LASER POWDER BED FUSION (LPBF) MACHINE EVALUATION INITIATIVE

ETN Global Report

January 2025

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Executive Summary

Energy & Turbomachinery Network's (ETN Global's) unique Laser-Powder Bed Fusion (LPBF) Machine Evaluation Initiative was developed by a consortium of selected members of our Additive Manufacturing Working Group. The initiative reviewed the capabilities of LPBF equipment available on the market, looking into similarities and differences in the ease of use and integration, quality and productivity. The Original Equipment Manufacturers (OEMs) were all asked to manufacture the same parts, using the same powder feedstock as basis.

A set of samples and a gas turbine heat shield geometry were fabricated from alloy 718 by LPBF OEMs for a test campaign with the aim to evaluate the variations of builds. The consortium defined a set of requirements for the build including minimum number of samples for each test, but the OEMs were allowed to define their layout and build paraments. All the samples were heat treated within the same cycle in order to eliminate variability introduced by heat treatment. The samples and heat shields were then tested for comparison.

Based on the findings in this work the following may be concluded:

- The material properties of Alloy 718 (UNS N07718), printed by various OEMs, remained consistent across different equipment brands when using the standard parameter sets used by the equipment manufacturers.

- The ease of use, openness, and productivity of these machines depend significantly on the broader support system setup and the availability of OEM support. In this study, all machines appeared easy to use, and there were potential integration opportunities to enhance overall production processes. When the build job was designed for maximum practical capacity of the machine, including test specimens and a safe distance between parts, the print time per part was similar. However, there were slight variations in machine size, layer height, part spacing, number of lasers, and process pauses. The productivity will therefore mainly depend on the support systems that improve the active time of the machines and general availability of LPBF machines and of post-processing activities.

Several challenges were encountered during the projects including parts design, logistics, long lead time from external vendors, and the sharing of information. As experienced during this project execution, the likely determining factors in the overall lead time will be the schedule for free capacity on the Additive Manufacturing machines and the capacity of other process steps (powder removal, post processing, heat treatment etc.). Despite the difficulties encountered, consistent quality was achieved across LPBF systems.

List of Abbreviations

CT	Computed Tomography
CVN	Charpy V impact test
LPBF	Laser Powder Bed Fusion
NDT	Non-Destructive Testing
OEM	Original Equipment Manufacturer
PCRT	Process Compensated Resonance Testing
PM	Powder Metallurgy
PT	Penetrant Testing
Ra	Roughness value Ra

1. Introduction

1.1. General

LPBF technology offers potential for innovative component designs, reducing costs and lead time of production. However, ensuring productivity and end-product quality is vital for enabling safe and mature adoption in the industry. ETN Global's LPBF Machine Evaluation Initiative carried out a study to better understand the capabilities of the said technology. The study intended to investigate similarities and differences between execution and results when several LPBF producers were asked to manufacture the same parts, all using the same powder feedstock as basis.

Three LPBF machine OEMs participated with building a build plate of small heat shields for a gas turbine design, with design information shared by Siemens Energy. Powder feedstock was supplied from the project, and all deliveries of powder came from the same batch of alloy 718 powder atomized by Oerlikon Metco, with a nominal particle size distribution of -45+15 µm (labelled as MetcoAdd718C).

The consortium decided on Key Performance Indicators, an assessment plan that included questions about the LPBF systems and system providers, mechanical testing of parts and samples, and inspection points. DNV was commissioned as an independent party by the consortium to facilitate the production and testing of the parts and collect and analyse the results from the assessment plan. The report summarizes the non confidential public results from the work. Detailed results are only available to the consortium members.

1.2. Scope of work

The scope of work consisted of the following:

- Establishing agreed confidentiality terms with machine OEMs for handling and use of the information.
- Establishing a quality plan for DNV's follow-up of the production of the parts and samples.
- Finalising test plan, questionnaire, and assessment criteria.
- Facilitation of production and testing activities.
- Assessment of results and reporting.

The aim of the testing and investigation was to:

- Compare the LPBF machines featured by the machine OEMs.
- Compare the quality from different builds and companies when the material and heat treatment are constant.
- Identify challenges in production and verification processes with LPBF.

2. The Consortium

ETN Global's LPBF Machine Evaluation Initiative was undertaken by a consortium composed of members from our Additive Manufacturing Working Group (see logos below). The consortium was formed to fund and execute the study.

We would like to acknowledge all the companies for their contributions to the initiative and give special thanks to DNV, which acted as a facilitator in the project, and had the responsibility of communicating with the suppliers, handling the logistics and evaluating the results, as well as reporting the findings to the rest of the group.

3. Experimental

3.1. General

The OEMs contributed in-kind with producing one build plate with parts using powder supplied by ETN Global. The OEMs were not part of the consortium, and all communication with them was managed through DNV to ensure they remained unaware of the identities and activities of the other OEMs. Each OEM signed a confidentiality agreement to maintain this arrangement.

The part design provided by Siemens Energy was a heat shield and is shown in *Figure 1*. The dimensions were 72.1 mm x 58 mm x 27.4 mm, and it includes internal cooling channels with small inlets and outlets on many of the sides.

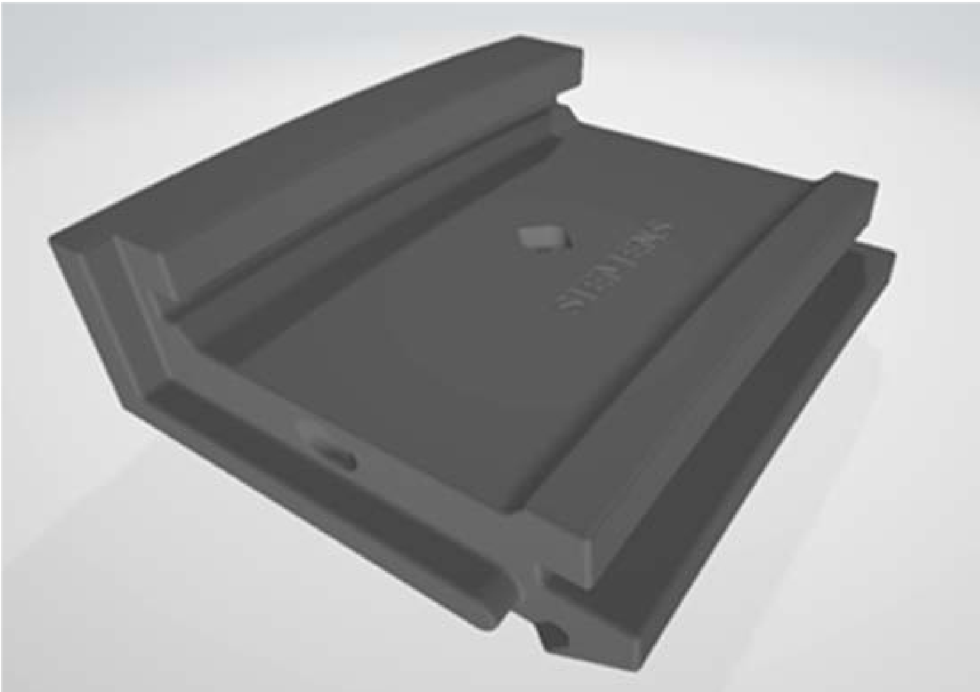


Figure 1: 3D model of the heat shield

3.2. Specifications

3.2.1. General

The sequence of activities is illustrated by the chart in *Figure 2*. The following activities were carried out:

- Powder supply.
- Parts printed at the different OEMS.
- Heat treatment and extraction was carried out.
- 3D optical scanning.
- Testing and Non-Destructive Testing (NDT) of specimens, powder samples and heat shields.

