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SHARE4.0

WORKPACKAGE REPORT

WP3.3 – SUSTAINABLE, RESILIENT PRODUCTION SYSTEMS

Version 1
FOTEC – Ackerl / Braunstorfer
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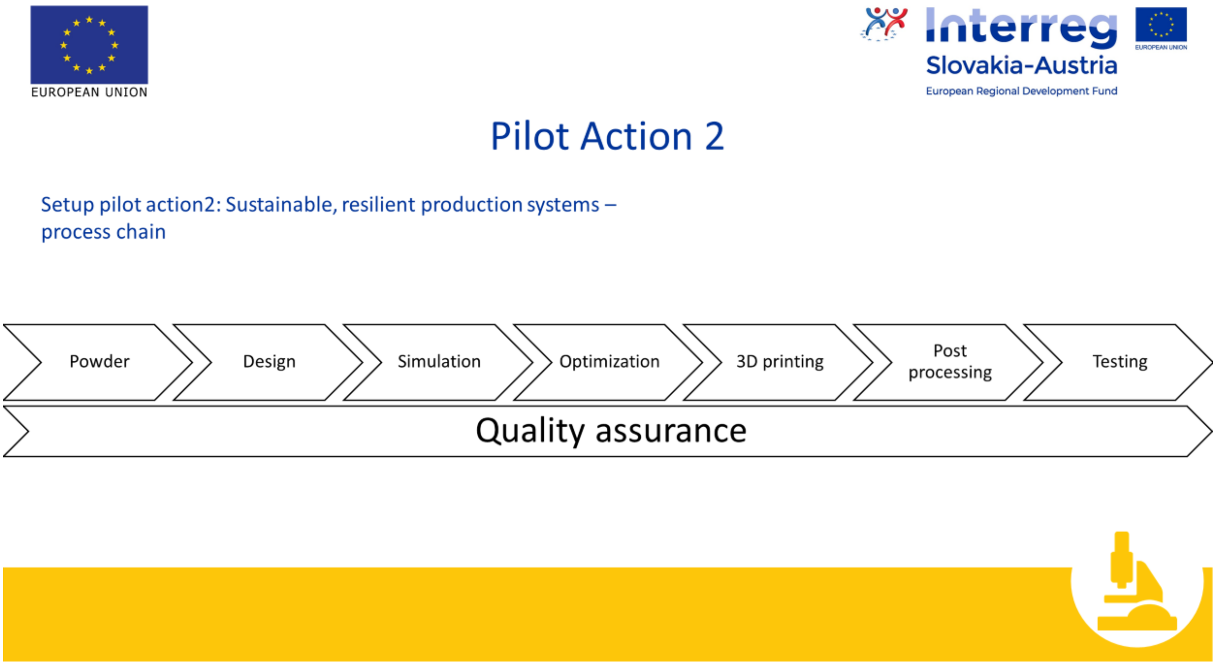
Table of contents

1 Introduction

One of the most important facts about 3D printing is that additive manufacturing is generally not a replacement for subtractive or formative manufacturing, but a complement to it. For example, it does not make sense to additively manufacture mature and conventionally mass-produced products, such as nails or screws. This statement naturally begs the question, "When does it make sense to use additive manufacturing for part production?"



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Pilot Action 2

Setup pilot action2: Sustainable, resilient production systems – process chain

Powder → Design → Simulation → Optimization → 3D printing → Post processing → Testing

Quality assurance

1.1 Application fields of additive manufacturing

As already mentioned, additive manufacturing should not be seen as a competitive process, but rather as a supplement to conventional manufacturing and has its justification for existence because added value can be created in many cases. The added value can mostly be divided into one of four subgroups:

- Lightweight construction (topology optimisation, bionics, etc.)
- Function integration (heat sinks, coupling, texture on the surface, etc.)
- Monolithic construction (reduction of individual parts, ideally 1 piece)
- Acceleration of production development (verification of simulation, haptics, etc.)

The advantages of additive manufacturing lie mainly in the following points:

- Components with a high degree of complexity can be manufactured.
- No special tools or fixtures are required for production.

- Geometry changes can be implemented quickly.
- Efficient processing of raw materials with significantly reduced waste.
- Components made of difficult-to-machine metal alloys can be produced (titanium).

