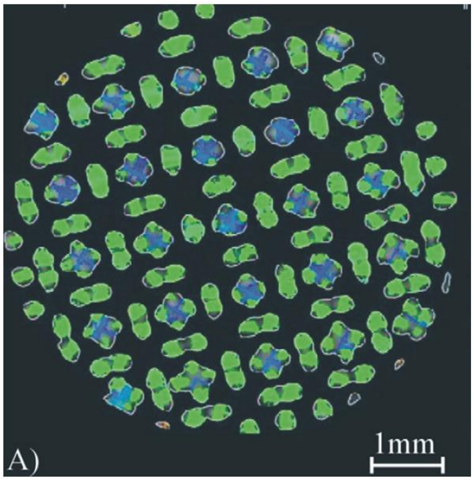
X-ray computed tomography



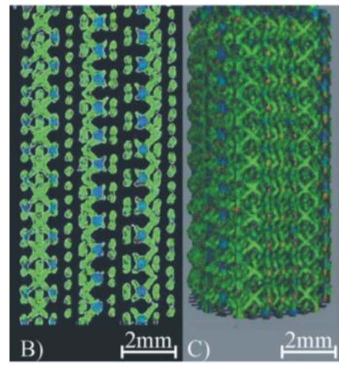
Lattice structures
CAD comparison



X-ray computed tomography

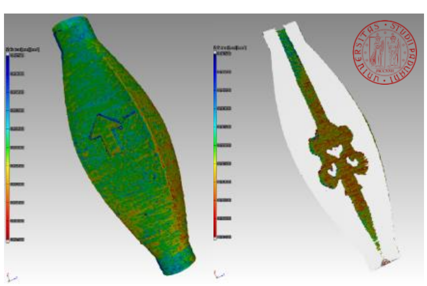


Lattice structures
Wall-thickness analysis



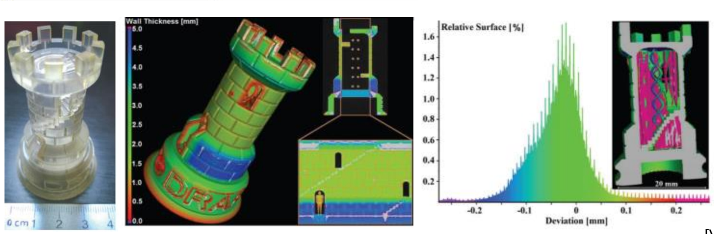
[Van Bael S. et al; Materials Science and Engineering 2011]

X-ray computed tomography



External and internal geometries
CAD comparison
Wall-thickness analysis

Ti6Al4V SLM micro-valve

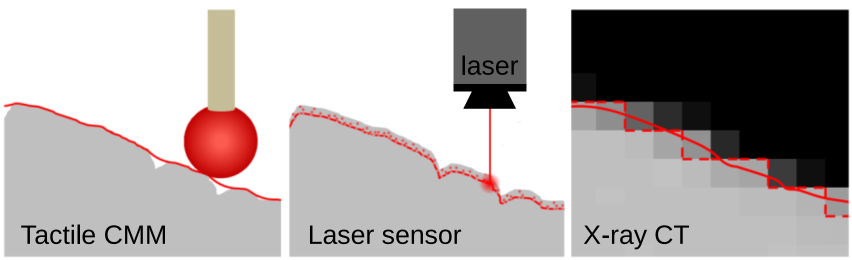


Chess rook

[Villaraga H. et al; ASPE 2015]

Comparison of different technologies

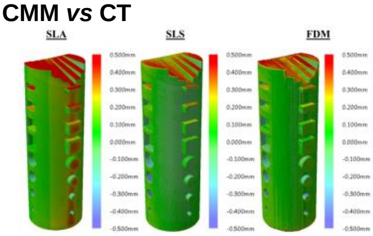
- Different Coordinate Measuring Systems (CMSs) have different measuring principles
- Influence of specific material properties (e.g. surface roughness, optical properties, type of material, etc.)
- Different error sources
- Functional properties of parts are mainly mechanically determined



Comparison of different technologies

Introduction AM performance verification Dimensional measurements Non destructive testing

CMM *vs* CT



List of features and tolerance allocation.