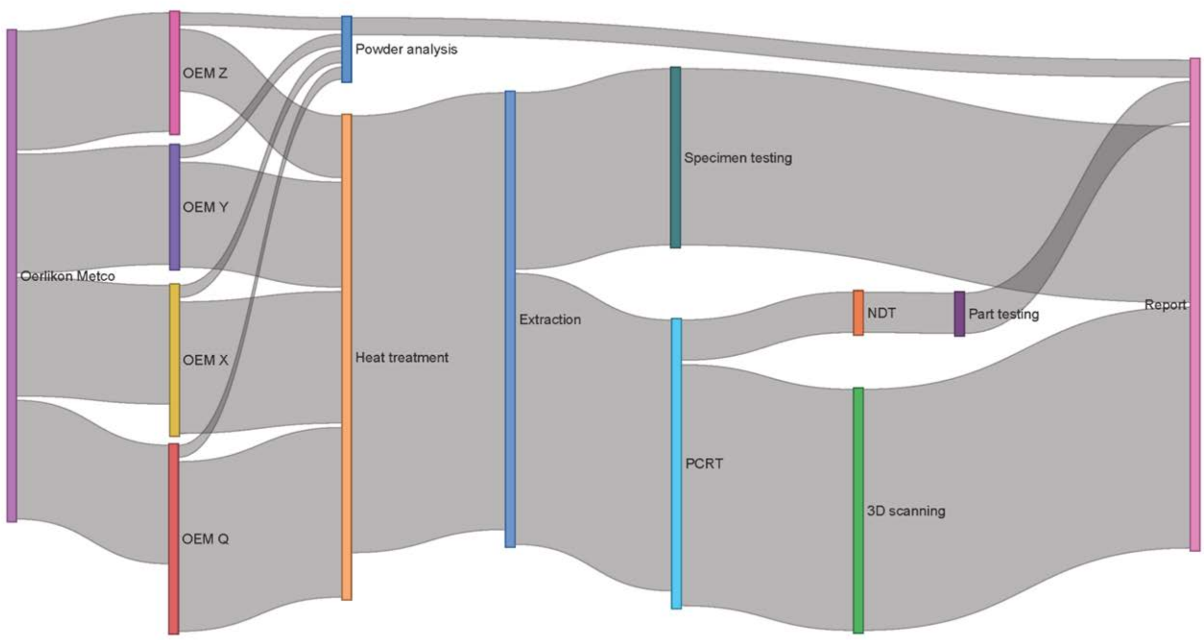


Figure 2: Chart showing the flow of parts and samples during the project execution.

3.2.2. Testing specifications

The consortium agreed on a test scope for the assessment. The test scope is presented in *Table 1* and *Table 2*, and lists testing on sample specimens and heat shields respectively.

Table 1: List of tests and methods for specimen testing.

Testing activities	Standard	Testing method
Tensile properties in heat treated condition	ISO 6892-1:2019, (Metallic materials — Tensile testing — Part 1: Method of test at room temperature)	Room temperature round specimen tensile test
Impact testing in heat treated condition	ISO 148-1:2016 (Metallic materials — Charpy Pendulum-Impact test — Part 1: Test method)	Charpy pendulum impact test
Density in heat treated condition	ASTM B311-17 (Standard Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity)	Archimedes principle
Chemistry, on powder sample, prior to heat treatment	ASTM F3055:14a	Chemical analysis, ASTM E1019
Powder characteristics, on powder sample, prior to heat treatment	ISO/ASTM 52911-1:2019 (Additive manufacturing – Design – Part 1: Laser-based powder bed fusion of metals)	Flowability (Hall Flow and static angle of repose) Size distribution Powder chemistry
Hardness ▪ Powder capsule wall, prior to heat treatment, and after heat treatment ▪ Samples after heat treatment	ISO 6507-1:2018 (Metallic materials — Vickers hardness test — Part 1: Test method)	Vickers hardness testing

Table 2: List of tests and methods for part testing.

Testing activities	Standard	Testing method
3D scanning	NA	Structured light?
PCRT	Not applicable	Add some text or provide reference to published info.
NDT – CT	Not applicable	Investigation of volumetric indications and artifacts, e.g. residual powder, integrity of internal channels
NDT – PT	ISO 3452-1:2013 (Non-destructive testing — Penetrant testing — Part 1: General principles)	Coloured penetrant testing to inspect for surface defects and surface porosity
Roughness testing	EN ISO 4288	Roughness testing on heat shields
Micrographic examination	Not applicable	Reporting of the microstructure with any relevant observations Magnification: 50x to 200x
Tensile testing – *Not performed due to part size limitations*	ISO 6892-1:2019, (Metallic materials — Tensile testing — Part 1: Method of test at room temperature)	Room temperature round specimen tensile test

3.2.3. Powder specifications

Each participating OEM was invited to complete two print jobs:

1. A print job with a -45+15 µm powder batch complying with ASTM F3055-14a, see *Table 3*. This powder was purchased and provided for the ETN Global consortium by Oerlikon Metco and consists of a single powder batch.

2. A print job with a powder batch selected by the supplier that was compliant to the ETN Global powder specifications, see *Table 3*, or most suitable powder according to the OEM. The powder supplier was required to provide the certificate for the powder batch.

The machine OEMs were required to provide information regarding any processing of the powder carried out post-delivery. This included any further blending, sieving (including the mesh sizes used) or drying carried out on the powder.

3.2.4. Heat treatment

Prior to the heat treatment the powder capsule was to be removed from all the build plates. The build plates, including all specimens and parts, were then subjected to stress relief and solution treatment and double aging heat treatment. The build plates with parts were heat treated at the same time in the same heat treatment cycle, i.e. same heat.

3.2.5. Acceptance criteria

The acceptance criteria for mechanical properties defined for precipitation hardened UNS N07718 in ASTM B637 was used for the assessment. The required mechanical properties are listed in *Table 3*.

Table 3: Mechanical properties in ASTM F3055-14 classification F, Stress relief, solution treated and aged.

Min Yield strength (X, Y / Z)	940 MPa / 920 MPa
Min Tensile strength (X, Y and Z)	1240 MPa
Min elongation (X,Y and Z)	12%

3.2.6. Build reports

After the build job was finished the OEMs sent build reports from the work consisting general information about the build job, such as number of layers, height of build, time of start and stop, which parameter set and build file was used. In addition, some reported graphs from sensor readings during the build, temperature, oxygen content etc. and warnings were received. All build reports have information that ensured traceability to process parameters, etc.

All OEMs could supply powder bed images of every layer of the build. One OEM also used a functionality that processed the powder bed images and identified layers where there was deviation in the powder bed. The report of processed image made it easier to review the powder bed images. At the time of writing the powder bed images can only be used as an indicative signal if something very critical is happening to the process during the build – it is not clear if the processed images can be related to the likelihood of imperfections in the build. In total 62 of these indications were reported in the shields on the build plate, and in total 53 in the samples on the build plate. The OEM confirmed that the indications did not mean that there are defects in the identified locations – only that there were deviations in the coverage in the given powder layer.

Another case that came up in the reporting of the build jobs were reported surface artefacts that appeared because of two unplanned build stops. This resulted in a splicing line at that specific layer in the shields on one edge of the build plate, on the side closest to where the gas flow enters the chamber. The finding was detected and reported, shown in *Figure 3*. No corrective action was taken by the OEM before delivery.

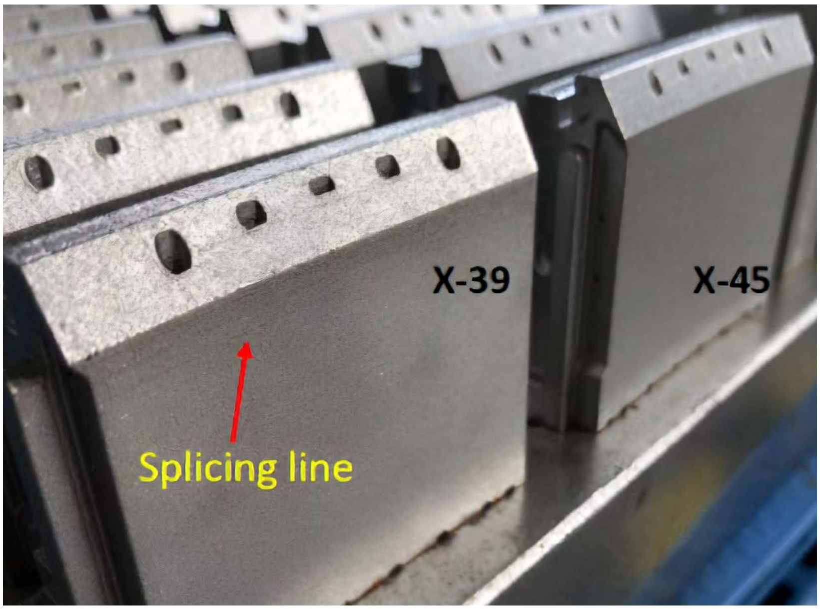


Figure 3: Reported splicing line that occurred due to an unplanned stop in the respective layer.

3.3. Test results – specimens

The list of tests carried out on the printed specimens is summarised in the table below.