The disadvantages of additive manufacturing lie mainly in the following points:

- High reworking costs if certain tolerances or surface finishes are required.
- The process is slow and expensive, as printing is only economical when the build platform is working at full capacity. Printing times of several days are not uncommon.
- The choice of materials is limited to a few metal alloys available on the market and, above all, also dependent on the process technology.
- No plug & play technology (especially in the area of metal 3D printing).

2 Process criteria for each development step

The individual development steps are listed in detail below. Quality assurance extends over the entire development process. For this reason, the respective quality assurance measures are listed in the respective development step.

- Choice a component for application or development

According the design (e.g. thickness of walls) and the usage (area of usage) of the component will be estimated the suitable powder (pre-alloyed powder)

-Selection of the powder (pre-alloyed powder)

Chemical composition

Suitable for 3D printer

2.1 Powder characterization

The powder forms the basis of the finished part. For this reason, several parameters must be clarified before the powder is selected, to choose the ideal material for the application. The necessary parameters include, for example:

- Application temperature
- resistance to chemicals
- mechanical properties in relation to the allowed mass
- thermal expansion
- etc.

As with conventional production, it is therefore crucial to know the exact application of the component in order to select the ideal material.

Quality assurance in the Powder segment takes place over several stages. First, only powder that meets certain properties should be used. This applies to a new filling of the machine, but in particular to the supplementing of an existing powder batch with new powder. If the quality here is insufficient and has an influence on the component quality, the existing powder must also be disposed of, because no more qualitative components can be produced. In principle, there are several ways in which the quality of the powder can be analyzed, and the quality assurance methods used at FOTEC are listed below.

2.1.1 PSD (particle size distribution)

Particle size distribution is performed to ensure that the spectrum of particle sizes is within a defined range. This is necessary because larger powder particles require more energy for the melting process than small particles. Because all particles must be completely melted, the energy input would have to be increased to melt larger particles as well. As a result, either the laser power would have to be increased, or the scanner speed would have to be reduced, resulting in a longer build time. In addition, increasing the energy input can lead to overheating of the melt pool. In addition, too large powder particles would cause problems during coating, because the particles would be larger than the distance between the component and the coater. As a result, the smaller particles would be processed into components, and the proportion of particles that were too large would become more and more.

