EXECUTIVE SUMMARY REPORT

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Assessing the use of advanced manufacturing to improve and expand space hardware capabilities

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Compiled by:	J. Meuthen
Reviewed:	E. Neubauer
Approved:	
Authorized	

Based on the roadmap of additive manufacturing made by ESA there are a couple of topics for technology development and technology demonstration within the next years which are linked to large sized structures (e.g. > 1 meter)

Additionally, space applications require most of the time a small number of parts and therefore lead time and costs are issues. Wire feed or blown powder based Direct energy Deposition (DED) processes like RHP's Plasma Metal Deposition (PMD) are candidate technologies for those applications, because no semi-finished products are needed, the building platform is scalable and in any case 1.5m x 1.8 m is a scalable at the .moment and the investment is low compared to laser based DED processes

Therefore, this study had a focus on the demonstration of a high building rate processes for additive manufacturing of Ti6Al4V structural parts. As a perfect candidate, the optical bench for the ATHENA mission has been chosen

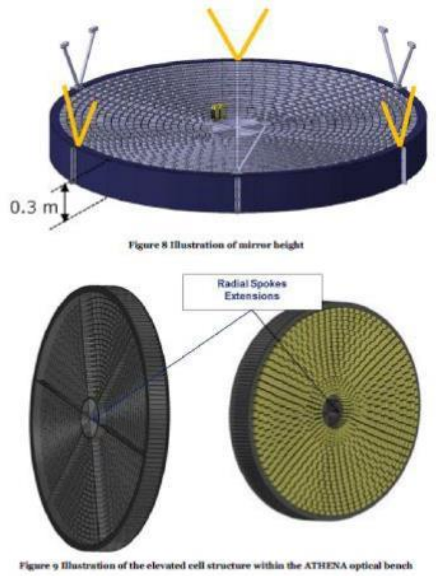

Figure 1 Optical Bench (ATHENA) with 3 meter diameter (ESA ITT TRP T224-004QT).

The main objective of this study was to manufacture "structural models" with a size of approx. 500 mm in size in order to demonstrate the capability of the plasma metal deposition process. In addition to that the study was allowing RHP to develop the strategy and process for additive manufacturing of "space relevant" components. Therefore, objectives have been defined:

1 Based on the given design of the optical bench a representative test structure will be extracted including the main features of the ATHENA optical bench (changes in wall thickness, areas for holes for mounting etc.) with size of >0.5 m.

2 Extract from given design the best building strategy (based on the design of the "test structure, the building strategy will be derived.) with a buy to fly ratio of less than 1.5:1.

3 Planning of the machining strategy: in order to ensure that the part after building can be manufactured/finished by milling operations a "virtual machining" of the component will be done.

4 Building of components using well defined raw materials: RHP will use the baseline process developed in the past. This will include one process using powder as feedstock and using wire as a feedstock.

5 Control of building process – Monitoring includes height control of the building process and recording of process relevant parameters (powder feeding rate/wire feeding rate; current, gas flow etc) with a targeted building rate of > 5 kg/hour , but priority is on control of properties

6 Secondary processing; including heat treatment; heat treatment of the component will be performed to apply a stress relief

7 Machining of components. Machining of the component will be done by milling

8 Extraction of samples for mechanical testing will done by EDM machining. Targeted material properties are: Tensile strength > 950 MPa; RP02: >800 MPa and > 8 % elongation)

9 Metrology of the component at different steps (after building, after heat treatment, after machining): Tactile processes will be used and compared with 3D scanning methods.

10 Quality control using destructive and non-destructive testing (NDT); within the study several test structures will be prepared. Within this study full NDT of the component will not be considered but for correlation of properties, microstructure additional NDT using a CT scan will be used.

11 microstructural samples will be extracted and investigated by NDT (ultrasonic inspection) followed by mechanical testing and microstructural analysis

12 Documentation of the manufacturing process chain and assessment: this includes the documentation of the manufacturing process, machining process and analysis process. Additionally, a cost assessment will be made ("determination of the buy to fly ratio").

