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In August 2016 ESA issued a competitive invitation to tender for a Space Additive Manufacturing Benchmarking Centre (AO/1-8738/16/NL/LvH). Among others, a bid was placed by the Manufacturing Technology Centre (MTC) in partnership with The Welding Institute (TWI), Magna Parva, and the Science and Technology Facilities Council Rutherford Appleton Laboratory. After proposal evaluation this consortium was awarded the contract and the ESA additive manufacturing benchmarking centre (AMBC) was established in May 2017 led by the MTC in Coventry, UK.

ESA was guided to set up this centre, with customers and industrial partners questioning them about the best way to explore 3D printing for the first time and examine the maturity of the results for their specific needs and applications. The AMBC provides a simple and easy way for ESA projects and hi-tech companies to investigate the potential of 3D printing for their work. The idea is that ESA missions and interested companies can investigate this new engineering world up to the point where they can take a decision whether to adopt this technology or not. If the decision is positive, then they can mature the technology further and even in non-space markets and applications, counting on the support and expertise of this centre of excellence. As the UK National Centre for Additive Manufacturing, the MTC is in a unique position to work with ESA as their AMBC and provide the space sector access to state-of-the-art production capabilities and competence to support industrial exploitation.

Newsletters are published regularly to provide an update of the work carried out for the benefit of the space sector.

Project 2 on Hybrid In718 parts using laser powder bed fusion was completed and written in newsletter #1

A website covering the work of the AMBC can be found here: http://ncam.the-mtc.org/who-we-are/esa-am-benchmarking-centre

The projects included in the current issue are:

- **Project 1:** Additively Manufactured Ring for International Birthing Docking Mechanism.
- **Project 3:** Additive Manufactured Copper Materials for Launcher Engines.
- **Project 4:** Advanced PropulsionMicro-lattice Filter.
- **Project 5:** Benchmark of a Software for Fatigue Assessment of AM Components
- **Project 6:** Hirtisation Process Evaluation for Surface Finishing of AM Components

In this issue:

ADDITIVELY MANUFACTURED RING FOR INTERNATIONAL BIRTHING DOCKING MECHANISM (IBDM)

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Collaborators: **The Manufacturing Technology Centre (MTC), Magna Parva, Cranfield University**
Start Date: **Aug 2017**
Completion Date: **Mar 2020**

The International Birthing and Docking Mechanism (IBDM) is the European docking mechanism compatible with the future International Space Station (ISS) US Orbital Segment (USOS) docking ports. The IBDM (original component shown in Figure 1) captures the vehicle flying to the ISS and it dampens the residual relative motion between the vehicle and the ISS. Once captured and dampened, the IBDM provides a structural pressurised connection between the vehicle and the ISS. The IBDM also allows berthing of a vehicle to a compatible ISS port by the ISS robotic manipulator. The IBDM consists of the Soft Capture System (SCS) that captures the spacecraft and actively dampens relative motion and misalignment, and the Hard Capture System (HCS) that provides the structural connections and carries the service connections. This project aimed to demonstrate the added value of 3D printing by manufacturing a 1:1 model of the SCS ring integrated with the petals that are part of IBDM ring, by the Wire-Arc Additive Manufacturing (WAAM) process. Introducing the roles of the partners involved in this project, Magna Parva established the product assurance requirements for space environment and monitored the product validation process of SCS ring; MTC was responsible for co-ordinating the design optimisation of SCS ring for the WAAM process, validation of design and the final machining of the part; and Cranfield University was responsible mainly for manufacturing of the SCS ring by WAAM process. The main objective of this project was the redesign of the IBDM SCS ring to improve the overall performance in terms of reduced mass, manufacturing cost and delivery time with minimal impact on the environmental and mechanical performance.

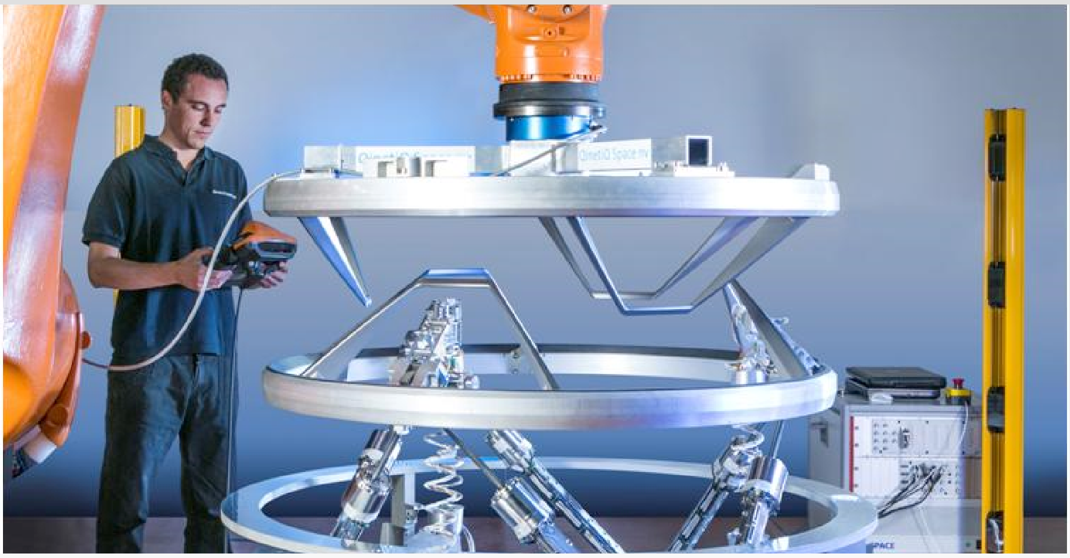
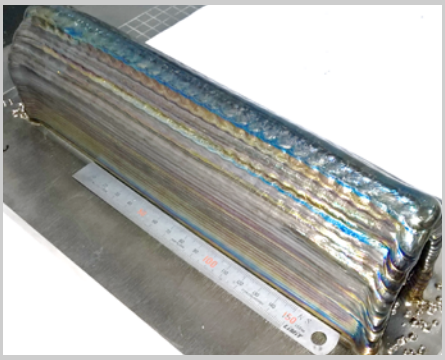


Figure 1
IBDM SCS System
Ref: QinetiQ



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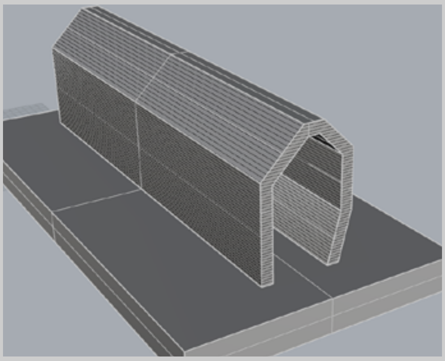
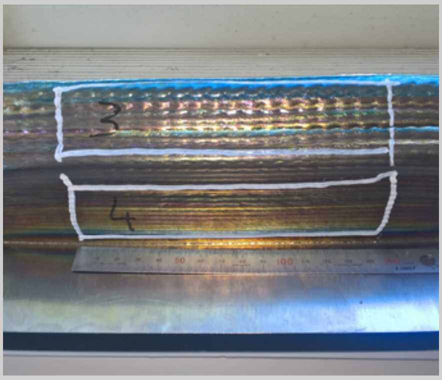