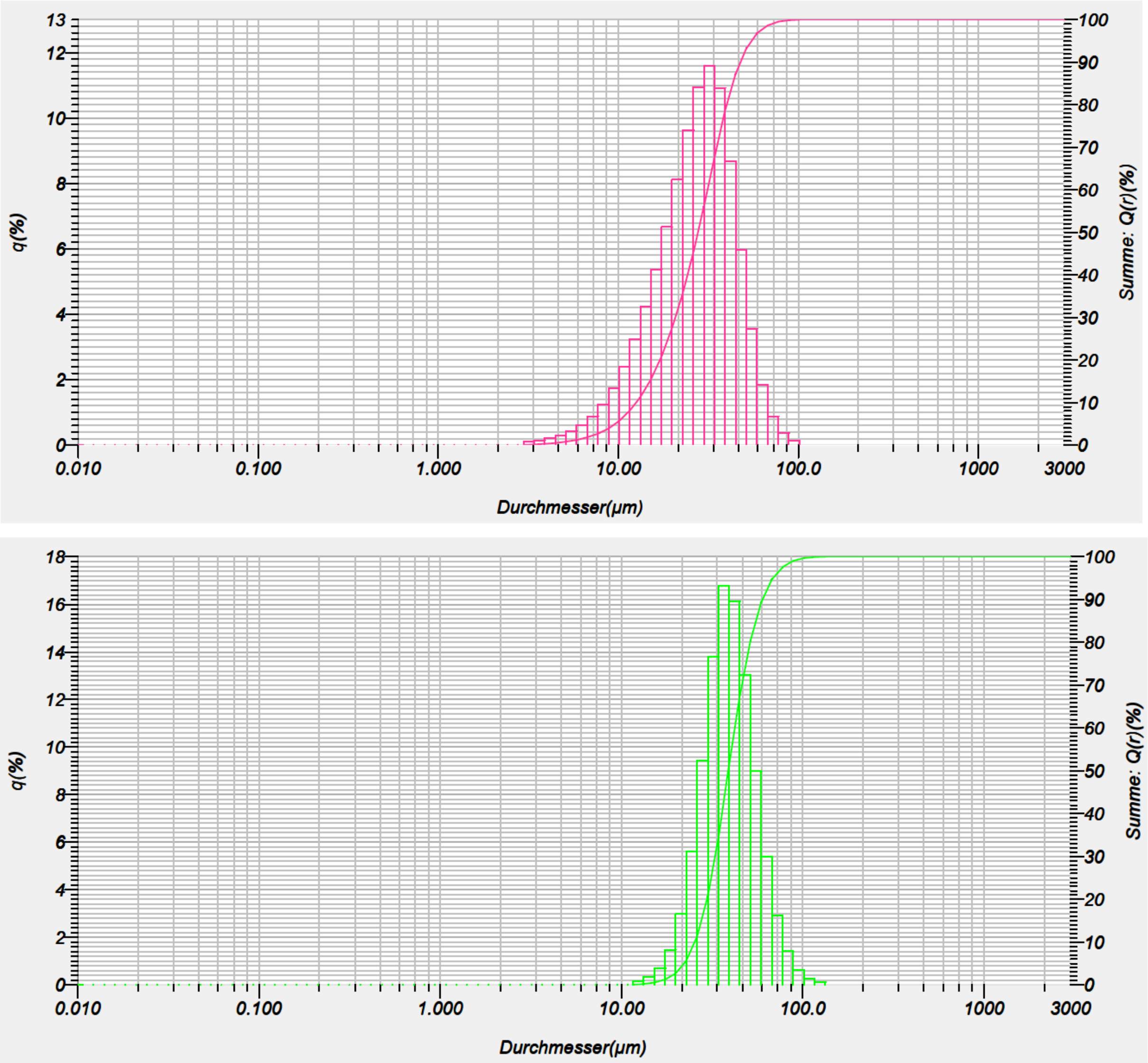

Figure 1: PSD results @ FOTEC (©FOTEC)

2.1.2 SEM (scanning electron microscope)

With the SEM it is possible to analyze the geometry of the powder particles. These have a great influence on the fusibility and the deposition behavior of the powder. In principle, spherical particles without adhesions are the target. The SEM is an ideal complement to the PSD, since no conclusions can be drawn about the shape of the particles from the particle size distribution. Via SEM are possible observed defects in powder particles and if SEM is equipped with Energy dispersive spectroscopy (EDS) are possible performed chemical analyses for verification of chemical composition and identification of possible in purities into powder or on the surface of powder particles