Feature	I.D.	U.I.D.	Tolerance
Slope Angularity	SA	SA1 SA2 SA3R SA3L SA4 SA5	Angularity
Cut cuboid perpendicularity	CCPE	CCPE1-4	Perpendicularity
Cut cuboid parallelism	CCPA	CCPA1-4	Parallelism
Cut cylindricity	CC	CCC1-4	Cylindricity
Boss cuboid perpendicularity	BCPE	BCPE1-4	Perpendicularity
Boss cuboid parallelism	BCPA	BCPA1-4	Parallelism
Boss cylindricity	BC	BCC14	Cylindricity
Hemisphere sphericity	HS	HS1-4	Sphericity
Pipe cylindricity	PC	PCC1-3	Cylindricity
Cut cuboid flatness	CCF	CCF1-4	Flatness
Boss cuboid flatness	BCF	BCF1-4	Flatness

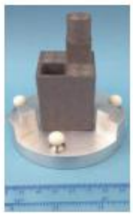
Percentage error % of CT measurements using reference results (lower is better).

Feature	FDM		SLS		SLA	
	CT1	CT2	CT1	CT2	CT1	CT2
SA	47.43	46.27	42.55	59.15	28.33	41.53
CCPE	57.86	56.92	24.56	23.97	50.81	60.14
CCPA	36.61	26.71	72.17	76.17	88.88	86.05
CC	39.52	40.88	30.50	31.81	24.49	13.64
BCPE	44.69	48.02	70.63	18.89	53.84	37.04
BCPA	42.34	37.52	85.21	65.28	74.81	55.77
BC	23.12	24.18	18.59	16.39	73.81	47.92
HS	32.46	32.74	36.82	31.30	24.23	35.34
PC	60.81	60.75	45.44	46.22	66.77	11.87
CCF	27.56	27.89	14.48	13.02	69.06	29.99
BCF	56.53	58.37	29.31	26.15	36.07	22.90

[Shah P. et al; CSNDT 2016]

Comparison of different technologies

CMM *vs* CT *vs* Optical

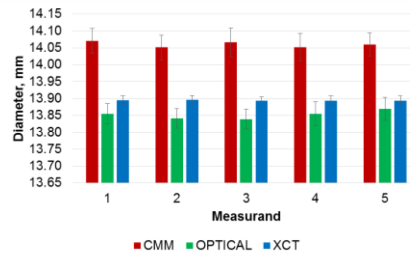


Design criteria

- Typical issues in AM manufacturing, e.g. distortion due to the layer by layer building
- Both external and internal features, accessible to every measuring instrument
- Features have a simple form
- 3 ceramic balls: diameters and centers were used to enable scale and surface determination of different techniques to be compared

Depending on the metrology system being used to capture the measurement data and the construction of the part being measured, systems can behave differently. As tactile, optical and XCT systems use different data capturing techniques, a **systematic difference in dimensional measurements may exist that will invalidate the chain of traceability.**

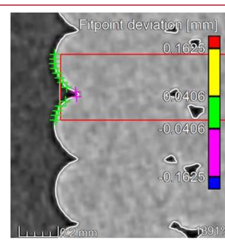
[Brown et al.; ASPE 2016]

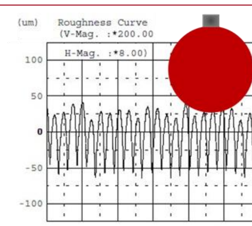


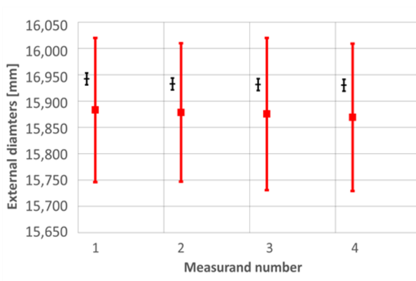
Comparison of different technologies

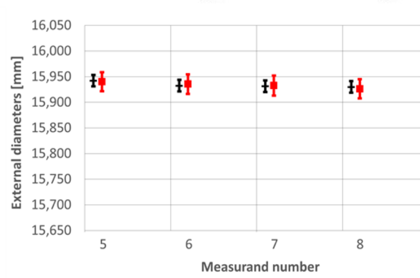
CMM *vs* CT
Influence of surface roughness

[Aloisi et al; Euspen 2015]