2a

Figure 2a
Trial representative geometry: CAD of section

Figure 2b
Trial representative geometry: Section manufactured by WAAM

Figure 2c
Trial representative geometry: Tensile specimen extraction locations



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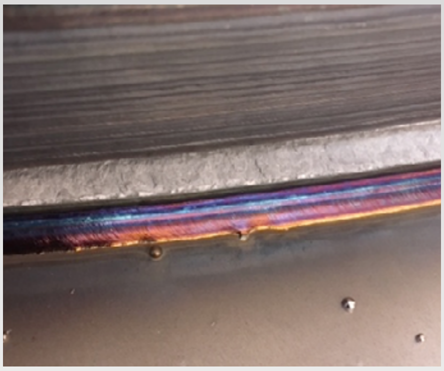
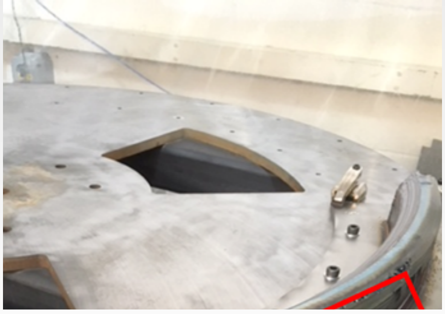
Cranfield University has finished the preliminary initial raw material and coupon testing covering tensile & hardness testing only (after stress relieving heat treatment and in as-built condition) and was working on optimising the manufacturing strategy for the trial representative ring sections, the 1/3rd of a ring and the full final ring. Figure 2, shows the outcome of the first of these tasks. The Manufacturing Readiness Review (MRR) took place in April'18, where the optimised design of IBDM ring by MTC and WAAM approach prepared by Cranfield University was reviewed by ESA.

The deposition of the third of a ring was started in Feb '19 with the full ring planned to be deposited immediately afterwards. Whilst depositing the third ring, stress built up in the radial section of the ring causing a large sheering load, which in turn caused the wall to move up to 6mm and cracks to appear in the baseplate (Figure 3). After the unsuccessful third of a ring deposition, in Apr'19 it was decided that the deposition of the full ring would be put on hold until new deposition strategies could be devised and simulated using a model created by Cranfield. These were completed in Nov'19 and were as follows:

- Periodic heat treatment: The simulation work showed that the part would have a high likelihood of success if manufactured in an alternating deposition then heat treatment cycle. However, due to suitable heat treatment not being locally available, this method would have logistical issues, time delays, and also a high risk of misalignment when fitted back onto the fixture for each deposition process.
- Manufacture a plinth to build from: The simulation work also showed that the part would have a high likelihood of success if deposited onto a plinth. However, this strategy was considered too risky as the deposition of the plinth itself was a complex geometry.
- Replace Ti6Al4V with Ti5553: The simulation work showed that compared to Ti64, using a different titanium alloy, Ti5553 resulted in 70% reduction in residual stress and 25% reduction in distortion with a lower young's modulus. Whilst this alloy was selected as most likely to overcome the issues with deposition, no further work regarding the design of the ring was carried out in the project to take into account of any differences between these two alloys that may affect functional performance in-service. The latter of the above options is the currently favoured approach and ESA have decided to stop work to deposit the ring geometry in this new alloy. This activity has demonstrated some of the challenges that arise with manufacture of large scale parts using AM owing to the stress build up. This provides useful knowledge for engineers who are considering similar parts, and has provided learning for the companies involved. A future project may be carried out to further this work .





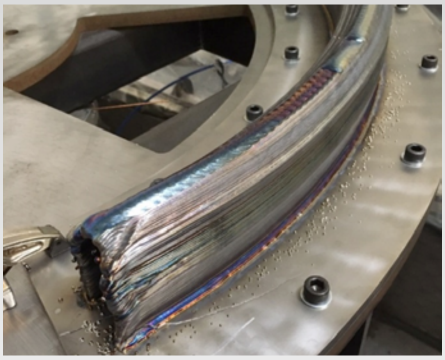


Figure 3
Unsuccessful deposition trial of building a third of a ring

ADDITIVE MANUFACTURED COPPER MATERIALS FOR LAUNCHER ENGINES

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Start Date: **Feb 2018**
Completion Date: **Feb 2020**

Liquid propulsion for launchers often requires rather complex thrust chamber assembly (TCA) liners, commonly produced of copper (Cu) alloys and reinforced with high-strength materials. Production of these components through traditional manufacturing techniques is considered challenging and incurs significantly high cost and lead-time; a case study where AM technologies can provide great benefit. Due to the commercial immaturity of the AM processes for Cu alloys at the start of this project, the project was broken down into two phases. In phase 1 (this project), different laser powder bed fusion (LPBF) machines and processing parameters were investigated to find the optimal processing strategy based on the desired outcome of high density. Phase 2 (future project) will focus on the test campaign defined by the MTC to provide room and high temperature tensile, low cycle fatigue and stress rupture properties of the material. It will also optimise the design based on a finite element (FE) or computational fluid dynamics (CFD) model to be generated by the MTC using the property data from the test campaign. Finally, the optimised geometry will be manufactured using the optimised process parameters for further destructive and non-destructive testing. In Phase 1, Fraunhofer ILT as the R&D partner of the project with Cu processing expertise, used various LPBF systems to build the samples (example shown in Figure 4) to investigate the applicability of these standard machines for producing Cu alloy samples with densities higher than 99%.