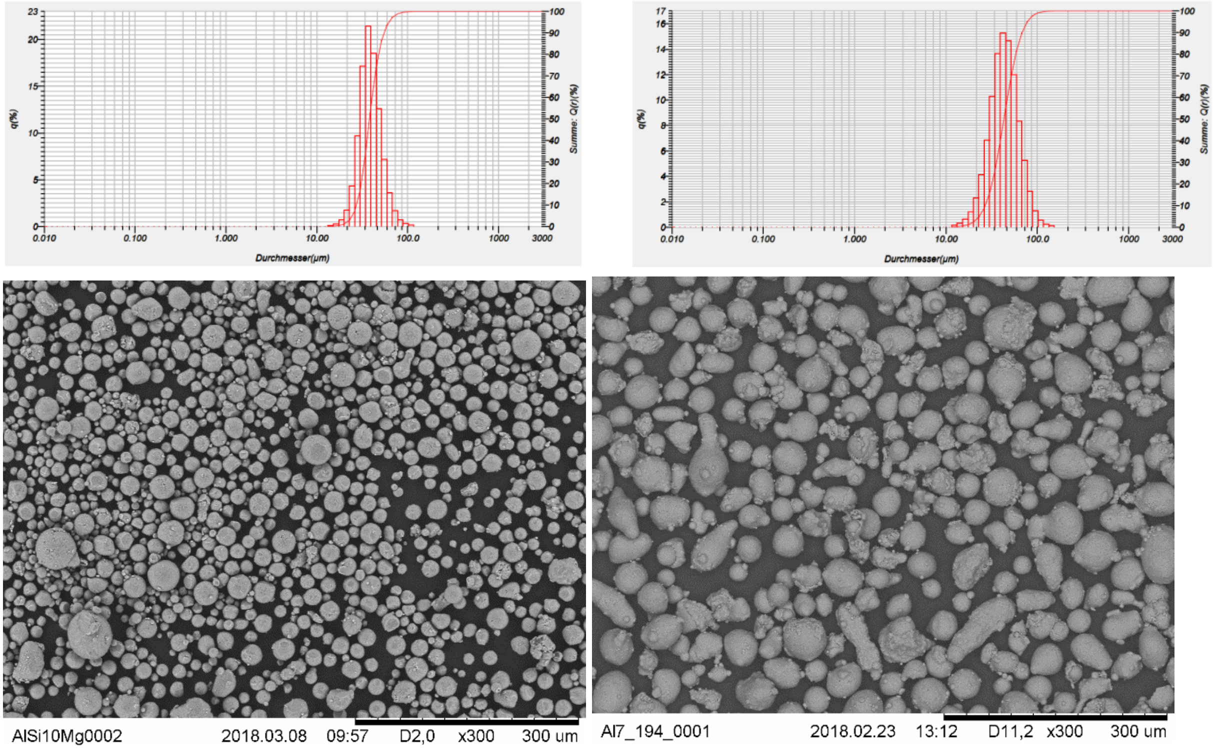

Figure 2: SEM measurements of PSD powder batches (©FOTEC)

Pre-alloyed powder Ti6Al4V was choosing for analyses and possible 3D-printing for suitable morphology of powder and powder size and shape. PSD result about size of powder particles and morphology is shown in fig.3.

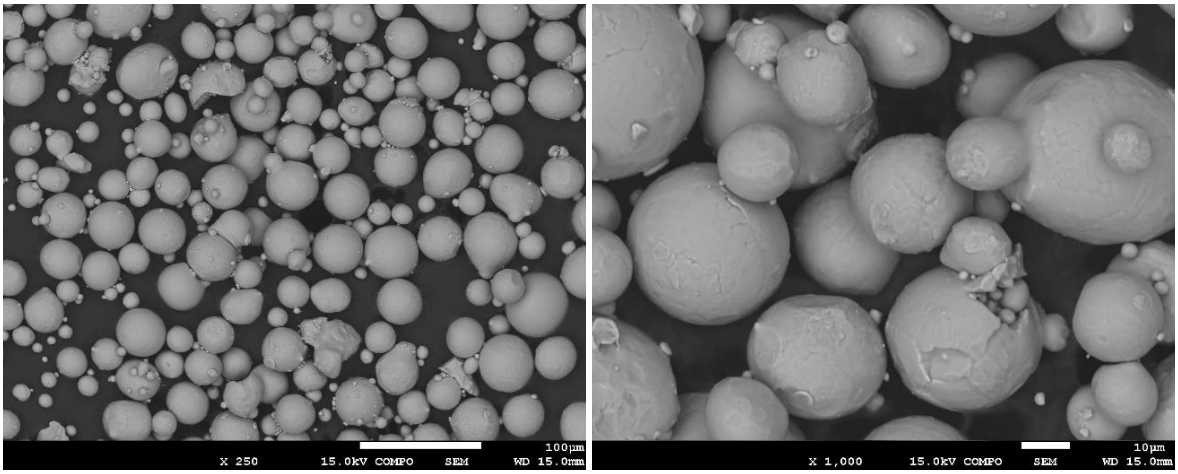

Figure 3: Morfology of pre-alloyed powder at different magnification (IMMM SAS)

Spectrum	Al	Ti	V	Total
1	5.46	91.20	3.35	100.00
2	5.87	90.76	3.37	100.00
3	6.20	90.12	3.68	100.00
4	7.38	89.55	3.07	100.00
5	6.64	89.89	3.48	100.00
6	7.54	89.02	3.45	100.00
7	6.16	90.36	3.48	100.00
8	5.86	90.51	3.63	100.00
Mean	6.39	90.18	3.44	100.00

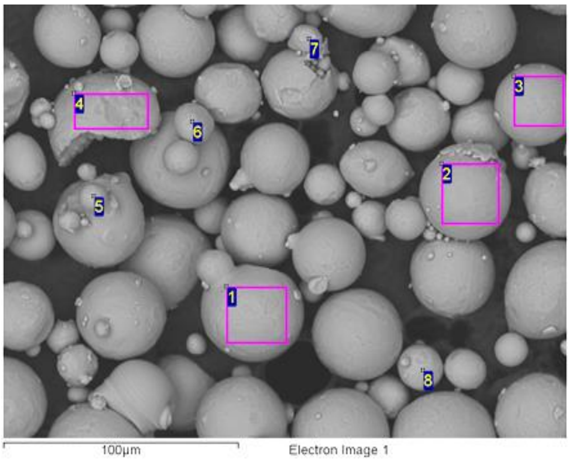

Figure 4: EDS of chemical composition on the pre-alloyed powder surface (IMMM SAS)

Via SEM was observed differences in powder particles with most spherical shape. Powder particles have on surface significant amount defects in the form of smaller particle (satellites). Also, was observed powder particles non-regular shape with surface defects. Chemical composition corresponds to chemical composition according technical list. Except EDS performed on the surface of powder particles was measured in cross-section of the powder particles. The chemical composition from cross-section fig.5 is comparable to chemical composition from the surface fig.4 of pre-alloyed powder Ti6Al4V. From SEM images on fig.4 are possible observed defects (pores) in powder particles.