To achieve those objectives, for each of the wire – and powder based process 3 structural models have been built The first to extract samples for destructive testing from the unmachined part and to test the building strategy, the second to test machining and verify the results from destructive testing and finally the third structural model to be fully machined as part to display and verify the machining strategy.

Definition of “structural model” and planning of “end-to-end” manufacturing

In a first step different features of the optical bench have been derived and a CAD model has been created. Subsequently the near net shape geometry (Figure 2) that was built later on by PMD have been elaborated followed by the building strategy including toolpath. Furthermore a machining and testing strategy have been elaborated The planning is summarised in the flow chart (Figure 3).

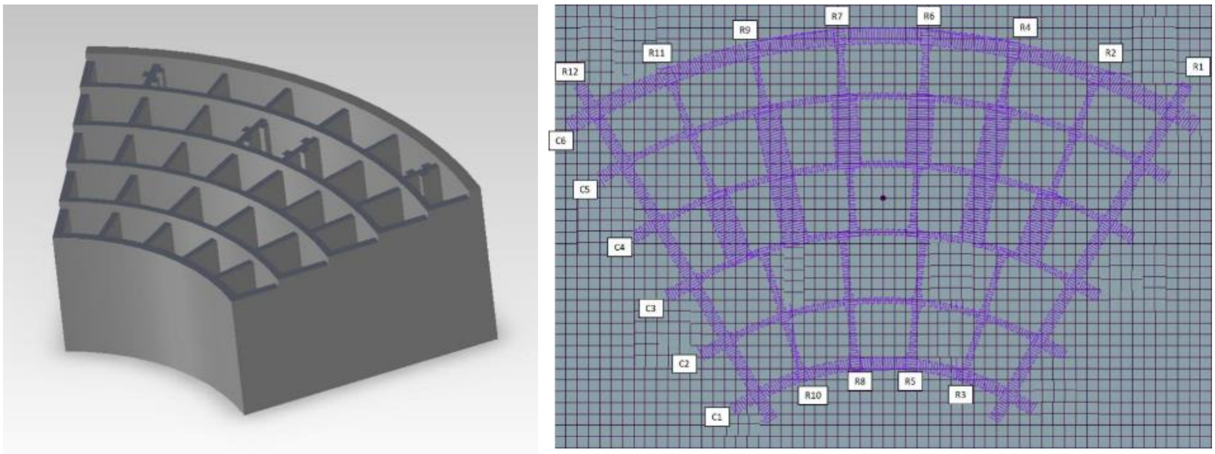

Figure 2 Derived near net shape geometry (left) and tool path

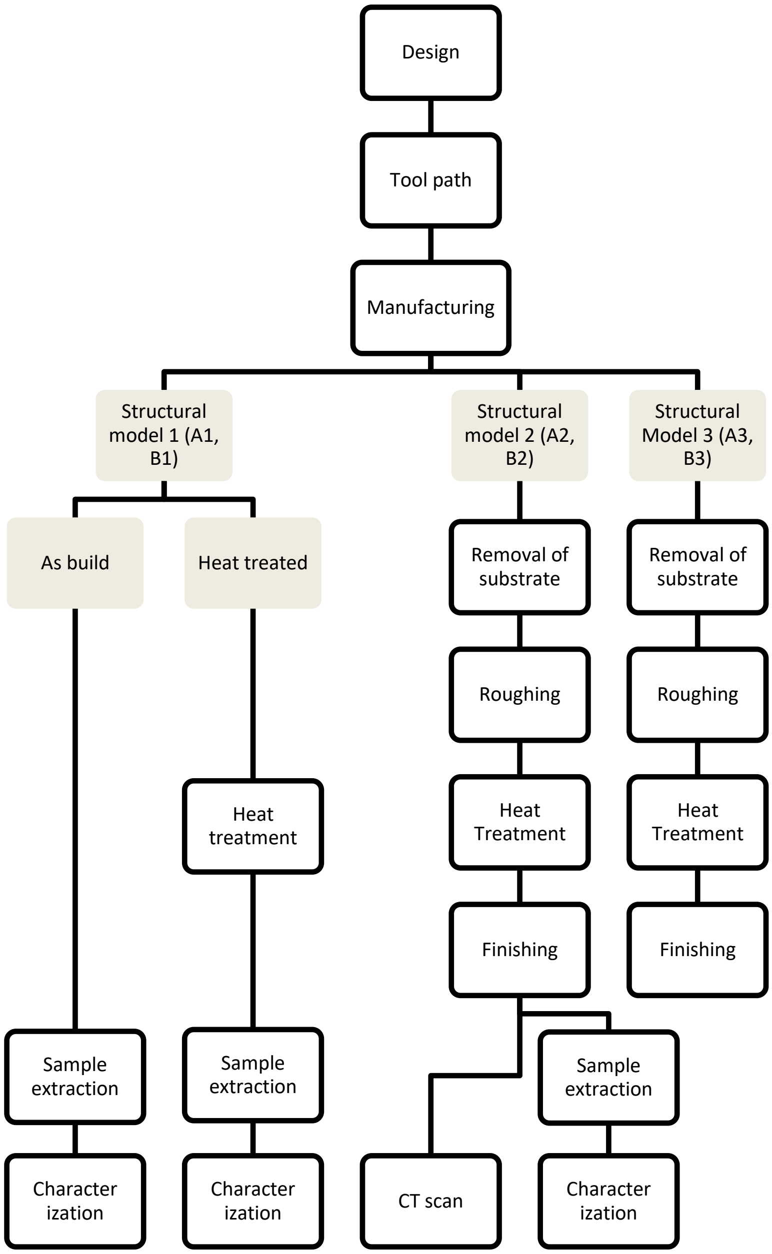

Figure 3 Planning flow chart

Manufacturing of "structural models"

Before manufacturing the structural models subsize models have been built to access the building strategy on a smaller scale. As shown in Figure 4

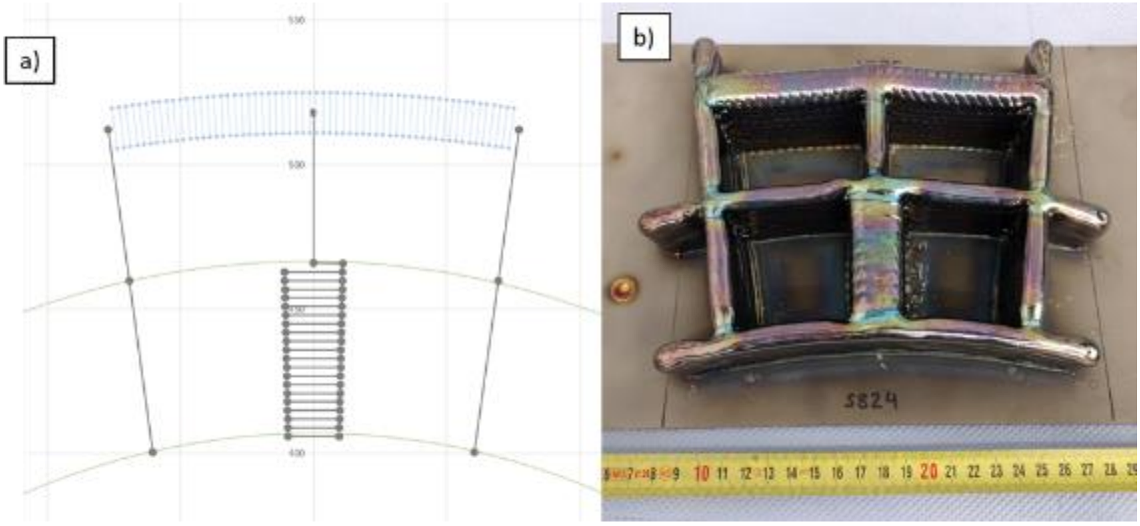

Figure 4. Subsize model: Toolpath and build part.