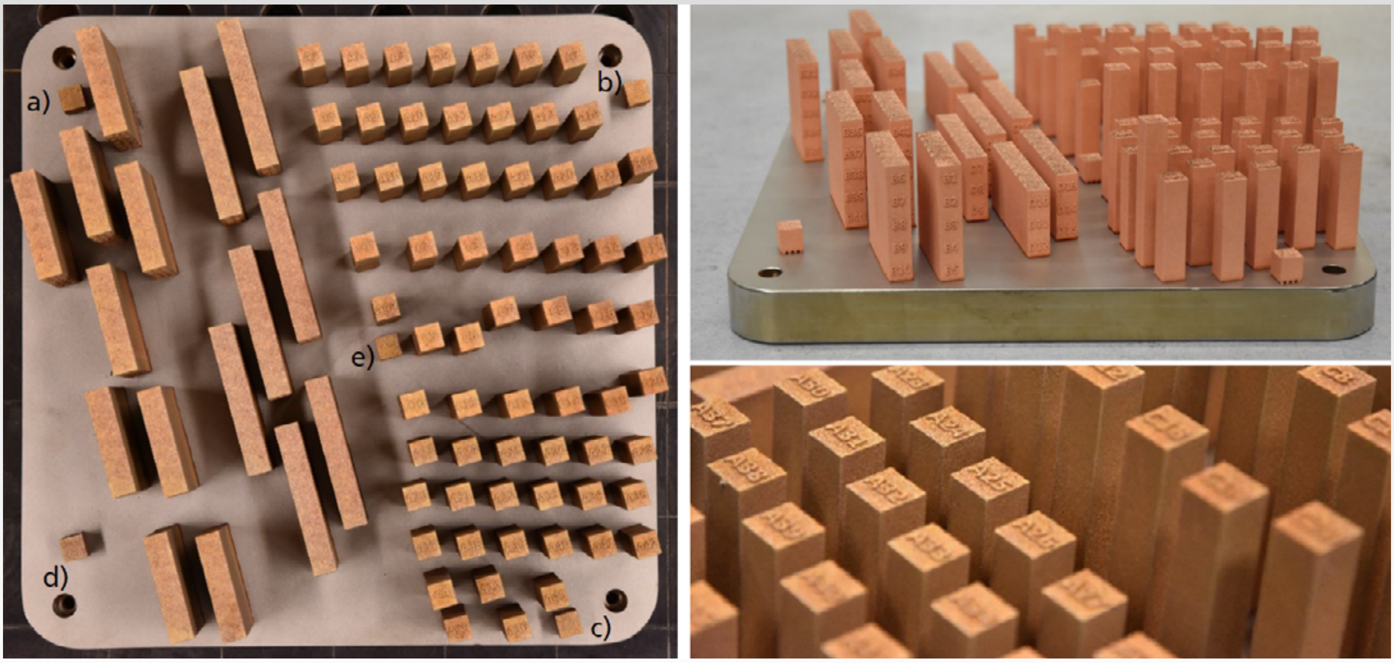
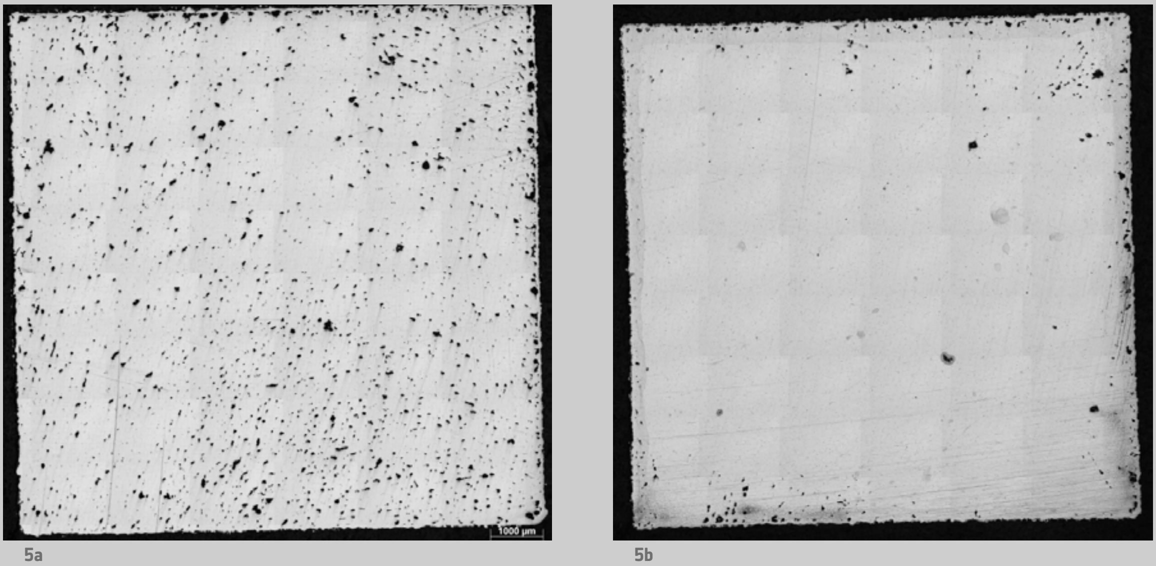


Figure 4
Build layout for tensile and stress rupture samples (images courtesy of Fraunhofer ILT)



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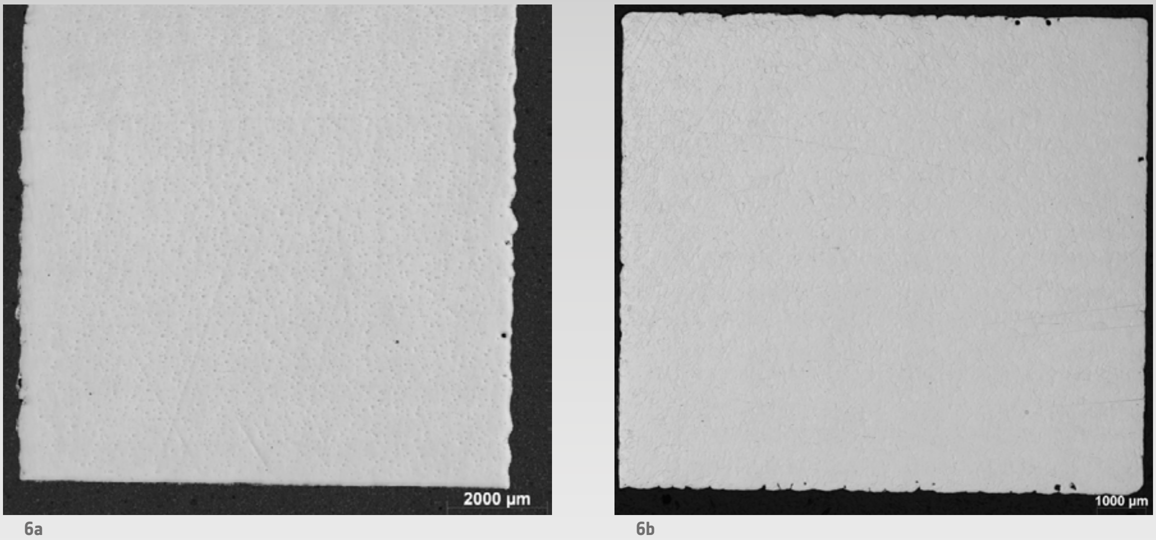
5b

Figure 5
Micrographs of a Cu alloy sample before and after a HIP cycle

It was, however, found by ILT that achieving this density required higher energy lasers due to the high conductivity and low absorptivity of the material. The level of porosity in the samples was higher than expected and due to the surface-connected nature of some of the pores, even adding a further hot isostatic pressing (HIP) post-processing cycle did not improve the density to the required level. Example micrographs of a sample before and after the HIP cycle are shown in Figure 5. Given the challenges experienced up to this point in the project, an alternative machine was identified based at 3T-AM in the UK who then joined the project as a production supplier. 3T-AM have access to a LPBF machine with a 1 kW laser and through their in-house knowledge of the optimised post-processing heat treatments, managed to produce samples with density levels higher than 99.5%. Example micrographs of samples produced by 3T-AM are shown in Figure 6 and this demonstrates promise of being able to manufacture usable parts for this application. In the next phase of the project, the samples produced by 3T-AM will be tested to find the tensile, fatigue and creep properties of the material. In order to assess manufacturability of crucial features including cooling channels and overhangs, cut out sections, a TCA liner downscaled to 75 mm in height and a complete sub-scaled TCA liner with the height of 200 mm will be manufactured.



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6b

Figure 6
Micrographs of two Cu samples produced by 3T-AM on a 1 kW LPBF machine

ADVANCED PROPULSION MICRO-LATTICE FILTER

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Start Date: **Oct 2018**
Completion date: **Feb 2020**

Propulsion filters are used in aerospace to enable the filtration of small particles (<50 μm) from large volumes of fluid being transported at high pressures. The current solutions for filtering down to such low filtrations rates include etched disk filters or wire mesh filters. The former of these is able to achieve good filtration rates over a large surface area but unfortunately suffers from being comparatively heavy because of poor material removal efficiency during the etching process. The latter of these suffers from movement of wire strands caused by particles damaging the surface thereby worsening the filtration rate over time. Furthermore, both of these solutions require that the filters be assembled from multiple components, which can be less time and cost efficient but can also result in component dislocation over time if they are not assembled well enough. The advanced propulsion filter concept (Figure 7) was established by ESA in order to out-perform these existing technologies. By utilising additive manufacturing (AM), the filter can be manufactured from one component rather than several, can be produced in reduced manufacturing times and can be made at both a lower cost and a reduced mass. The key challenge when producing such a component by AM is achieving the small pore sizes (<30 μm) required for the application. In order to achieve such a low pore size the technology utilises multiple strategies across the design, AM and post-processing aspects of the filter development. Within the design aspect of filter development, complex unit-cell geometries or the use of stacked, offset layers are utilised in order to reduce orifice sizes as much as possible. Such intricate models can result in computational challenges such as file size handling and transfer. In order to get around this, various approaches have been taken including reduction of surface area by using hexagonal struts rather than cylindrical ones, direct slicing of parts and implicit modelling utilising state-of-the-art software.