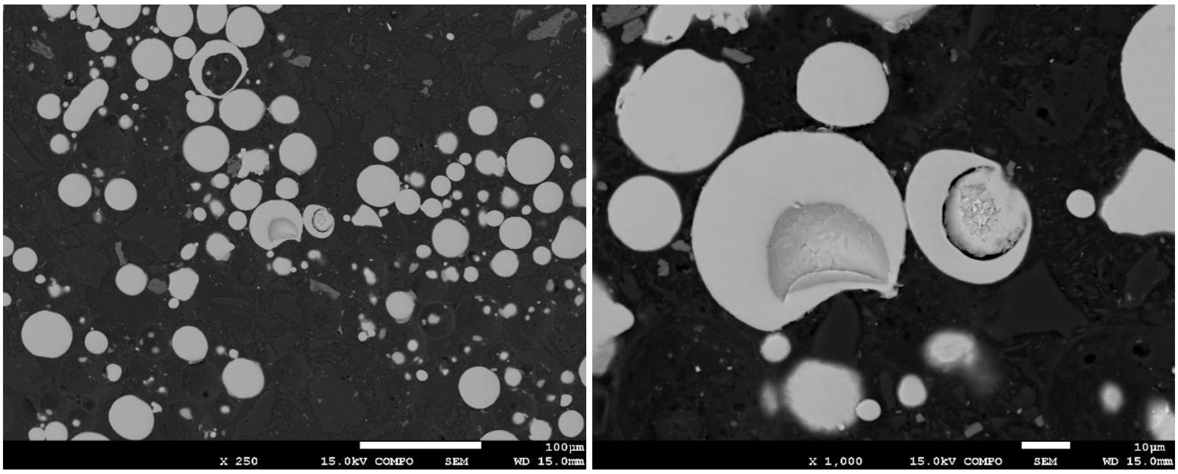

Figure 5: SEM images of cross-section on the pre-alloyed powder (IMMM SAS)

Spectrum	Al	Ti	V	Total
1	5.95	90.67	3.38	100.00
2	6.22	90.63	3.15	100.00
3	5.77	90.76	3.47	100.00
4	5.69	90.81	3.50	100.00
5	6.37	90.21	3.42	100.00
6	6.33	90.25	3.41	100.00
7	5.99	90.76	3.24	100.00
8	6.21	90.48	3.31	100.00
Mean	6.07	90.57	3.36	100.00

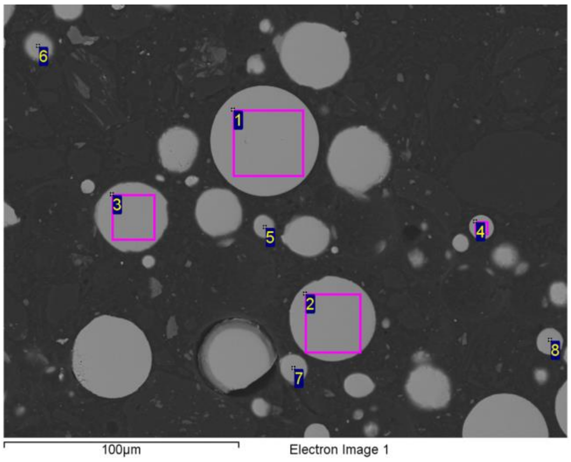

Figure 6: EDS of chemical composition on the pre-alloyed powder in cross-section (IMMM SAS)

Powder particles observed in cross-section shown defects into particles. Defects are observed into particles bigger than 15µm. In some particles observed in cross-section was find thin oxides layer analyzed by EDS elemental mapping (line-scan) see in fig.7.