Based on the manufacturing plan 6 structural models have been build. In Figure 5 the additive manufacturing is shown for a wire based part. In Figure 6 a powder – and a wire based structural model are shown as finished near net shape part.

Figure 5 Building of structural model

Afterwards the baseplates were removed and the parts were heat treated to relief stresses. Only a part of the first model were not heat treated to compare mechanical properties in as build conditions with heat treated conditions.

Figure 6. Finished Structural Model powder based (left) and wire based (right)

The models have been removed from the substrate before or after heat treatment by band-sawing. A “high speed milling “ process was used that allows to mill with less forces.

To mill fast, on the top surface up to 2 mm of material has been removed in a roughening step as shown in Figure 7. After the part is fully machined, the part has a shiny surface as shown in Figure 8 for a fully machined model.

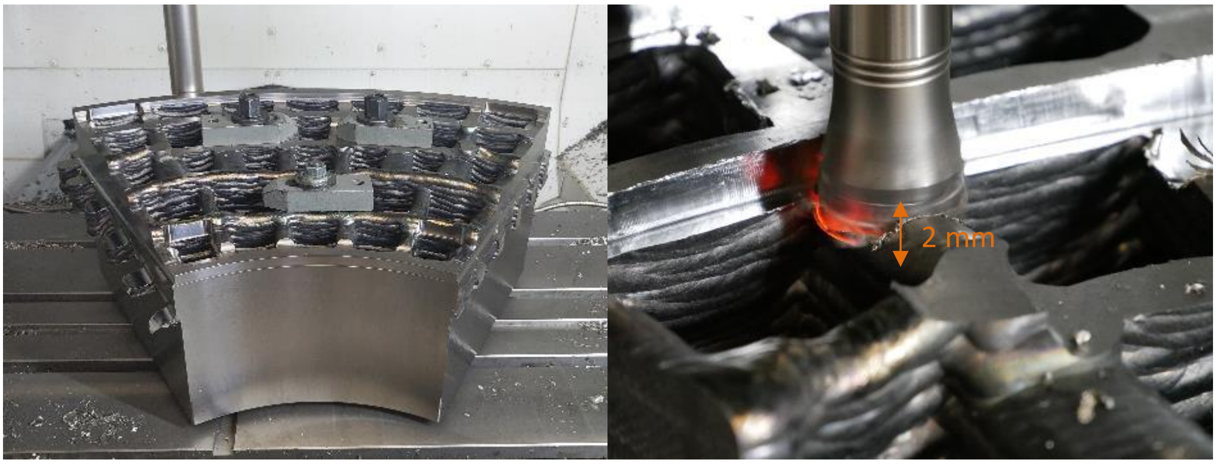

Figure 7 Machining of Model B3 top and outer structure with high rates

Figure 8 Fully machined model

Analysis and lessons learned

The mechanical testing turned out that the wire-based demonstrator shows better elongation properties than powder-based demonstrator, on the other hand, the highest UTS values are obtained in samples extracted from the powder-based model as shown in Table 1 with averages for each model.

Table 1 Average UTS and Strain at break of model A1/B1 in as built and heat-treated conditions

Model	UTS avg. [MPa]	Strain avg. [%]
Model A1 ab	958.69	8.20
Model A1 HT	979.79	7.90
Model B1 ab	923.91	9.22
Model B1 HT	939.28	10.51

After the heat treatment, wire-based samples improve elongation in average without having a loss in UTS. On the other hand, UTS of powder-based samples improves in average with a decreasing on elongation after applying a heat treatment, see **Figure 9**. Samples with bad properties in elongation or UTS are showing defects like poor interlayer connection or lack of material on crossing points. The explanation of the increment of UTS on powder-based samples after heat treatment can be explained as the interstitials (such as Nitrogen or Oxygen) diffuse into the matrix during the heat treatment making the material stiffer.