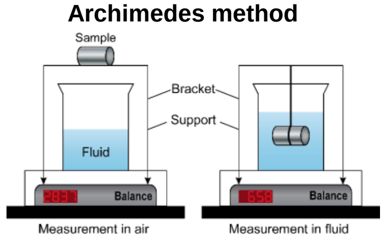
Non destructive testing (NDT) for AM

- **Internal defects and surface flaws**
- Geometric accuracy
- *In-situ* process monitoring

Methods	Internal defects	Surface flaws	Global(G) / Local(L)	Surface sensitive
Visual testing	N	Y	L	N
Radiography	Y	Y	L	Y
X-ray CT	Y	Y	G, L	N
Archimedes method	Y	N	G	N
Gas pycnometry	Y	N	G	N
Ultrasonic	Y	Y	G, L	Y
Eddy current testing	Y/N slightly subsurf.	Y	L	Y
Magnetic methods	Y/N slightly subsurf.	Y	L	Y
Penetrant testing	N	Y	L	Y

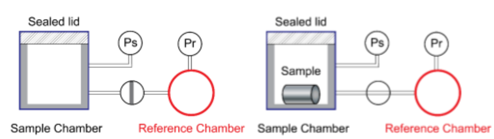
NDT defect detection

Archimedes method



- Non-destructive
- Fast and simple to perform with commercial instrumentation
- Only total fraction of porosity
- No information about porosity distribution
- Nominal density may be not accurate for non-homogeneous parts, such as the AM parts.

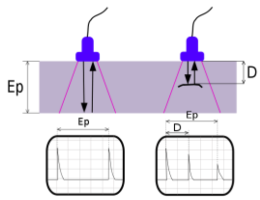
Gas pycnometer



- Non-destructive
- Fast and simple to perform
- Limited detection volume
- Only total fraction of porosity
- No information about porosity distribution
- Nominal density may be not accurate for non-homogeneous parts, such as the AM parts.

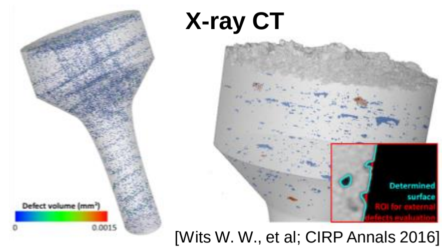
NDT defect detection

Ultrasonic technique



- Non-destructive
- Detection of surface and sub-surface defects
- Detection of cracks and inclusions
- Parts that are rough, irregular in shape, very small or thin, or not homogeneous are difficult to inspect.
- Reduced accuracy for high porosity content (>10%)

X-ray CT



[Wits W. W., et al; CIRP Annals 2016]

- Non-destructive
- Pore size, distribution and morphology
- Detection of surface defects
- Inability to reliably detect cracks.
- High cost
- Traceability establishment is still challenging
- Influence of artefacts, thresholding and resolution

NDT defect detection

Eddy current testing

- Electric current is created in the sample in the presence of an alternating magnetic field. Features that interrupt the current are detected.
- Useful for finding cracks
- Surface finish and grain structure play a hige role in the success of the method in finding critical defects (high background noise due to surface roughness).

Magnetic particle testing

- A ferromagnetic material with surface cracks or discontinuities “leaks” magnetic field. Magnetic particles are attracted by these locations. Visual inspection identifies these locations.
- Surface sensitive

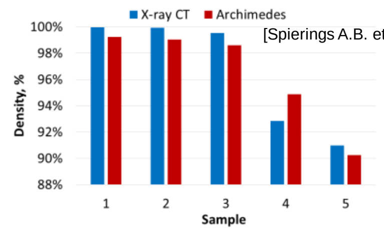
Penetrant testing

- Detection of surface defects;
- Require a relatively smooth inspection surface, so it may not be a realistic for rough AM parts without special post-process machining and polishing (high background noise due to the as-manufactured surface roughness).
- Many techniques applied to reduce surface roughness close up surface flaws and cracks.