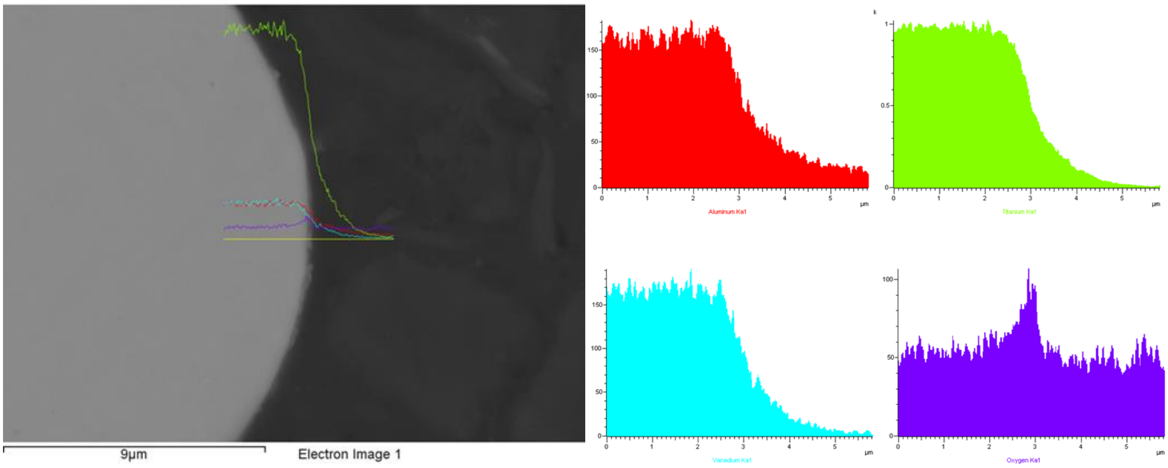

Figure 7: Linescan of chemical composition on pre-alloyed powder in cross-section

Pre-alloyed powder particles are most spherical with satellites on the surface. Some amount of particles has non-regular shape with surface defects. Particles above 15µm contain cavities also was Therefore printing parameters will by most important for achieved walls of component without porosity or others defects as roughness of walls. 3-D Nano tomography will be used for this observation.

2.1.3 Moisture Measurement

Powder moisture is a critical point, which has a great influence on the processability of the powder. If the powder is too moist, the flowability is drastically reduced. The flowability is critical in the coating process, because poor flowability is caused by the powder particles sticking together, which is also noticeable during coating. For this reason, it is very important to record and track the powder moisture. It is also recommended to check the powder moisture again, when a powder is stored for a longer period of time, because the powder may have absorbed moisture from the humidity in the air.

2.2 Design

Components produced by Additive manufacturing technologies have special properties due to the layer construction principle:

- The layer geometry is generated directly from the CAD data.
- No use of product-specific tools necessary.
- Mechanical properties are generated during the building process.
- Components can be built in any orientation (no clamping problems during production). Caution: In mechanical reworking, the clamping strategy is very important.
- Machines on the market can be controlled with the same data set (STL).

These properties have also an impact on the cost side of a project. The following figure illustrates several circumstances very clearly. On the one hand, component costs are by far not as significantly influenced by geometric complexity as is the case with conventional manufacturing. The figure also clearly shows that, from a cost perspective, simple components should be manufactured conventionally. Additive manufacturing shows its strength in the case of more complex components, since above a certain level of complexity it is cheaper than conventional manufacturing and can produce components that cannot be manufactured conventionally.

On the other hand, the initial production costs are significantly lower than with conventional manufacturing. No part-specific tools or molds are required. In addition, preparing the data from the 3D model to the layer information for controlling the process is much faster and easier than creating a CNC program for a milling machine or lathe. This circumstance results in the graph on the right, in which is illustrated that the production of a single component or components with small quantities is often significantly cheaper than conventional production. In addition, there is almost no difference whether 10 identical or 10 individualized components with similar dimensions are produced.