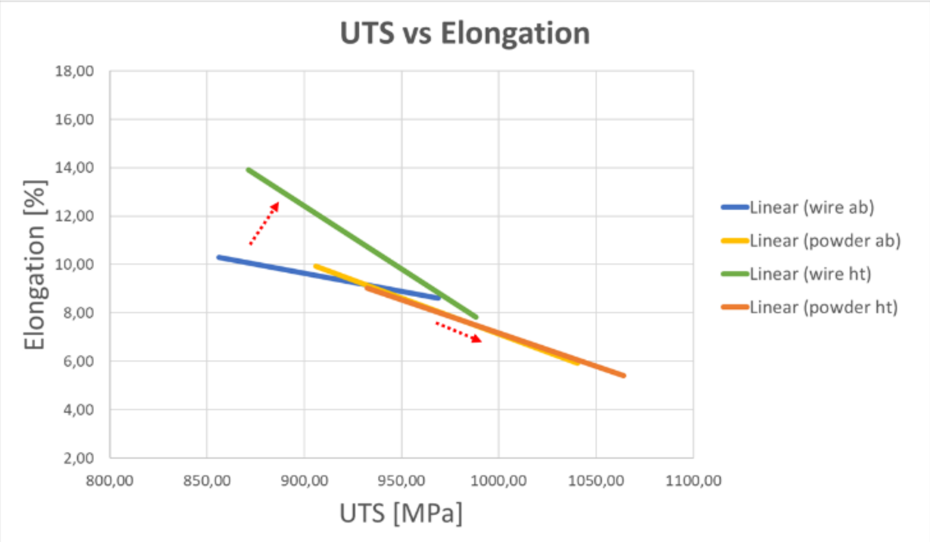

Figure 9. UTS vs elongation.

The macro- and micro-structure of as built and heat treated models have been tested on sample base. The macrostructure of both wire and powder based process are similar. In the top view cross-section of prior β-grains growing columnar almost parallel to the build direction (z-direction) reveal as shown in Figure 10. These grains grow across deposited multilayers and they grow epitaxially from the grains of previously deposited layer due to the similarities in the composition and surface energy. The as built samples show the typical acicular α´ martensite microstructure.