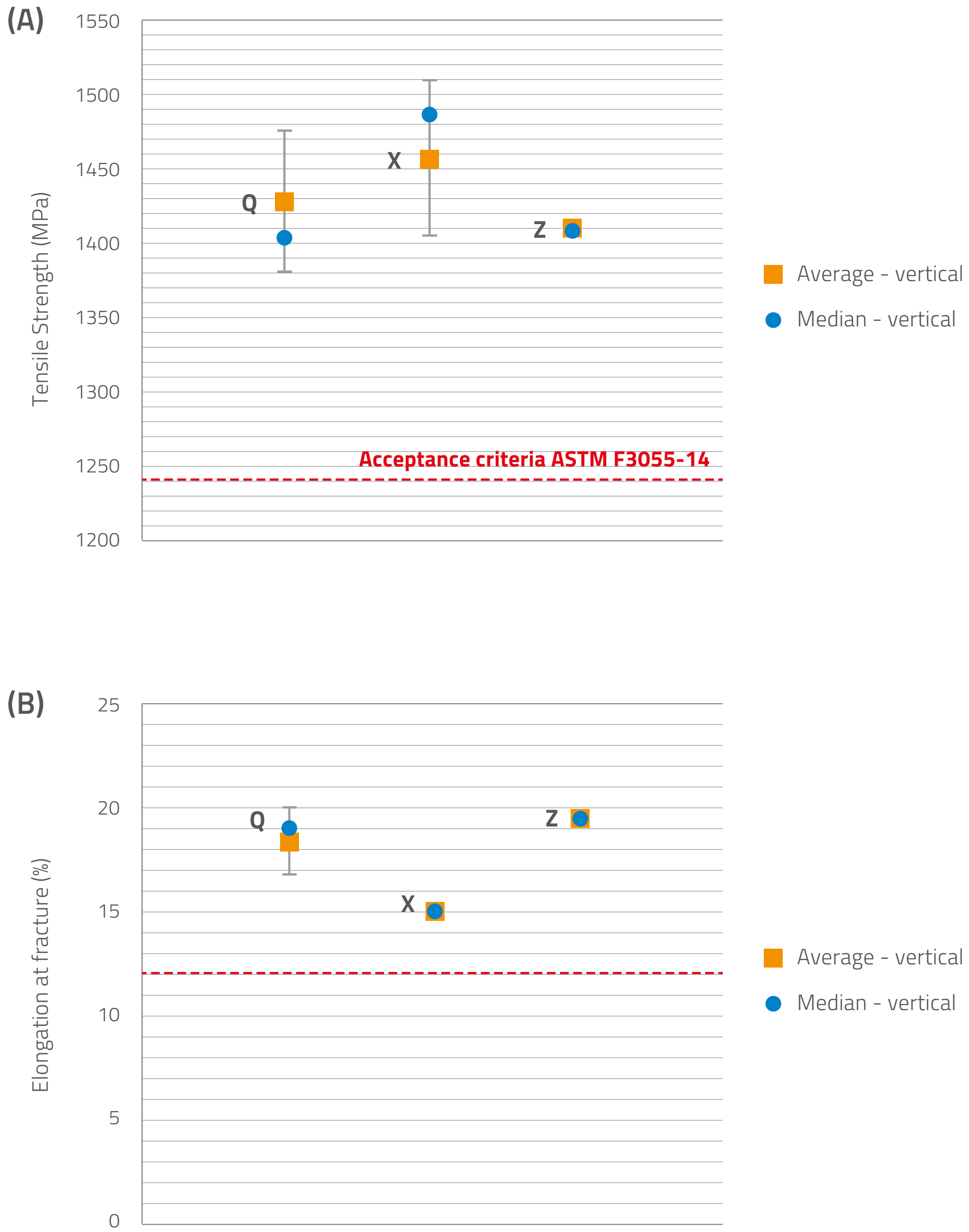
Table 4: Testing covered for test specimens.

1) Destructive tests on printed specimen:		
Tensile		
Charpy impact test (CVN)		
Powder assessment		
Relative density		
Hardness		

A limited amount of data and analysis is being issued in this public report. Only consortium members have access to the complete set of information.

3.3.1. Tensile properties

The tensile sample set consists of the 3 horizontal and 3 vertical printed tensile specimens tested at room temperature. The testing was performed in accordance with the test standard: ISO 6892. *Figure 4* below shows the tensile test results in the vertical (4a, 4b) and horizontal (4c, 4d) direction for each of the OEMs.



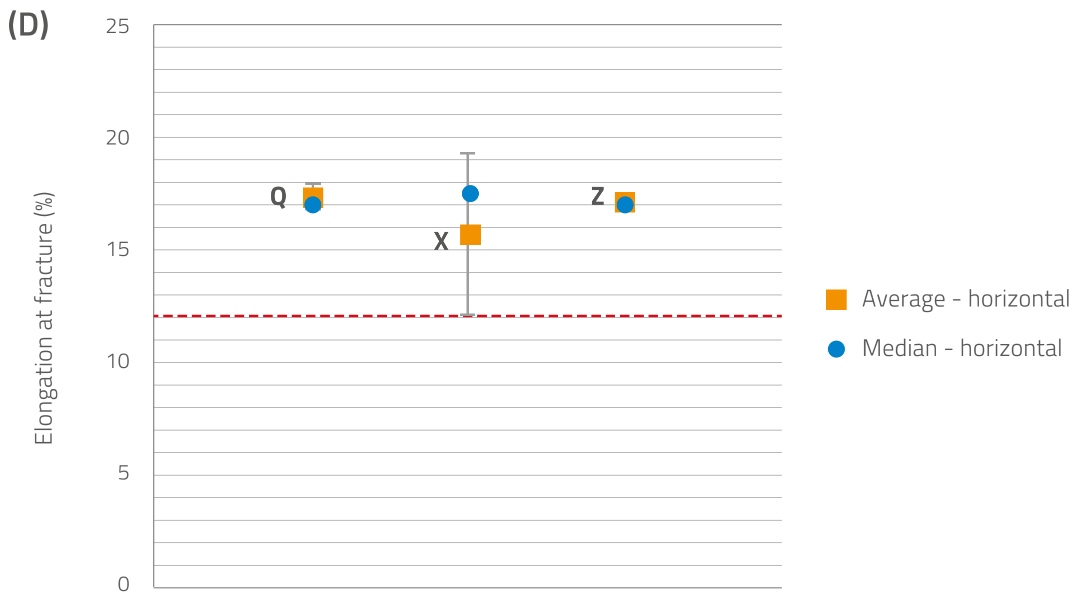


Figure 4: (**A**) shows the results of the average tensile strength values and the deviation of results for the OEMs for vertical (z-direction specimens); (**B**) shows the results of the average fracture strain values and the deviation of results for the OEMs for vertical (z-direction specimens); (**C**) shows the results of the average tensile strength values and the deviation of results for the OEMs for horizontal (x/y-direction specimens); (**D**) shows the results of the average fracture strain values and the deviation of results for the OEMs for horizontal (x/y-direction specimens).

The tensile strength and yield strength results exceeded the minimum requirements in all tested samples. However, one tensile test samples failed to meet the elongation criteria of min. 12%.

3.3.2. Impact testing

The impact testing sample set consists of the 5 horizontal and 5 vertical printed specimens, testing was performed in accordance with the test standard: UNI EN ISO 148-1 Rev 2016. Results are shown in *Figure 5*. No significant variation in impact toughness was observed between samples produced by different OEMs.

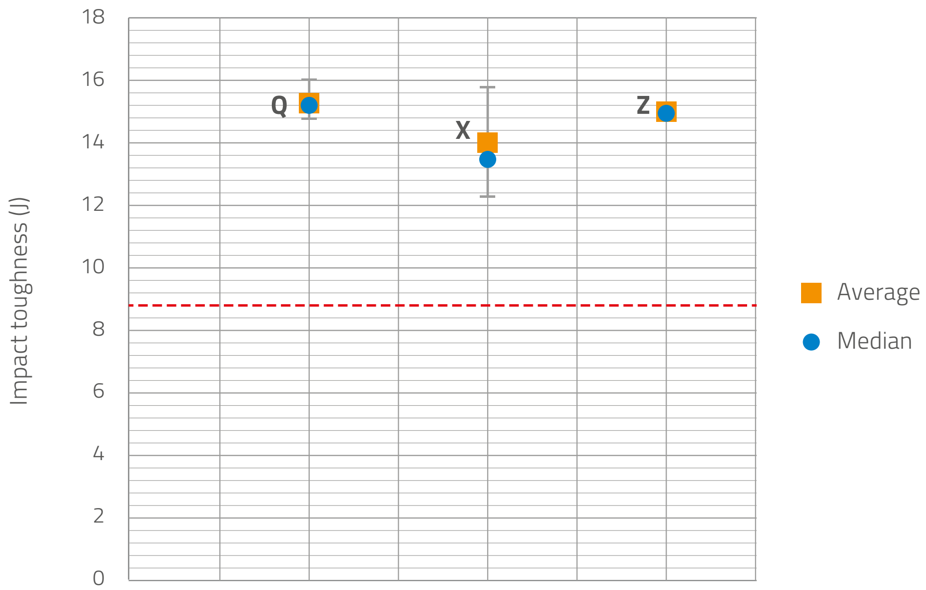


Figure 5: A graph of the average impact toughness values and the deviation of results for the OEMs.

3.3.3. Density

The density of the specimens was measured using Archimedes relative density measurements. The cubes (10x10x10mm) have been cut from each of the 3 bars per OEM build plate at three heights low, mid-range and high (9 cubes total). The low sample covers the baseplate, the midrange sample covers the mid-point of the specimen build and the high sample covers the top of the build. Although some variation was seen between different OEMs, this remained within the margin of error of measurement.