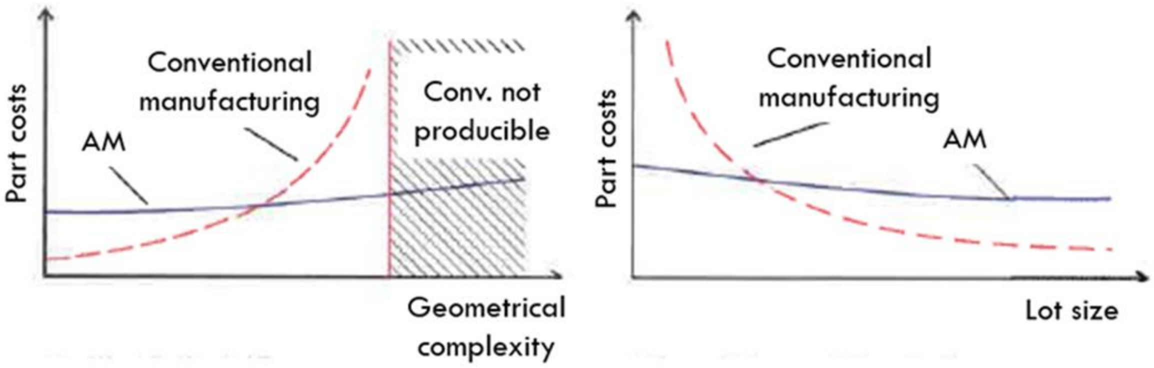

Figure 8: Part costs vs. Geometrical complexity and Lot size (©ETHZ pd|z)

The properties above result also in specific characteristics in the additive manufacturing process which will be described further down the line:

The **anisotropy** of materials describes the direction dependence of their mechanical properties. The position of the individual layers in relation to the loading direction, which are determined by the position of the component on the building platform, are crucial for the possible loads in the corresponding space directions.
Taking tensile test specimens as an example, it can generally be said that specimens built upright usually exhibit poorer mechanical characteristic values than specimens built lying down.

The **support structures** (or auxiliary geometries) fulfill various process-relevant tasks in the additive manufacturing process. Mainly, they are necessary to ensure mechanical stability, heat transfer and the prevention of deformations.
The necessity as well as the type and characteristics of support structures depends on the additive manufacturing process as well as on the component itself. The increased material requirements, longer production times and the often time-consuming process of removing the support structures after the manufacturing process cause costs and effort, which must be minimized.
Two possible solutions can be mentioned here (see Figure 9):

- Re-design of the component by changing holes to teardrop shapes as well as by adding angles instead of jumpy edges.
- Changing the orientation of the part on the build platform to reduce the need for support structure.

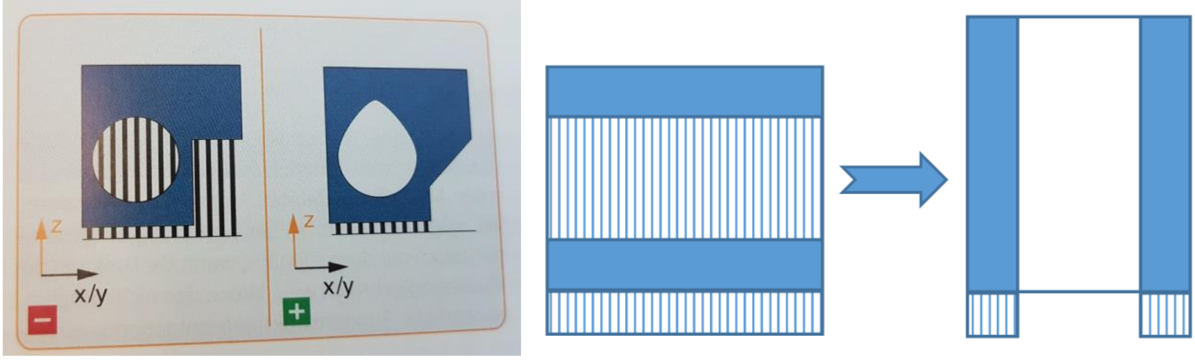

Figure 9: reduction of supports by 2 solutions - Left: Re-design of component(© Leutenecker-Twelsiek 2018); Right: orientation change of the part (©FOTEC)

The effects of angled support-free areas on components with different opening angles to the building platform are illustrated in Figure 10. It can be seen that clearance angles below 45° can only be realized with a noticeable reduction of the surface quality up to obvious defects on the component.