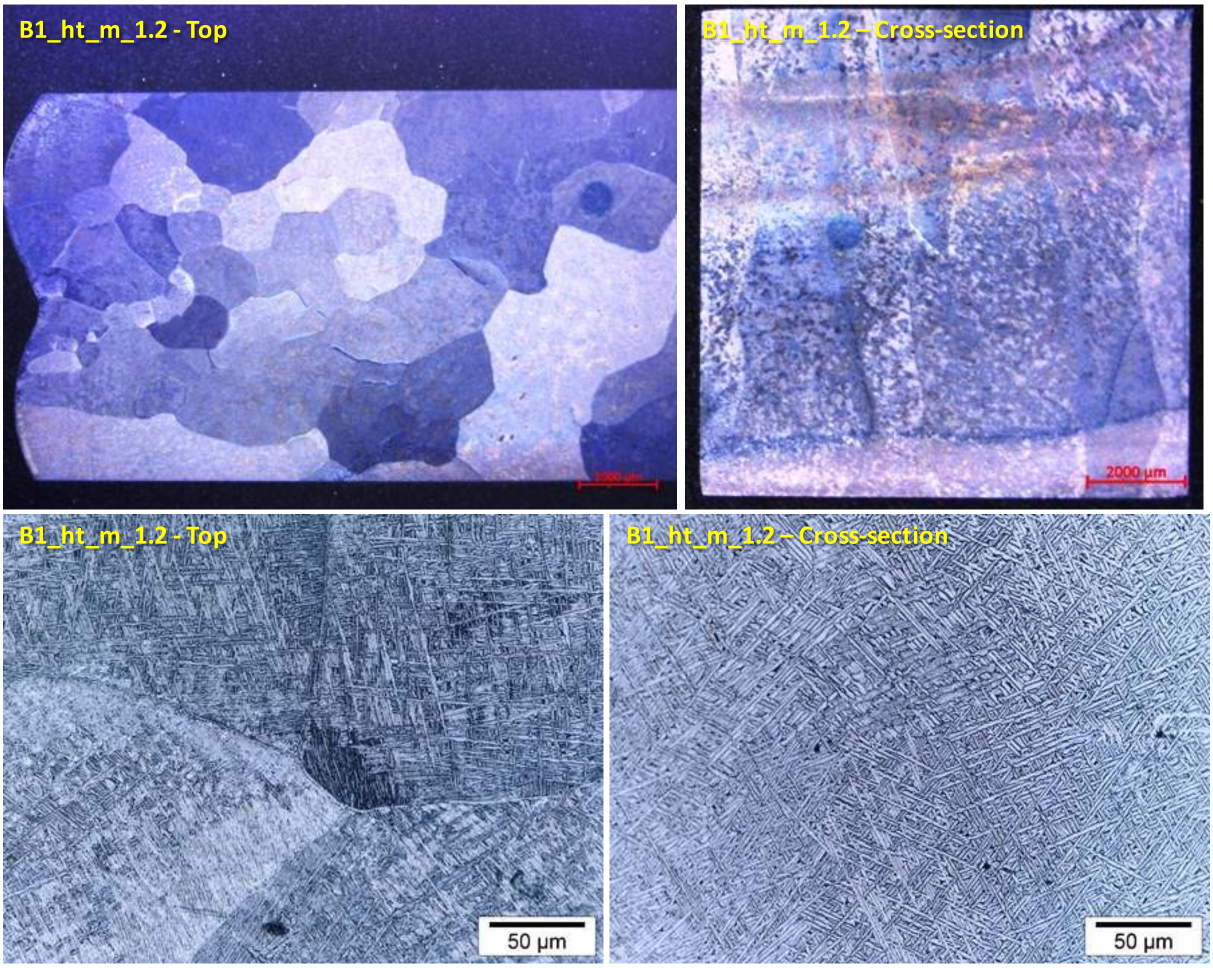

Figure 10 Optical micrographs of the top surface and cross-section heat treated Ti64 specimen extracted from wire based model

Due to the large size of the part in combination with the power of the x-ray source it is not possible to reconstruct the surface for metrology. Nevertheless, cutaway views of the part give an insight. It is possible to identify voids in certain areas. In some t-nodes voids in every

2nd layer appear as well as in the bottom area (Figure 11) that are related to a not optimal building strategy. In Figure 12 a plane free of defects is sown. Apart from voids that can be correlated to building strategy the material is fully dense.