Within the AM process itself, the use of fine titanium powder (PSD <7 μm) enables the “laser powder bed fusion (LPBF)” process to produce parts at layer heights on the order of 10 μm (z-resolution) with similar resolution in x and y. This allows for accurate parts to be made that include the necessary stock material required in order for the parts to maintain accuracy after post-processing.

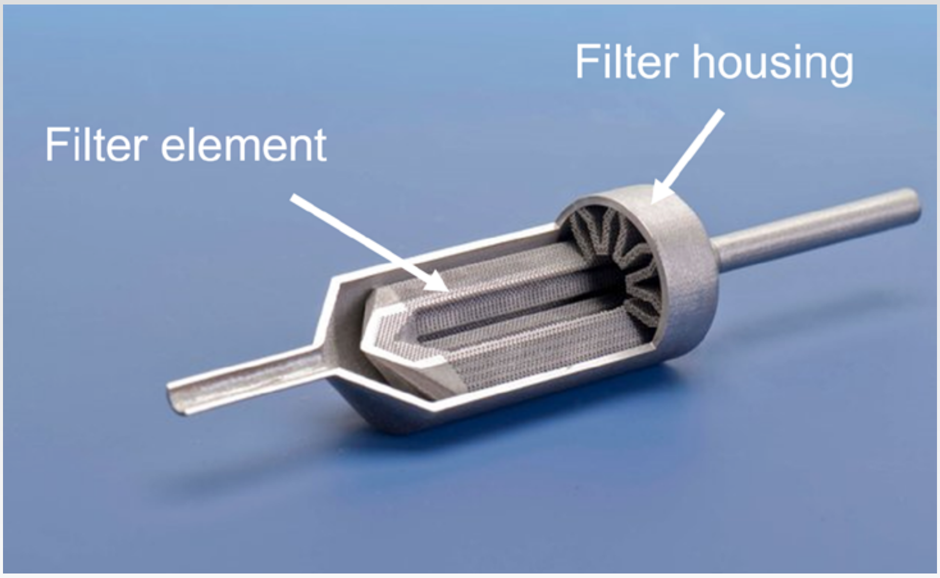

Figure 7
Image of cross-sectioned advanced propulsion filter

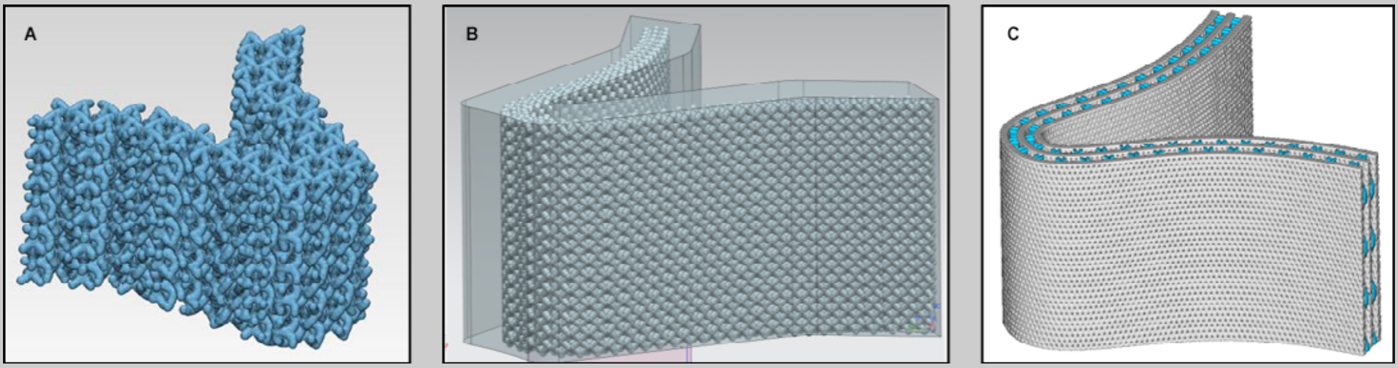

Figure 8
Illustration of the three design approaches taken producing each of the samples.

The post-processing technology used allows for excellent control of material removal homogeneously from all surfaces including internal geometries. Thus far, proof of concept work has been carried out that confirms pore sizes of < 100µm are achievable. To determine this, smaller sections of the filter were designed using 3 different unit cell/layering approaches (Figure 8).

Upon manufacture and post-processing designs A and B were found to be the most suited to being manufactured via the micro LPBF process whilst also demonstrating a potential to be uniformly post-processed as to achieve the desired pore sizes. The uniformity of material removal was confirmed both externally via scanning electron microscopy (SEM) and internally via micro computed tomography (CT). Upon scaling up of designs A and B it was found that only design B could be scaled up because design A's file sizes grew too large to be computationally processed within reasonable time-scales. Thus, the remaining development samples were fabricated using Design B. After fabrication of design B in the larger sample sizes de-lamination (Figure 11a) was observed in the largest of the three samples.

Upon investigation it was discovered that this was caused by high oxygen content in the powder supply which 3D MicroPrint are currently trying to overcome. Unfortunately, this resulted in the final samples having to be reduced in size to ensure delamination did not occur so that testing of the filter could be conducted. Post-processing of the larger samples results in greater control over the process and a pore size of closer to 50 µm could be achieved (Figure 11c).

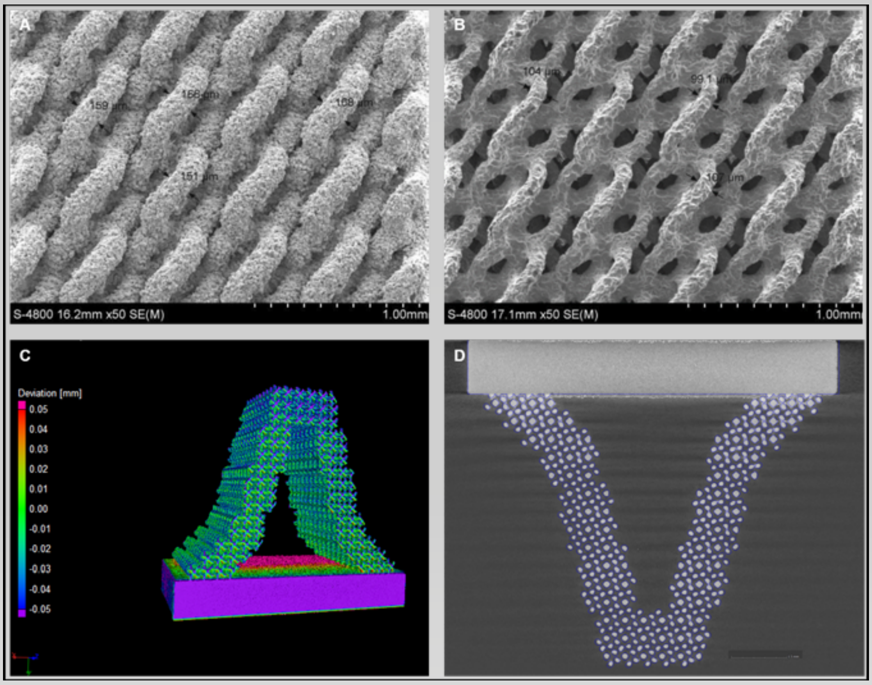

Figure 9
SEM images of design A before (a) and after post processing(b). MicroCT data demonstrating the deviation of the produced part away from the designed CAD geometry, both in 3D(c) and 2D(d)