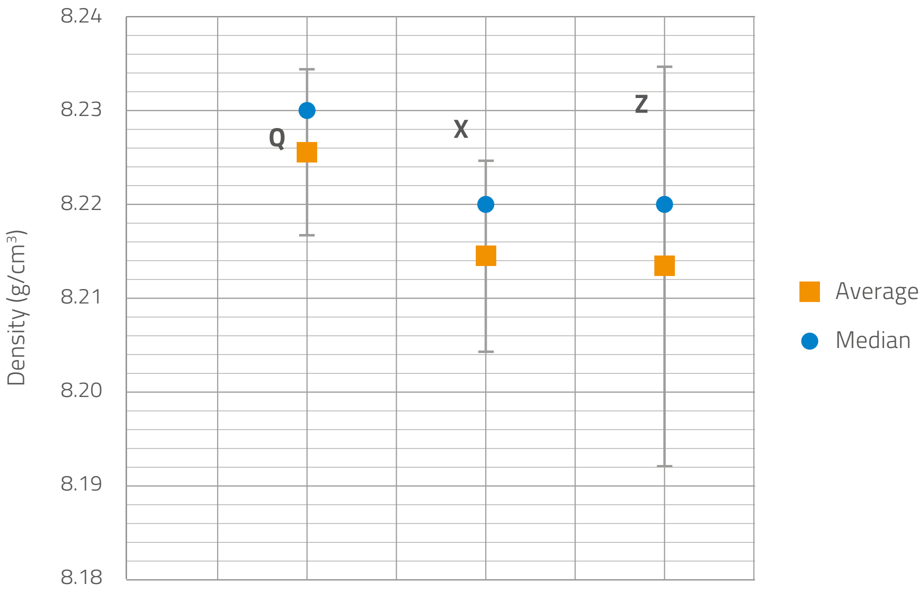


Figure 6: A graph of the average density values and the deviation of results for the OEMs.

3.3.4. Hardness

The powder container was removed from each of the OEM plates prior to the heat treatment of the plates. The wall of the powder container was tested for micro-hardness using Vickers Harness with 1 kg load, in order to measure the hardness in thin-walls in the as built condition. Further hardness indentations were carried out on the wall of the powder container after heat-treatment as well as on material from the heat-treated density cubes. The results are presented in the graphs below. Although some trends may be deduced from the measured values, all hardness values remained broadly within 20 Hv10, which is insignificant. As expected for age hardening material, hardness increased after heat treatment.

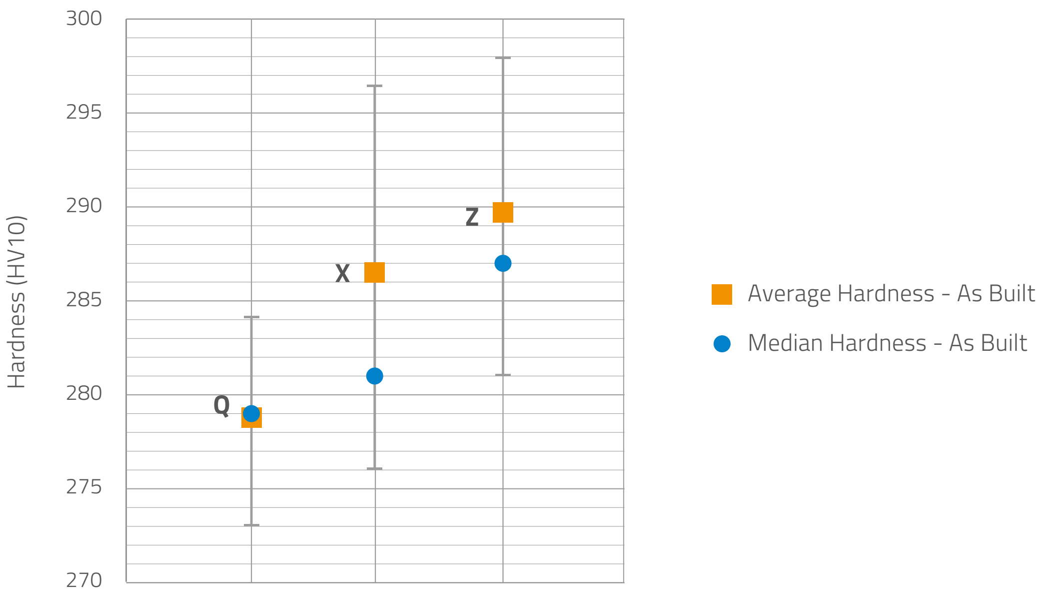


Figure 7: A graph of the average hardness values and the deviation of results for the OEMs carried out on material that has not been heat treated (as built) from the powder capsule.

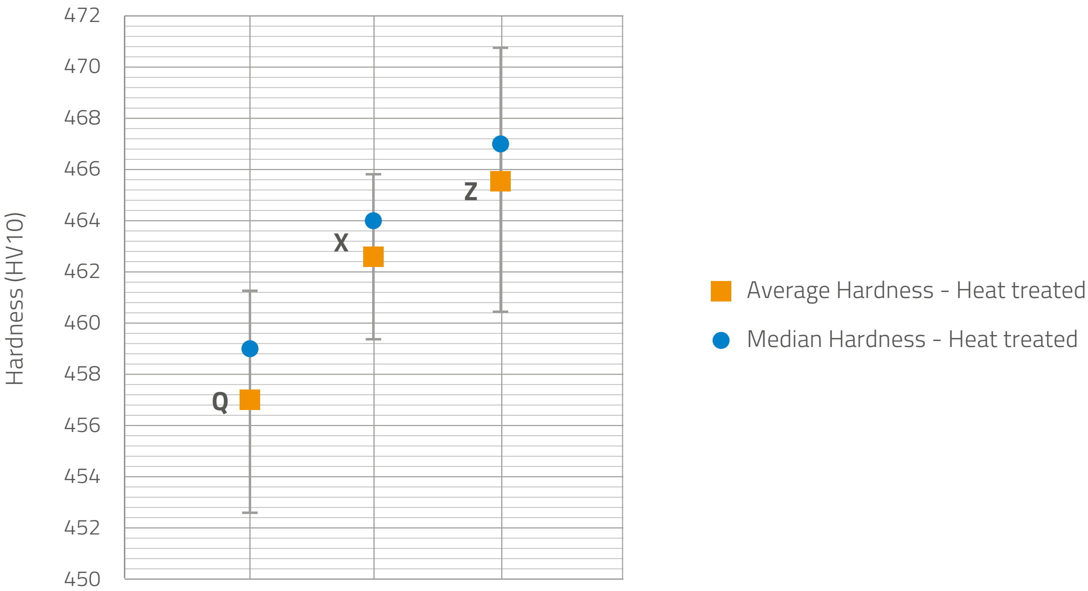


Figure 8: A graph of the average hardness values and the deviation of results for the OEMs carried out on heat-treated material from the powder capsule.

3.4. Test results – heat shields

The list of tests carried out on the heat shields can be seen summarised in *Table 5* below.

Table 5: Testing covered for heat shields.

	2) Non-Destructive tests on heat shields:	3) Destructive tests on heat shields:
	Geometry – 3D scanning	Tensile – not performed
	Surface roughness	Microstructure /Porosity /Crack
	Penetrant	
	PCRT on heat shields	
	Waterflow test	

3.4.1. 3D scanning

3D scanning was carried out on a selection of parts. The scanned data was compared with 3D model (STL format) and aligned using a "3-2-1" set up: with three points in the Z-direction, two points in the Y direction and a single point in the X-direction.

The deviation, indicated by the service supplier as shrink, was captured as the difference between the dimensions of the STL model and the 3D scan of the shield in six (6) locations in x-direction, five (5) in y-direction and nine (9) in z-direction. These positions are shown in *Figure 9*.