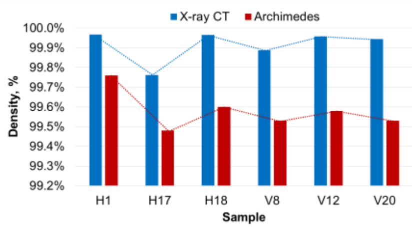
Comparison between porosity methods

Introduction · AM performance verification · Dimensional measurements · **Non destructive testing**

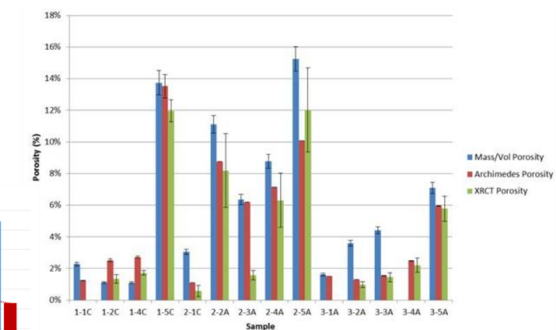
Archimedes *vs* X-ray CT



[Spierings A.B. et al; Rapid Prototyping Journal 2011]



[Wits W. W., et al; CIRP Annals 2016]

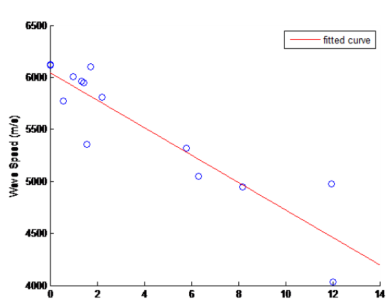


[Slotwinski J.A. et al; Journal of Research of the National Institute of Standards and Technology 2014]

Comparison between porosity methods

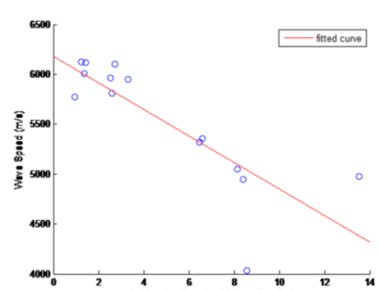
Introduction · AM performance verification · Dimensional measurements · **Non destructive testing**

Ultrasonic *vs* X-ray CT

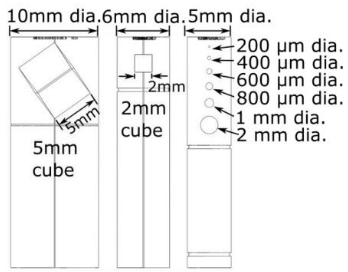


[Slotwinski J.A. et al; Journal of Research of the National Institute of Standards and Technology 2014]

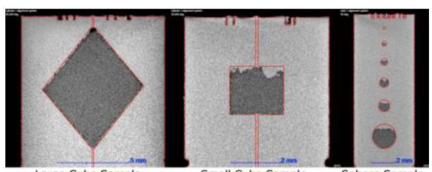
Ultrasonic *vs* Archimedes



Reference objects with internal features



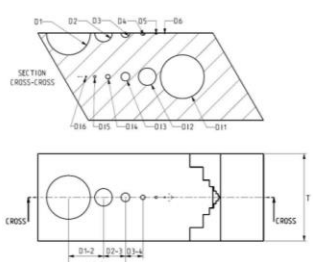
- Internal features built using AM
- Measurement by CT
- Aim: understand PoD of CT porosity analysis

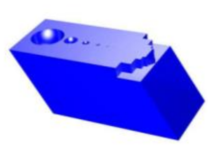

Large Cube Sample Small Cube Sample Sphere Sample

Optimized design

[Kim F. H. et al; ASPE 2016]

Reference objects with internal features





- Internal spherical features and external hemispherical features with same nominal diameters
- CMM calibration of the external features
- CT measurement of both external and internal features

[Jansson A. et al; DIR 2015]

Reference objects with internal features

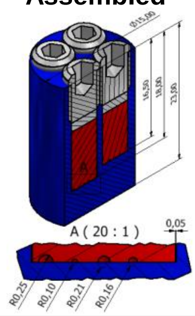
Components | **Assembled** | **Pin**

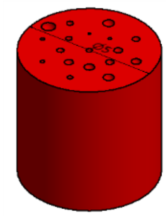
4x M6 polyamide screws

4x soft rubber washers

4x aluminum pin

Cylindrical aluminum body





[Hermanek P. et al; CSNDT 2016]

Ø15 mm cylindrical aluminum body
4x Ø5 mm cylindrical pin with artificial defects
Various height position of pins (defects)
72 artificial defects of hemispherical shape
Defect size range: 100 – 500 µm

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Thank you for the attention

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