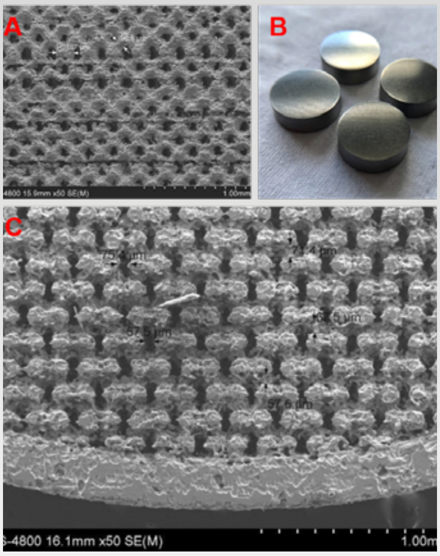

Figure 11
Images demonstrating delamination (A), the final samples (B) and the final porosity achieved after further post-processing development

BENCHMARK OF A SOFTWARE FOR FATIGUE ASSESSMENT OF AM COMPONENTS

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Start Date: **Oct 2018**
Completion date: **Feb 2020**

Despite the disruptive benefits of Additive Manufacturing (AM), the application of this technology for safety-critical structural parts in aerospace is still far from being achieved and standardised. The necessity to comply with very strict reliability requirements is hindering this final step because of the large scatter and low reproducibility always associated with AM, especially in terms of fatigue strength. In this regard, manufacturing defects are the most important and complex issue, but several other sources of variability have an effect as well. To address this issue, POLIMI with the support of ESA have developed ProFACE, a fully-probabilistic software that aims to robustly assess the fatigue strength and critical locations of complex components in the presence of defects by adopting models based on a similitude between defects and short cracks. ProFACE stands for "probabilistic fatigue assessment of components with defects". Following on from the previous work on this tool, the AMBC project intended to validate the performance of the ProFACE simulation approach for fatigue assessment and its compliance with experimental results. The output will be a ready-to-use software tool based on the existing ProFACE codes. Parts have been made using laser powder bed fusion AM in AlSi10Mg alloy. The ProFACE tool enables the user to identify fatigue-critical regions of a component using finite element analysis (FEA) enabling designs to be made robust to the defects that may exist within AM components. Fatigue failure in the presence of defects is caused by the largest defect present in the critical volume, the so-called 'killer defect' size. Defects near the surface are also more likely to be a cause of failure. The defect distribution can be detected by, for example, X-ray Computed Tomography (XCT), and then represented by a cumulative distribution function which enables determination of the maximum applicable stress and the maximum load. Fractographic analysis using Scanning Electron Microscopy (SEM) is also used to identify the size of the defect(s) at the failure interface. The design of the components for validation are shown in Figure 12 and the clamping arrangement for testing shown in Figure 13. The 'wishbone' shape geometry was chosen as a classical bracket similar to those adopted in the landing gears of aeroplanes. In this case, the two long beams are subjected to a large and almost constant axial stress. The aim was to increase the highly stressed volume to increase the probability that a large manufacturing defect could fall inside these critical regions.

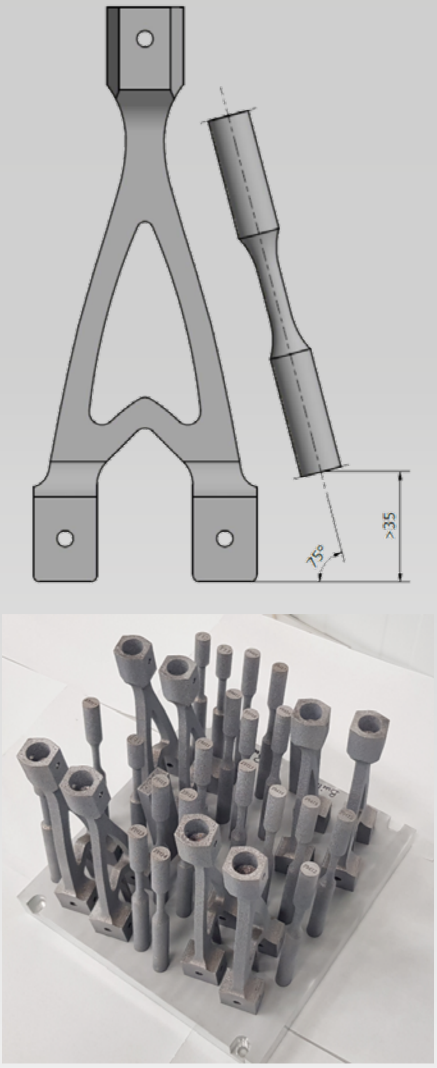

Figure 12
Wishbone and specimens for validation testing

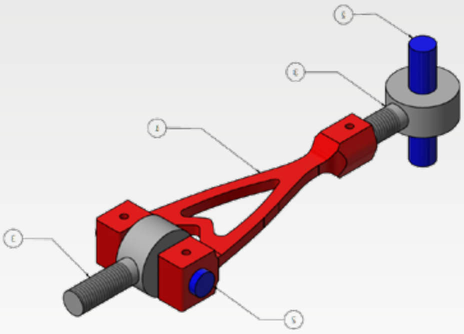

Figure 13
Clamping arrangement for testing

Three identical builds were completed using an EOS M280 laser powder bed fusion (LPBF) machine giving a total of 24 wishbone components and 57 corresponding mechanical specimens (tensile, fatigue crack growth, load-controlled fatigue tests). Some of the components were to be fully machined (including in the critical regions) and some were partially machined (leaving the critical regions as-built).

To achieve the tolerances required for the testing, considering the typical variability of parts made using LPBF and the intentional lack of stress relieving heat treatment for these experiments, significant work was required to optimise the machining steps. An example of a work holding arrangement used for some of the machining operations is shown in Figure 14. Following the post-processing and inspection, the components and mechanical specimens were tested by ESA and POLIMI. This consisted of fatigue and crack growth testing of the mechanical specimens, XCT scans, and fatigue testing of the 'wishbone' components.

In parallel to the manufacturing work, a preliminary fatigue assessment of the part was performed based on evaluation of the 90% volume, V90. This approach assumes that the failure probability of a component can be estimated by evaluating the failure probability of the most stressed region, while the regions subjected to lower stress play a negligible role on the overall failure probability.

Therefore, the extension of the critical volume can be estimated as the volume of material subjected to a stress larger than 90% of the maximum stress acting on the component.

This was estimated for the 'wishbone' component based on finite element simulation results shown in Figure 15. As the fatigue failure in the presence of defects is caused by the largest defect present in the critical volume, the next step for fatigue strength assessment is the estimation of the maximum defect size expected inside V90. This can be achieved by applying statistics of extremes considering a defect distribution, which can be described by a cumulative distribution function. Knowing the size of the most critical defect expected in the component, the last step is the determination of the maximum applicable stress, and thus of the maximum load. This can be achieved by evaluating the relationship between the defect size and the fatigue limit of the material through the Kitagawa diagram. Knowing the shape of the Wohler curve allows this concept to be extended to fatigue life assessment as shown in Figure 16. The testing of the components is currently underway to enable comparison with the simulation results with the intention of being able to validate the tool. The ProFACE tool is planned for widespread use across industry enabling robust design of AM components in the presence of defects. The results will be published in due course.