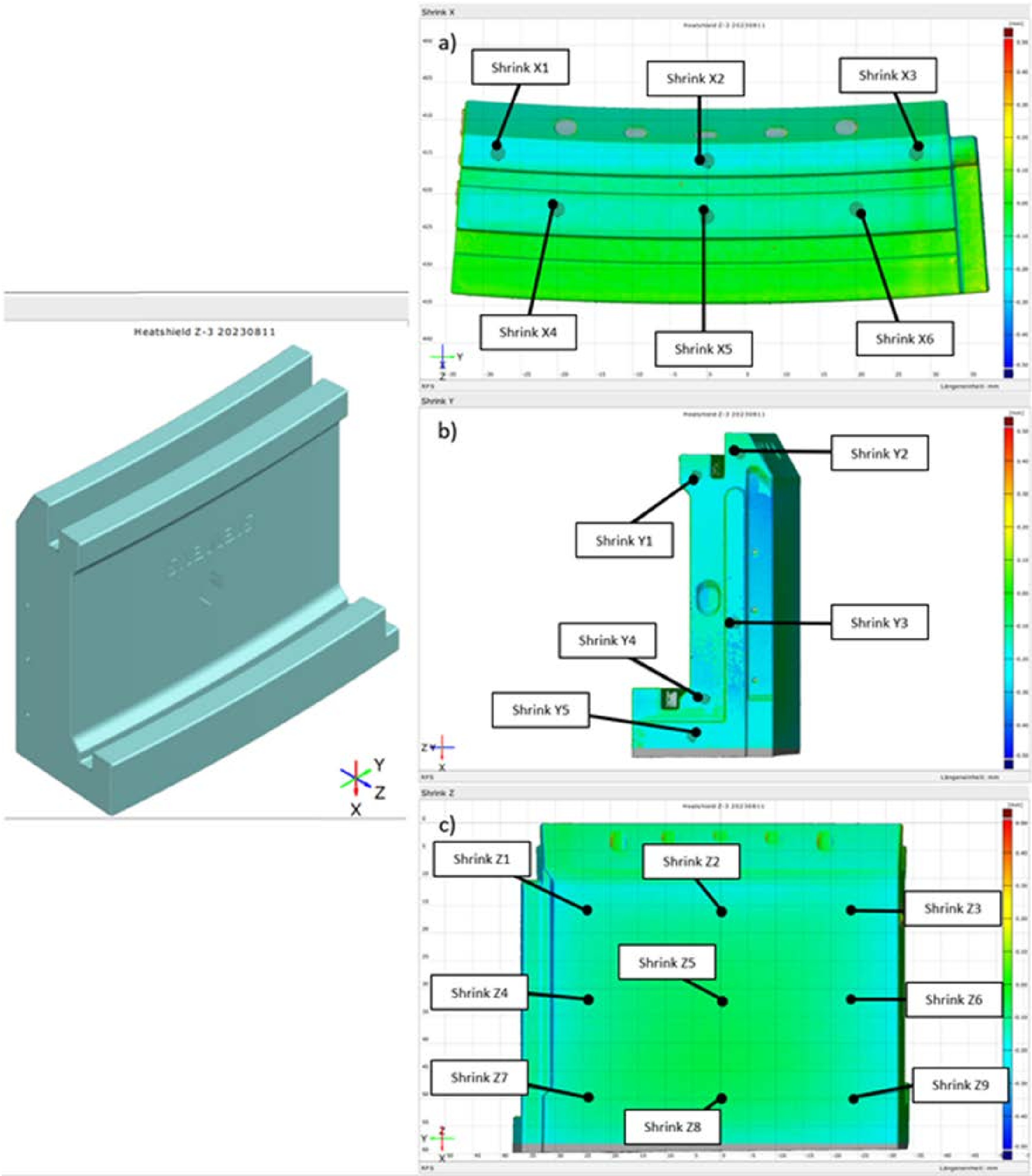


Figure 9: An example image from the 3D scanning showing the locations the measurements were collected from a) shows the x-positions b) shows the y positions and c) shows the z positions.

Some of the measurements was found to be influenced by a misalignment in the X-Y or Z direction. To eliminate this effect, the data was filtered to remove the largest effects of the misalignment.

The actual dimensions of all the parts are smaller than the dimensions of the provided STL model.

- The average deviations vary in the X-direction from -0,02 to -0,10 mm.
- The average deviations vary in the Y-direction from -0,28 to -0,40 mm.
- The average deviations vary in the Z-direction from -0,11 to -0,19 mm.

3.4.2. Non-Destructive Testing (NDT)

3.4.2.1. Computed tomography (CT)

One of the scaled-up shields was selected from each of the OEM plates to act as the representative sample part. CT was carried out according to the laboratory's internal procedure with a Tomographic System DIONDO d7 3,5 MeV – flat panel detector 0,139 mm.

Laboratory internal procedure reported residual powder to a various degree in the internal structure in all the parts inspected. No relevant indications of material defects were reported.

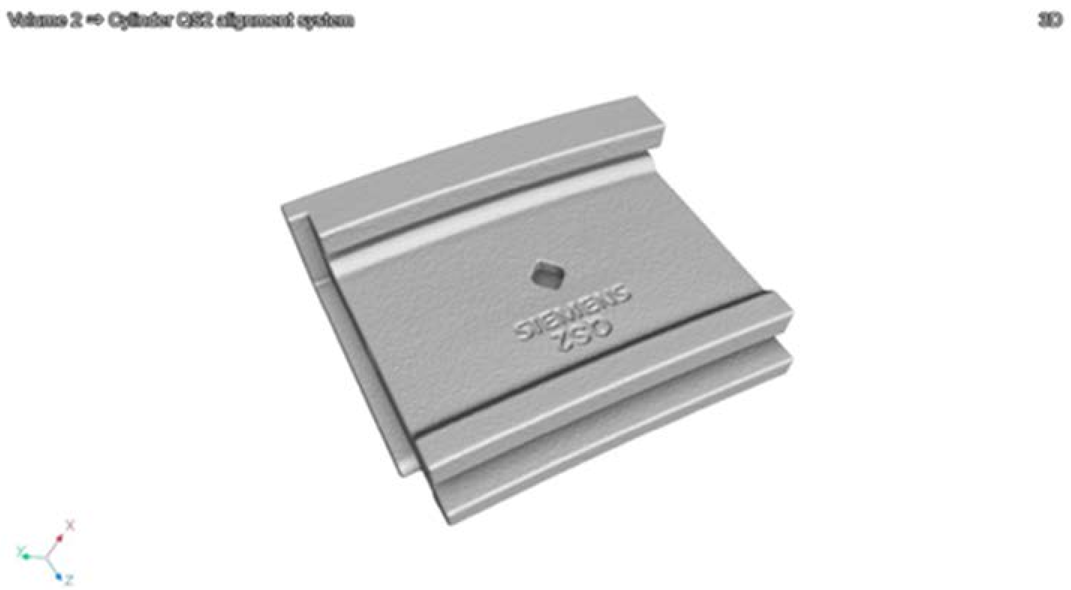


Figure 10: An example image of the 3D volume.