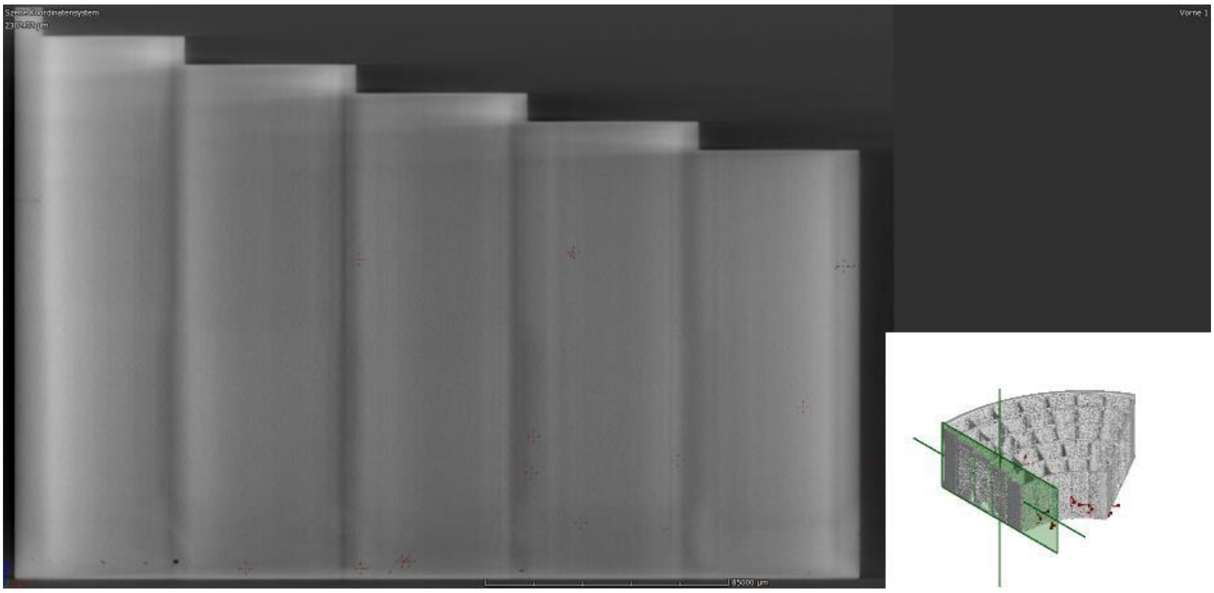

Figure 11 Cu-away view of side wall. Defects in bottom area.

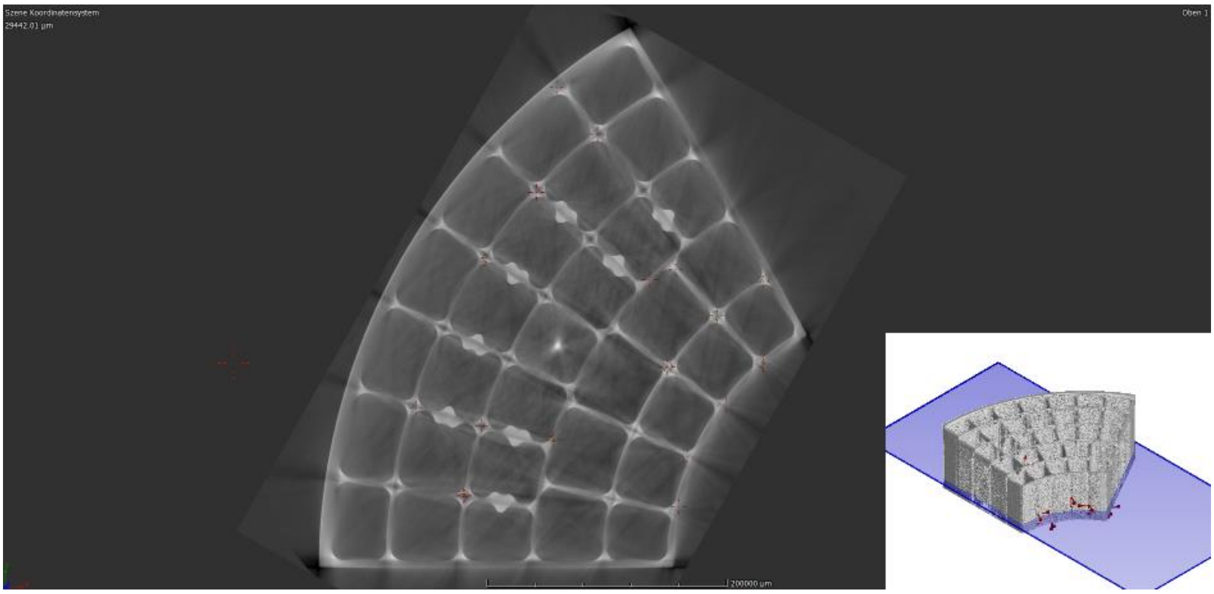

Figure 12 Cut away view of x-y-plane without defects.