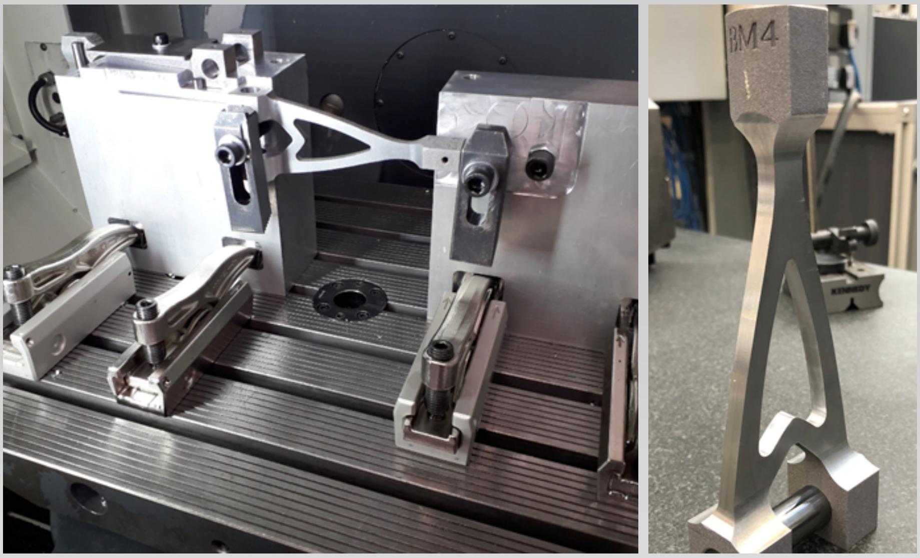

Figure 14
Machining work holding arrangement and example finished part for testing

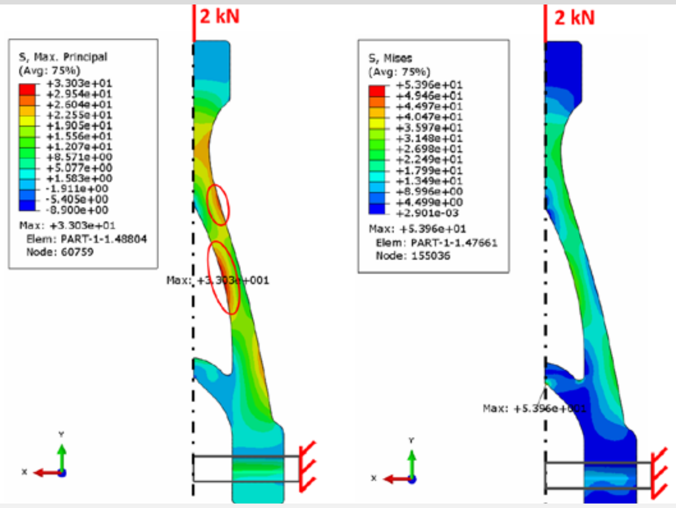

Figure 15
Results of the static FE simulations
a) max principal stress, b) Von Mises stress

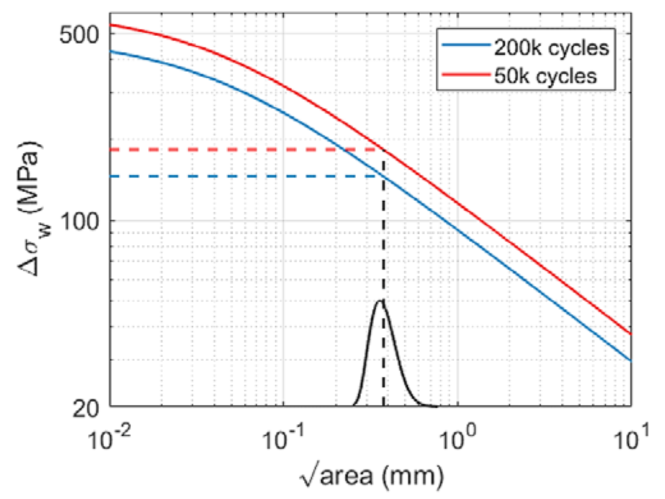

Figure 16
Results of the static FE simulations on the final component shape subjected to tensile loading

HIRTISATION PROCESS EVALUATION FOR SURFACE FINISHING OF AM COMPONENTS

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Start Date: **Sept 2019**
Anticipated Completion Date**: Dec 2020**

Additively manufactured (AM) materials usually suffer from high surface roughness as a result of the manufacturing process.

Affecting mainly fatigue life, this can be detrimental to overall materials and components performance. Moreover, removing the supports (and powder) used during manufacturing is time-consuming and can even be impossible in highly complex designs, especially with parts with internal features such as channels. This is typically the case in almost all metal AM processes. The industry as a whole is aware of this issue and is developing solutions through a variety of approaches. One such approach is the Hirtisation® process which has been developed by Hirtenberger for the post-treatment of AM components to address the aforementioned AM constrains/issues. The method is based on a combination of electrochemical pulse methods, hydrodynamic flow and particle assisted chemical removal and surface treatment and has shown potential for the treatment of highly complex AM parts.

The objective of this feasibility study is to assess the effectiveness performance of the AM Hirtisation® treatment in decreasing the surface roughness and removing the manufactured supports without modifying any other properties of the samples. To evaluate these there are 3 sets of components that will be manufactured by MTC using laser powder bed fusion AM: **1.** A geometric artefact for exploring the capabilities of the technique on different features in AlSi10Mg on an EOS M280 machine (Figure 17a). **2.** A set of 269 mechanical test components (tensile, fatigue, mini-fatigue) in In718 on an EOS M400-4 machine to be treated by several different post-processing techniques including Hirtisation, and then tested by ESA. **3.** A thrust chamber demonstrator component and segments also in In718 on an EOS M400-4 machine for evaluation on a representative geometry with complex internal channels (Figure 17b).