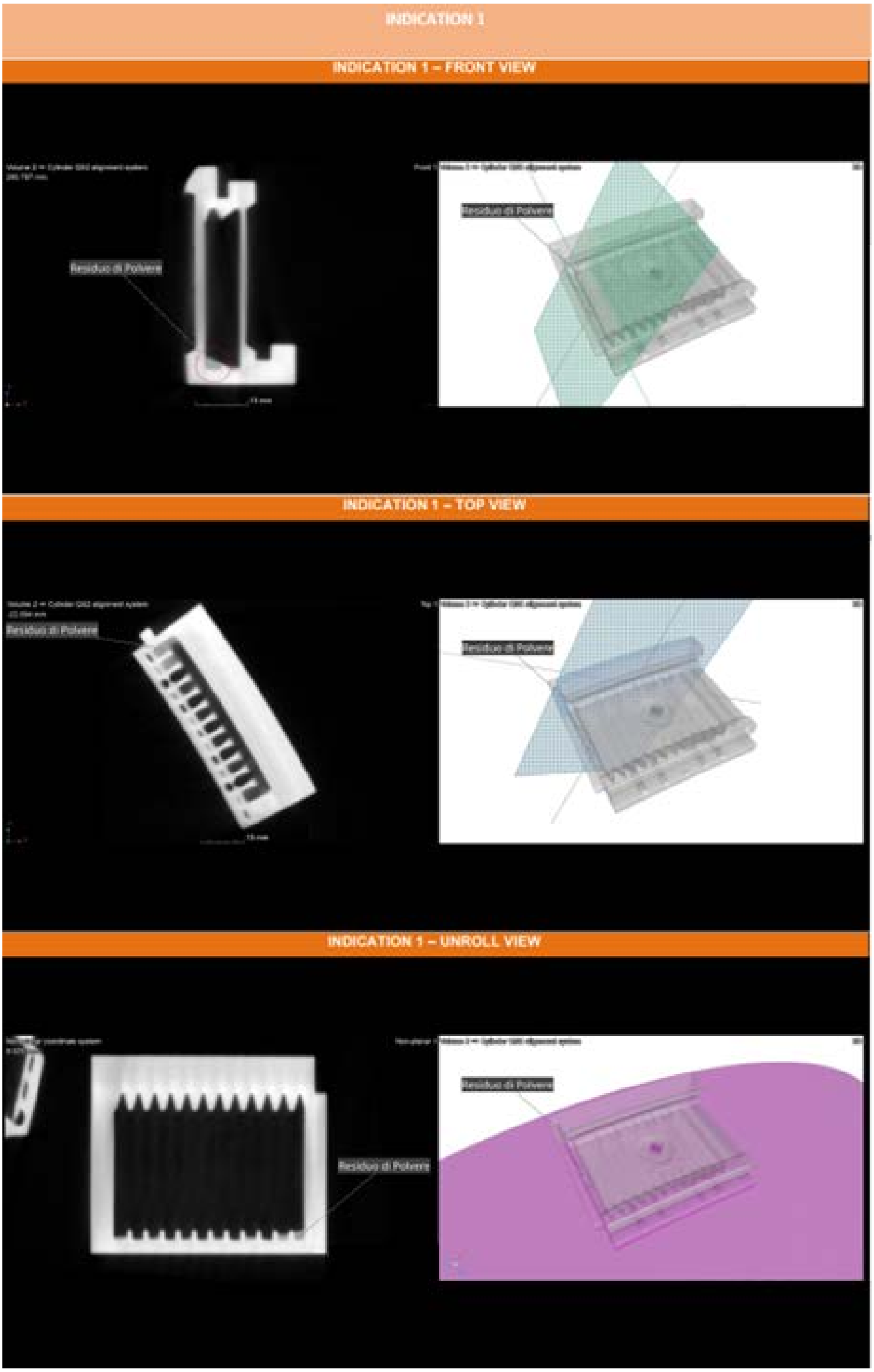


Figure 11: Example of reported cross sections of the heat shields, showing "indication 1" - residual powder in internal channels and voids.

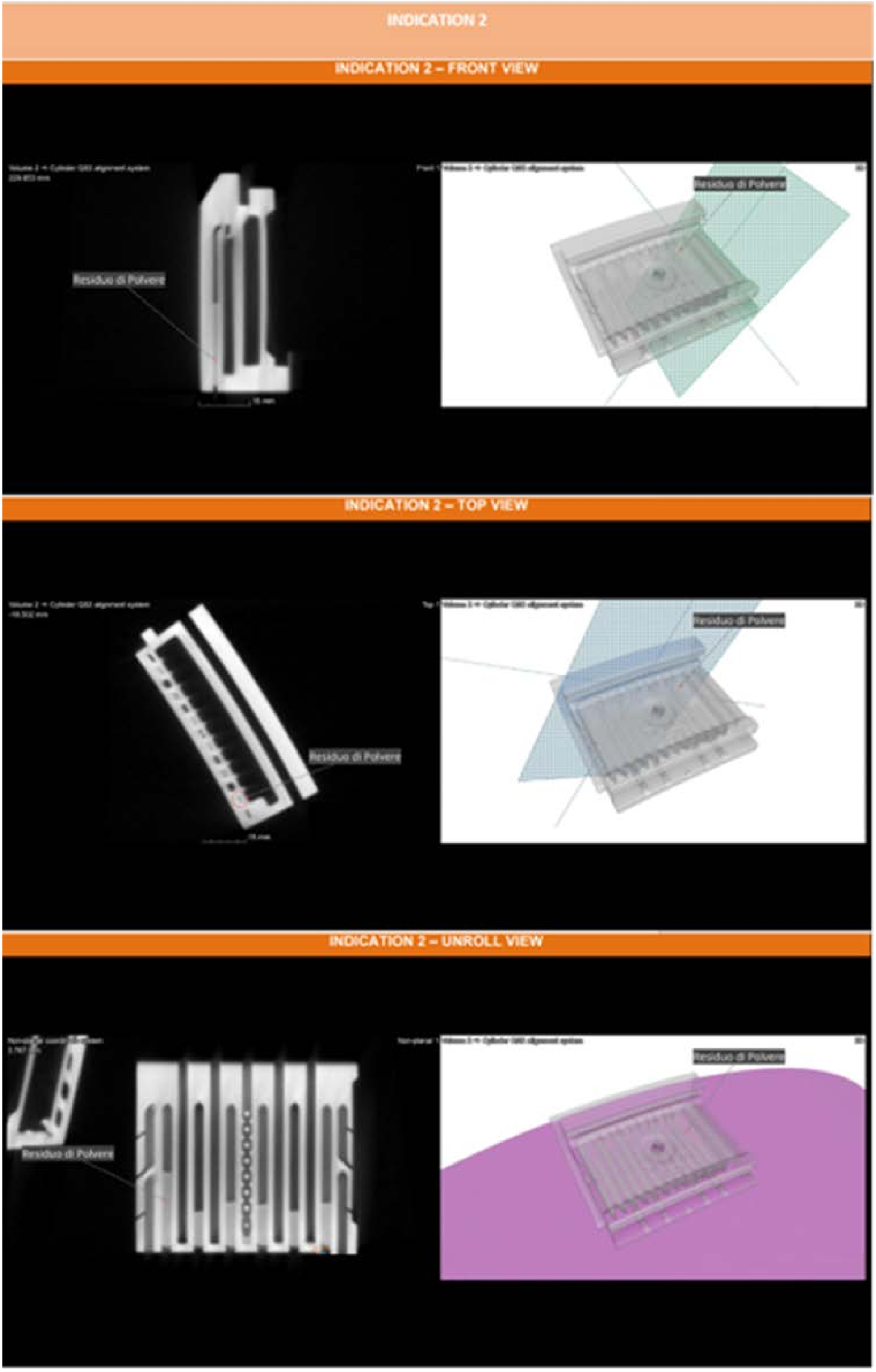


Figure 12: Example of reported cross sections of the heat shields, showing "indication 2" - residual powder in internal channels and voids.

3.4.2.2. Penetrant testing (PT)

In addition to the shield that was analysed by CT two further scaled up shields and two standard sized shields were selected from each of the OEM plates to act as representative parts. PT testing was carried out using red colour contrast penetrant with a 15-minute penetration time and developer with a 12-minute development time.

An example of the PT test being carried out on a shield can be seen below in *Figure 13*. All inspected walls passed PT inspection, with no relevant indications reported. An example of the shield after the development time was completed can be seen in *Figure 14*.

Figure 13: PT test being carried out on a shield (A) shows shield before inspection (B) shows the shield with contrast penetrant (C) shows the shied with the developer.

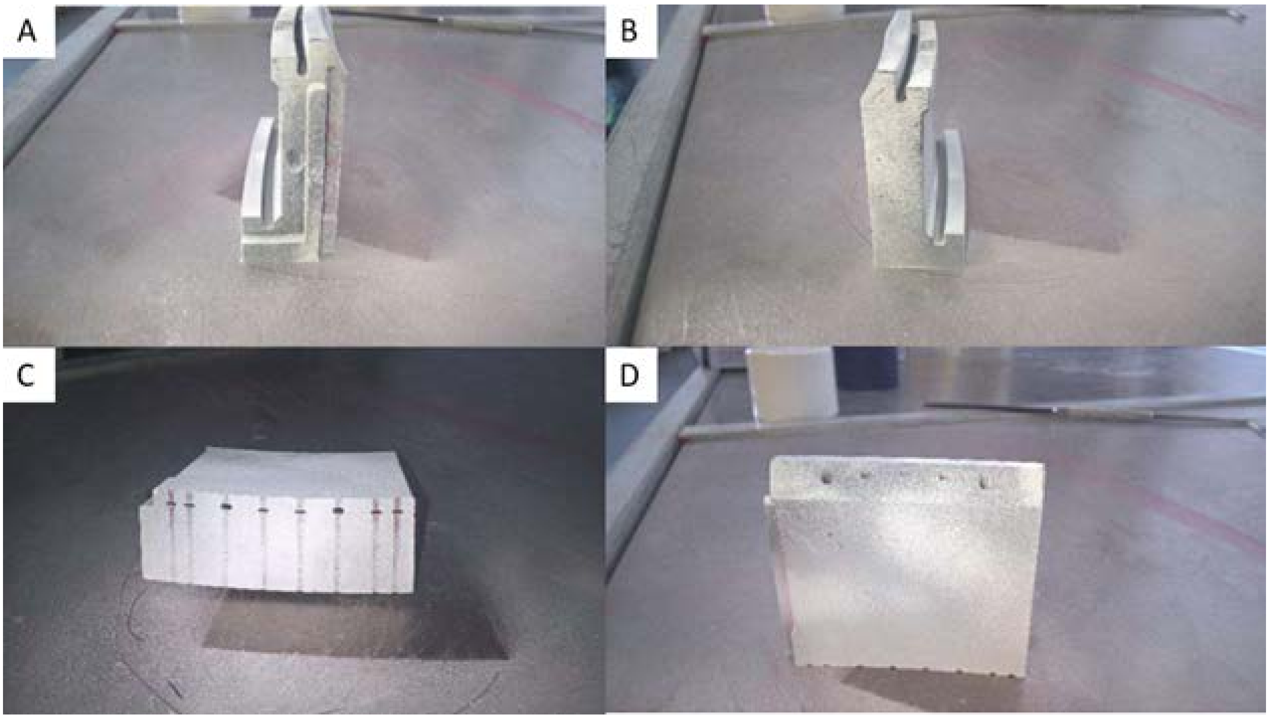


Figure 14: An example of a shield after the 12-minute development time has been completed from different view orientations.