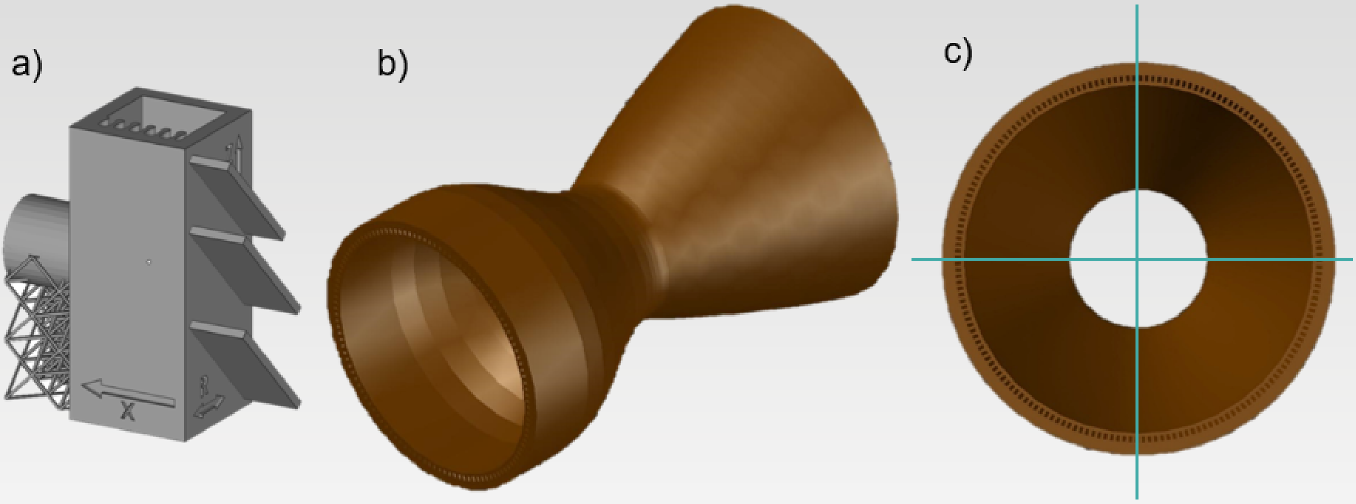
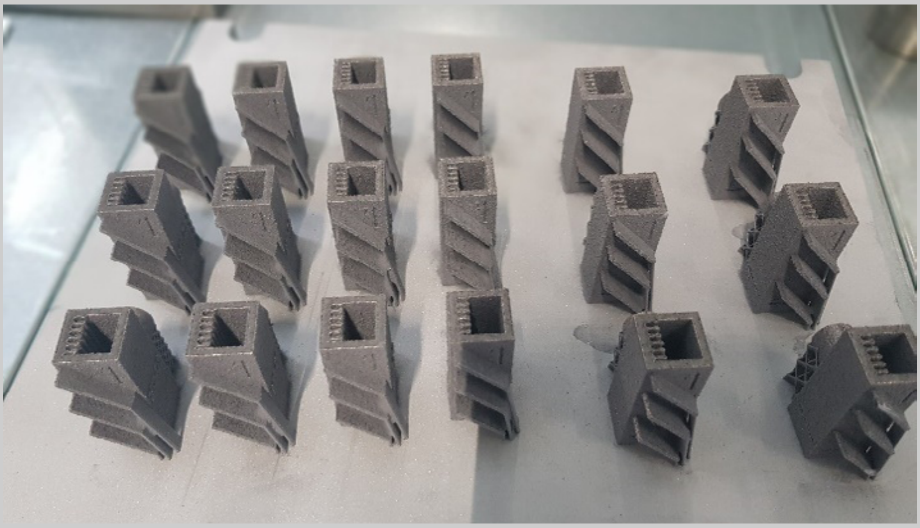


Figure 17

a) AlSi10Mg artefact b) In718 thrust chamber component c) Quarter segments



18a

18b

Figure 18

a) Manufactured AlSi10Mg samples, and b) example build of In718 test specimens

Some examples of parts manufactured for the aluminium artefact and the mechanical test specimens are shown in Figure 18. Due to the sensitivities of the machine in processing very fine lattice structures in the aluminium artefact, process parameter optimisation was required to achieve good quality parts. Also, due to the recoating forces experienced during the manufacture of the vertical mechanical test specimens in the M400 machine, stiffening structures were used.

To enable the thrust chamber component to be post-processed effectively using the Hirtisation process, some additional features were required to be designed and added to the part (see Figure 19). This included a manifold to enable the flow of an electrolyte through the part for the electrochemical process to work effectively in the long channels as well as an electric connection plate to enable attachment of electrical connectors.

In addition, some features were added to the base to aid removal of powder from the internal channels following completion of the build. To reduce risk of build failure and to improve geometrical conformance, build simulation was carried out prior to the design finalisation (see Figure 20 and Figure 22). This highlighted some regions that required further consideration to reduce contact with the recoater blade. To enable trials to be conducted to optimise the post-processing route prior to the full component, a quarter version of the thrust chamber was designed as shown in Figure 21a.

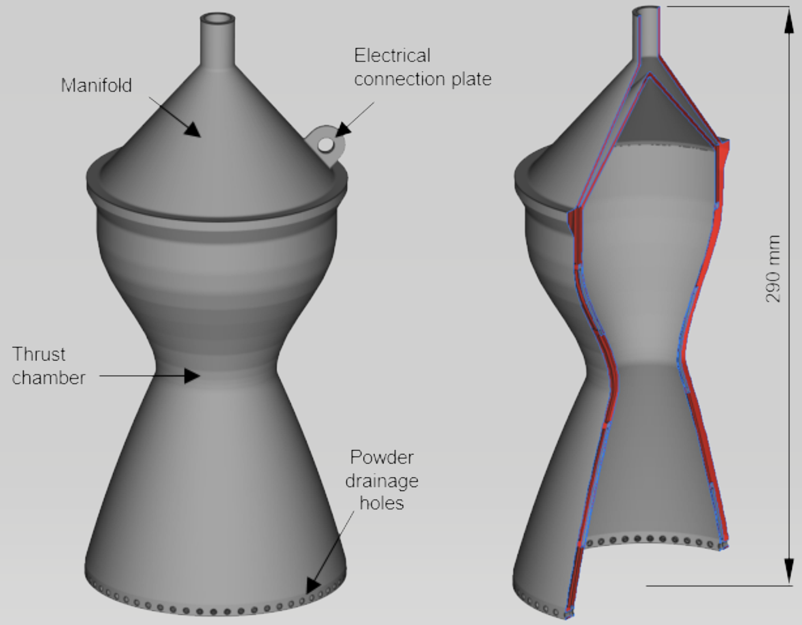


Figure 19

Thrust chamber demonstrator part (and section view) with modifications to aid manufacture and post-processing

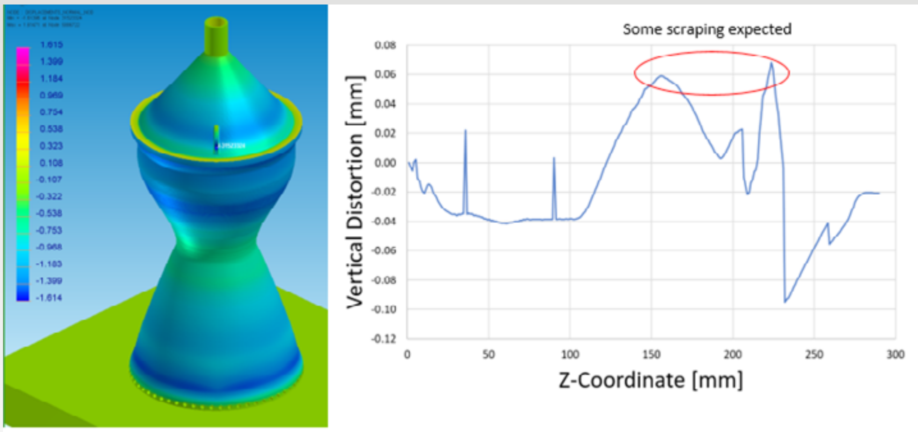


Figure 20

Prediction of vertical distortion during build using ESI AM build simulation software

Four of these quarters were then assembled together as shown in Figure 21b in preparation for building in the AM machine to avoid distortion issues, to be later separated using wire electrical discharge machining (EDM). The features necessary to add to the thrust chamber demonstrate the importance of designing for post-processing as well as for the build itself. The results of the evaluation of the surface finishing techniques will enable further knowledge to designers of achievable surface finishing and geometric limitations.

The remaining work for this project is to finish the manufacture and post-processing of the mechanical test samples, and to manufacture the thrust chamber components, prior to the Hirtisation processing.