3.4.3. Roughness testing

Roughness testing was carried out on the shields that underwent PT analysis (the 3 large and 2 normal sized shields from each build plate). Two regions were inspected on each of the shields: the flank and the top (locations shown on *Figure 15*), testing was carried out according to standard UNI EN ISO 4288. The results for the average roughness (Ra) values can be seen in *Figure 16* for the top and *Figure 17* for the flank of the shields. There is noticeable difference in surface roughness Ra between different OEMs with OEM Z resulting in the smoothest surface finish.

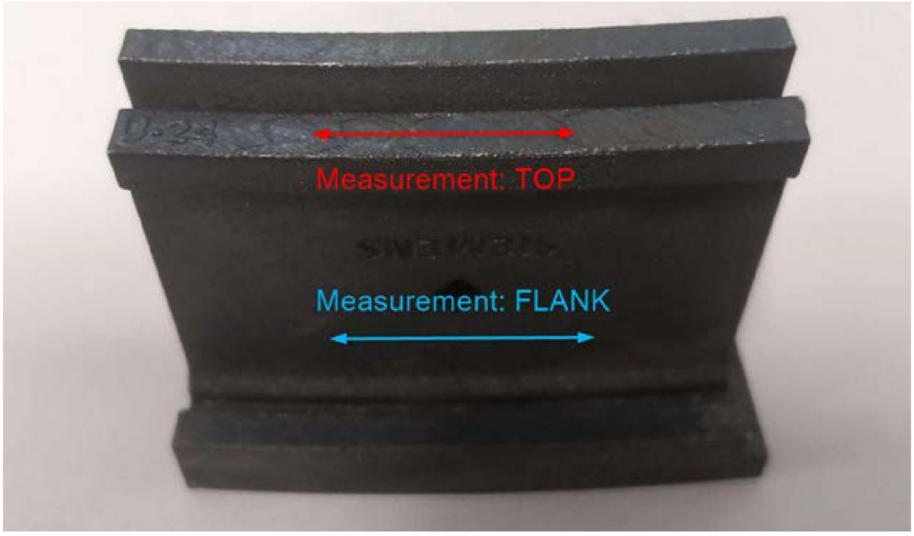


Figure 15: Labelled photograph of a shield indicating the Top and Flank measurement locations. The parts were built with the build direction in the z-direction (the top is the up-skin surface).

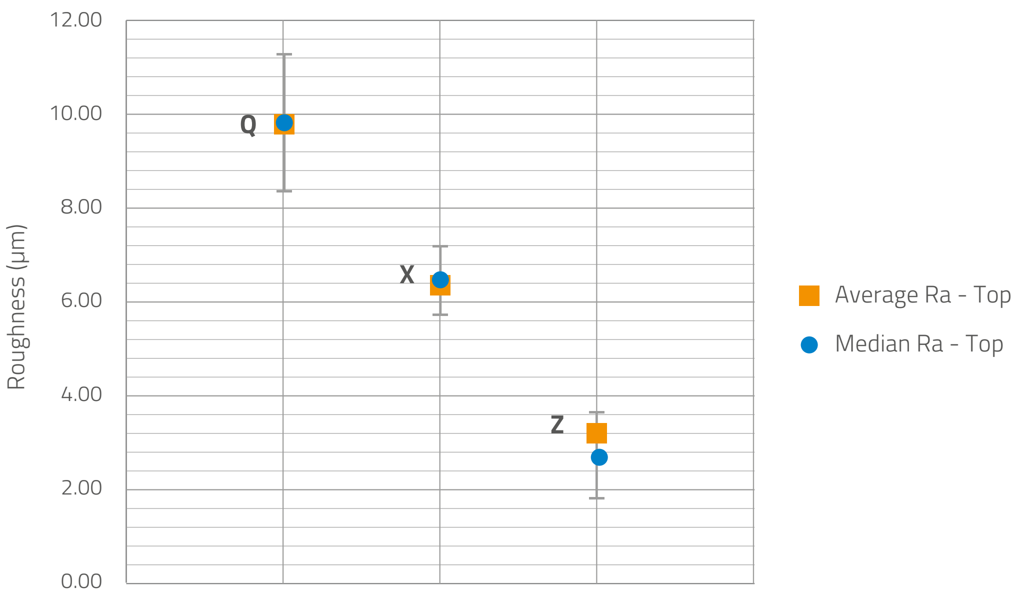


Figure 16: A graph of the average and median Ra roughness values and the deviation of results at the top of the shields for the OEMs.

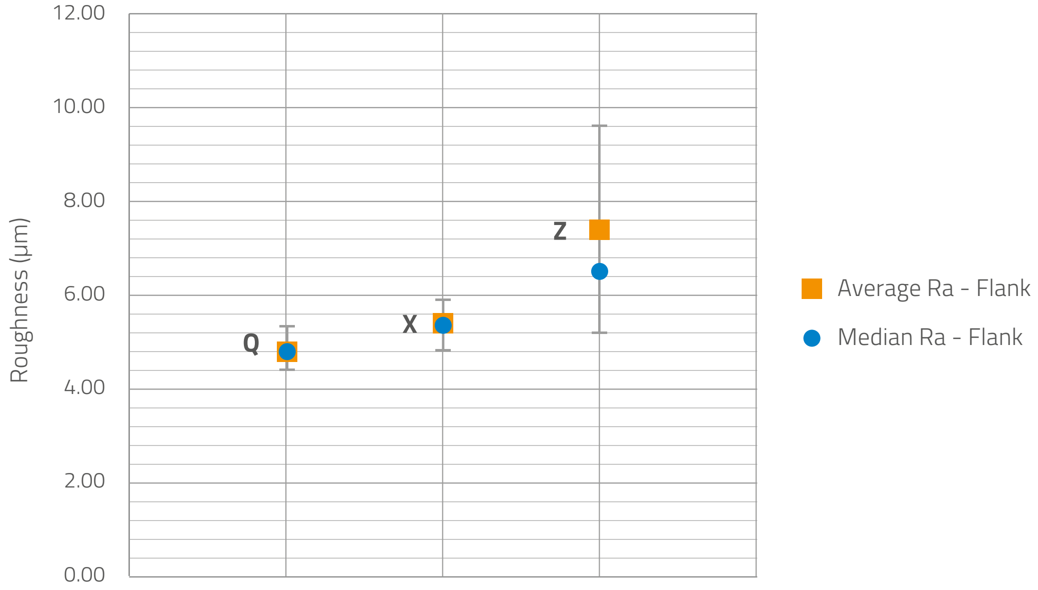


Figure 17: A graph of the average and median Ra roughness values and the deviation of results at the flank of the shields for the OEMs.

Significant deviations were registered for the average and median Ra results at the top of the shields. By contrast, minor and reduced deviations are reported for the average and median Ra results at the flank of the shields.

3.4.4. Micrograph

The shield that had undergone CT inspection from each of the OEM plates was used as the representative sample part for the micrograph section. The following metallographic examination was carried out:

- assessment of the bulk material microstructure,
- assessment of the sub-surface material microstructure,
- assessment of micro-cracks, planar defects, or porosity in connections points,

The average grain size determination was carried out on a transverse section of the samples according to standard ASTM E112. The grain size in as-built and heat treated condition did not vary significantly and ranged between 7 and 8. This is consistent with the small trend in hardness where although the hardness increased after heat treatment it followed broadly the same trend between the OEMs, i.e. OEM with high hardness in as built condition will have high hardness in the heat treated condition. This is most likely liked to small grain size differences between samples from different OEMs.

In the as built condition, after metallographic etching with Kalling 2, a straight columnar and cellular microstructure is observed at the core of the components These microstructural features are typical of additively manufactured INCONEL718 components in the as built condition.

On the etched heat-treated components, an austenitic polygonal grain microstructure is observed. These microstructural features are typical of additively manufactured INCONEL718 components that have been solubilised and aged.

Images of the microstructure before and after heat treatment for one OEM as an example can be seen in *Figure 18*. The microstructure in all samples displays a similar morphology and characteristics.