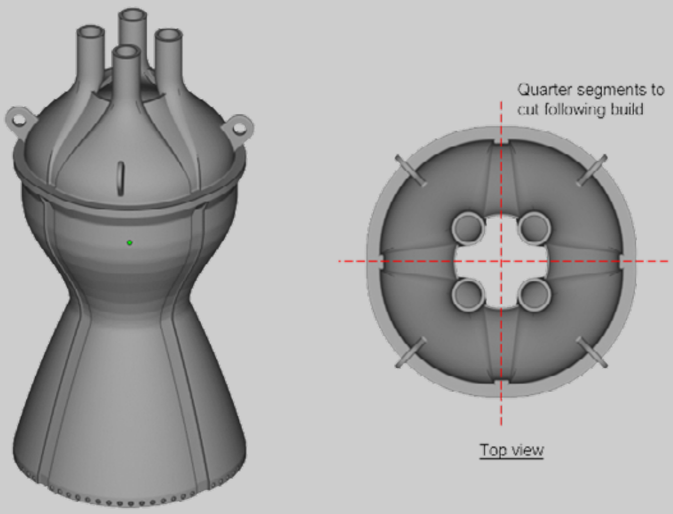


Figure 21

Quarter test samples merged together for AM build to be separated following build through wire EDM

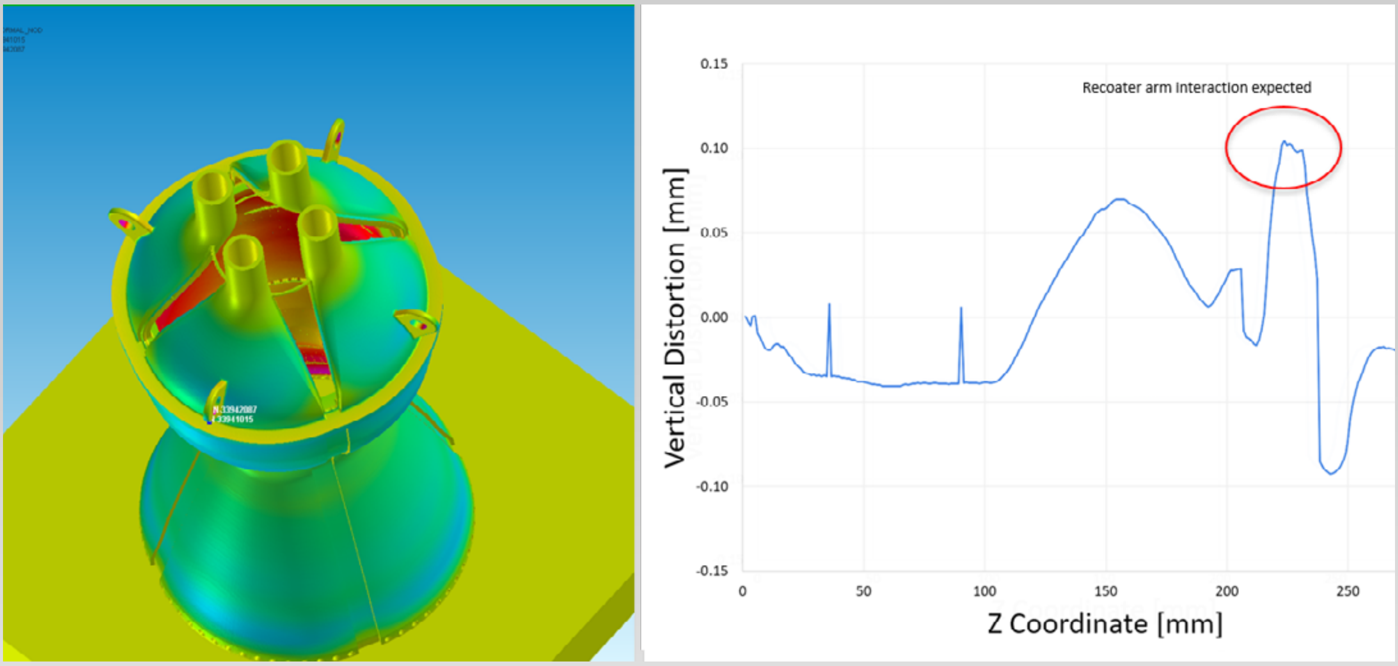
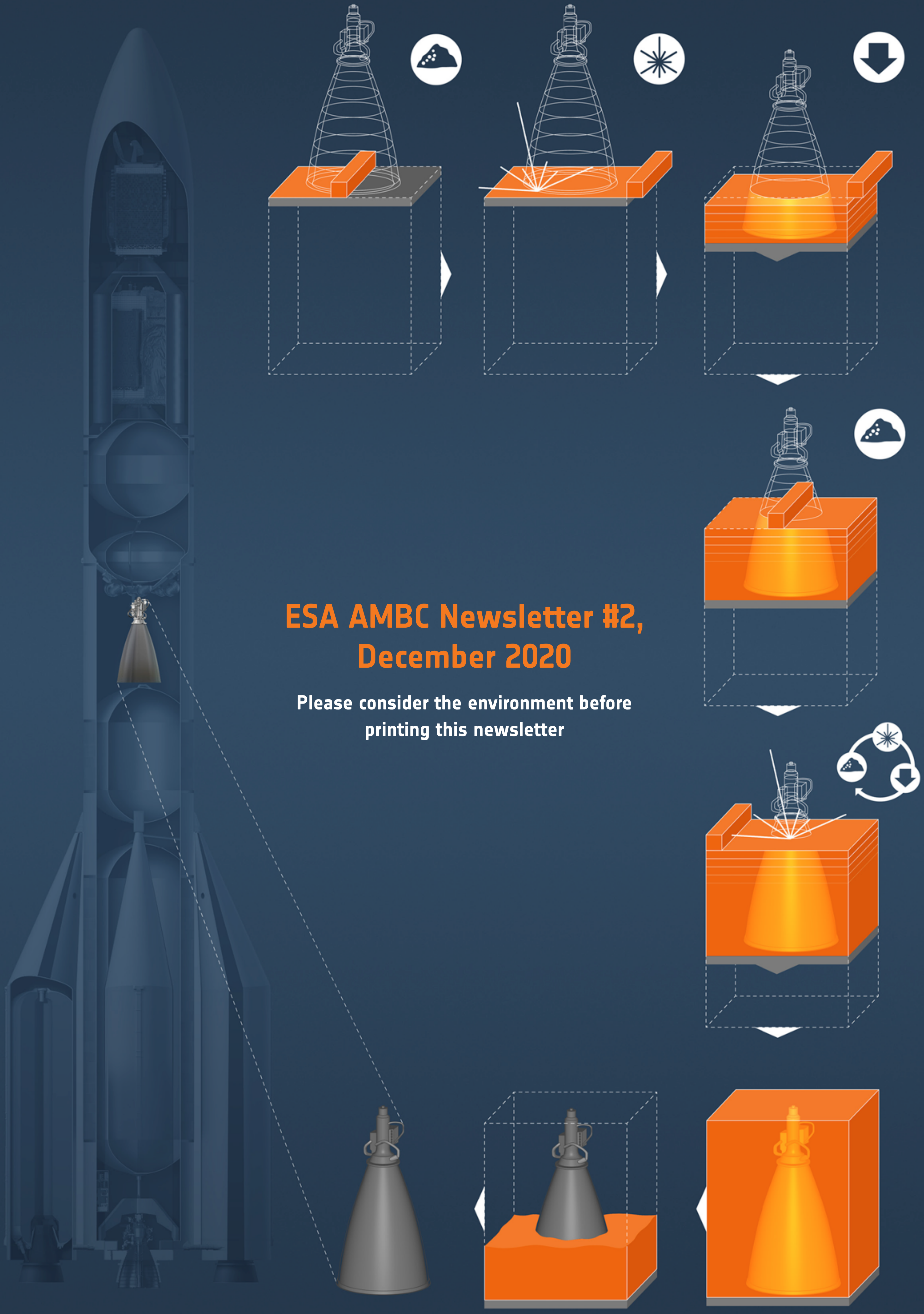


Figure 22

Prediction of vertical distortion during build using ESI AM build simulation software



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