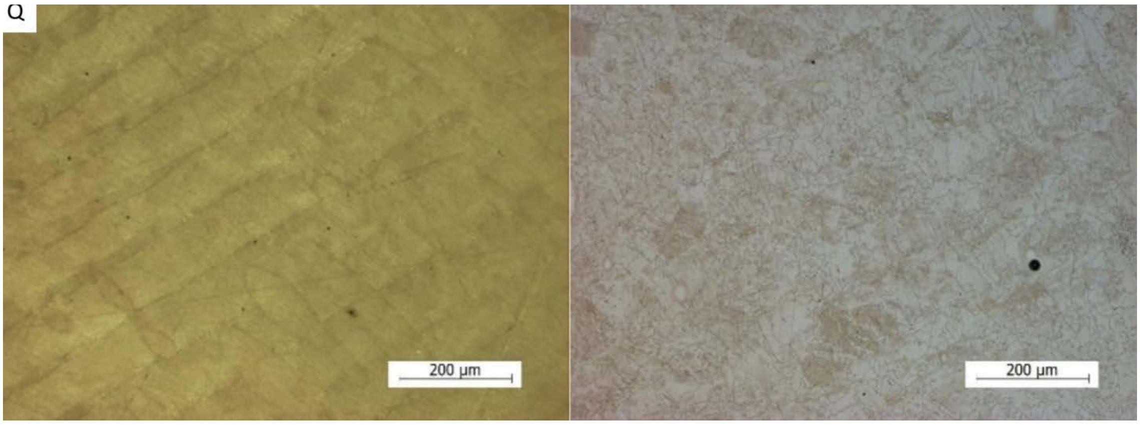


Figure 18: An image of the microstructure of the material from OEM Q before (image on left) and after heat treatment (image on right) at 100x magnification

The channel at the edge of the shield (*Figure 19*) was sectioned for macro-analysis (see *Figure 20*). Each section displays fine spherical porosity on the order of 1-10 µm distributed throughout the section. Irregular shaped pores up to 100 µm in length containing un-melted particles were identified ~100 µm below the surface. The presence of un-melted powder correlates with defects noted in the CT analysis.

Figure 19: Diagram showing the location of the cross-section sample.

The surface of edge of the channel presented an irregular surface characterized by geometrical features up to 100 µm in size protruding along the inside surface of the channel. These features are reminiscent of loosely sintered powder incompletely fused to the bulk.

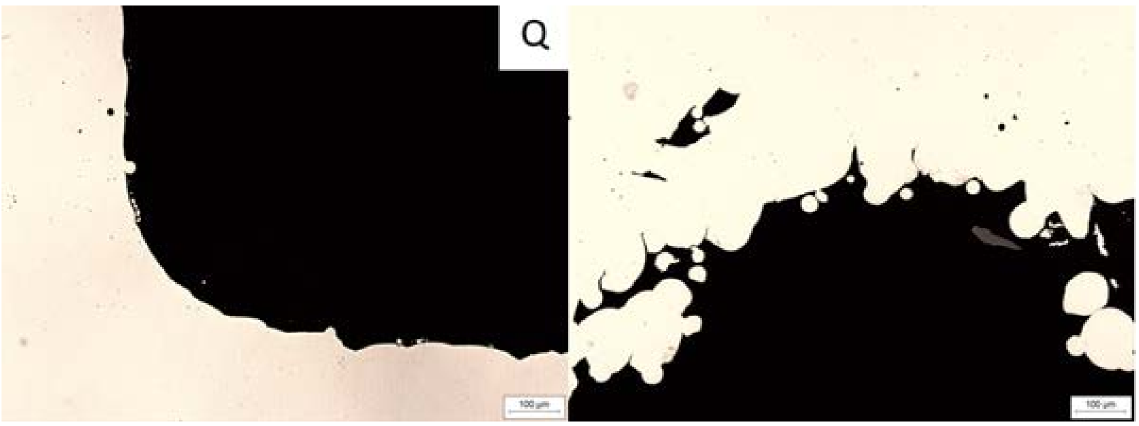


Figure 20: Cross-section image of the end channel of the shield from OEM Q.

3.4.5. Water flow test

Due to concerns about trapped powder in the channels, a simple water flow test was performed on the shields (*Figure 21*). For the two build plates that had channels included in the build for powder removal, the flow test showed waterflow through all the internal channels. This was not the case for the others, meaning that it is likely that there is sintered powder in some of the internal channels that are difficult to remove. The sequence of heat treatment in this project made this worse, because the parts were extracted from the build plates after the complete heat treatment. The findings show that to avoid trapped powder, the design for powder removal and the powder removal process before stress relieving is crucial to the quality.

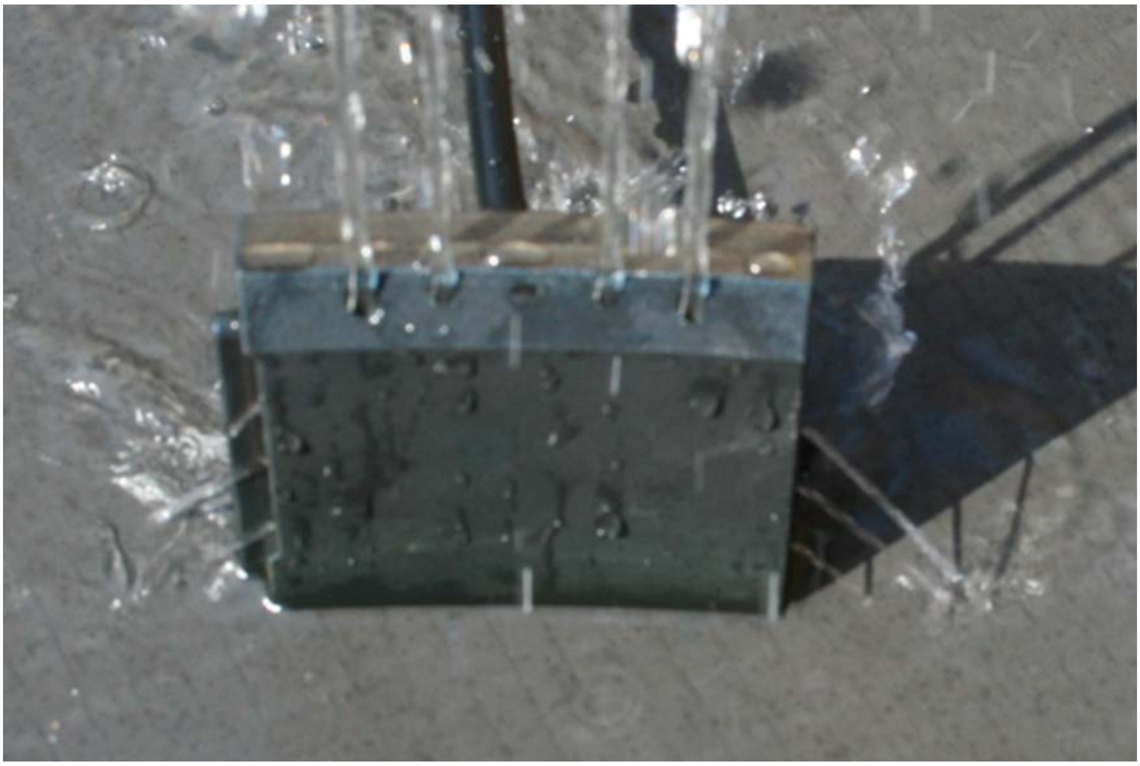


Figure 21: Waterflow of heat shields, showing evidence of blocked holes

4. Discussion and concluding remarks

4.1. Evaluation of results

Details of process basics, material portfolio, build envelope and productivity, digital integration and data access, and quality are provided in a confidential report accessible to consortium members only.

4.2. Conclusions

ETN Global's unique LPBF Machine Evaluation Initiative was developed by a consortium composed of selected members of our Additive Manufacturing Working Group. This study analysed the similarities and differences in the performance and outcomes of L-PBF equipment. To ensure consistency, all manufacturers produced the same parts using the same powder feedstock as basis.

A set of samples and a heat shield geometry were fabricated from alloy 718 by different LPBF OEMs for a test campaign with the aim to evaluate the variations of builds. The consortium defined a set of requirements for the build including minimum number of samples for each test, but the OEMs were allowed to define their layout and build paraments. All the samples were heat treated during the same cycle. The samples and heat shields were then tested for comparison.

Based on the findings in this work the following may be concluded:

- The material properties of alloy 718 (UNS N07718), printed by different equipment makers (OEMs) were consistent over the tested equipment brands, using the standard parameter sets from the equipment makers.

- The ease of use, openness, and productivity of these machines depend significantly on the broader support system setup and the availability of OEM support. In this study, all machines appeared easy to use, and there were potential integration opportunities to enhance overall production processes. When the build job was designed for maximum practical capacity of the machine, including test specimens and a safe distance between parts, the print time per part was similar. However, there were slight variations in machine size, layer height, part spacing, number of lasers, and process pauses. The productivity will therefore mainly depend on the support systems that improve the active time of the machines and general availability of LPBF machines and of post-processing activities.

Several challenges were encountered during the projects including parts design, logistics, long lead time from external vendors, and the sharing of information. As experienced during this project execution, the likely determining factors in the overall lead time will be the schedule for free capacity on the LPBF machines and the capacity of other process steps (powder removal, post processing, heat treatment etc.). Despite the difficulties encountered, consistent quality was achieved across LPBF systems.

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