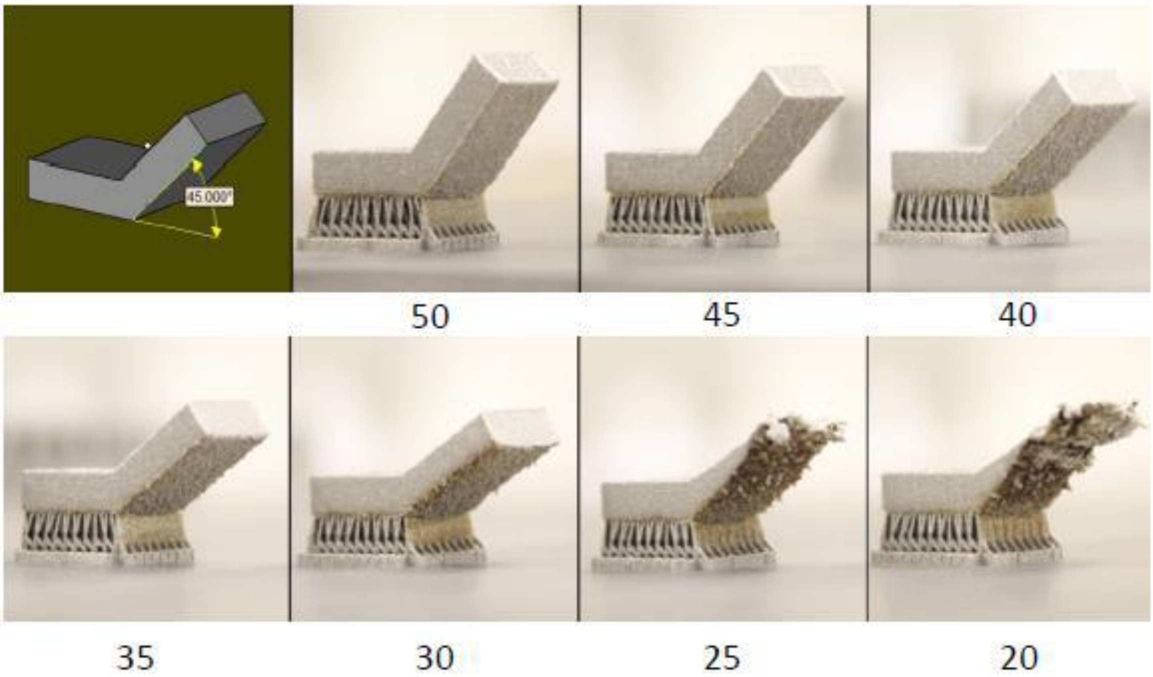

Figure 10: effects of different clearance angles (©FOTEC)

Residual stress induced **warpage** reduces the dimensional accuracy of the part and can lead to rejects or high rework costs. In more extreme cases, warpage causes the termination of the building job. To prevent this, the designer should counteract warpage as early as possible in the CAD design. Adjustment is only possible if the function of the component is not affected or is only affected to an acceptable level. The abrupt increase of surfaces in the build direction should therefore be avoided.

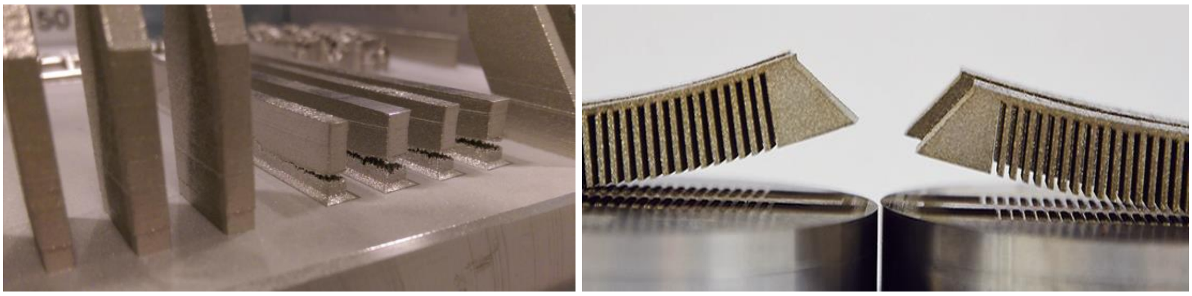

Figure 11: effects of residual stress induced warpage (©FOTEC)

Four possible solutions can be mentioned here (see Figure 12Figure 9):

- Re-design of the component
    - Slopes (at least 45 degrees) for more stability (or less support material)
    - install Supports which stabilize each other
    - Thin-walled structure is an advantage

- Pre-deforming through simulation: warpage is measured using special test build jobs and the CAD model is deformed accordingly
- Laser parameters and exposure strategy
    - Use of chessboard exposure
    - More homogeneous temperature distribution for large components
- Solid support structures and heat treatment
    - Reinforcement of support structures by anchors
    - Increase of temperature and duration of heat treatment in post processing

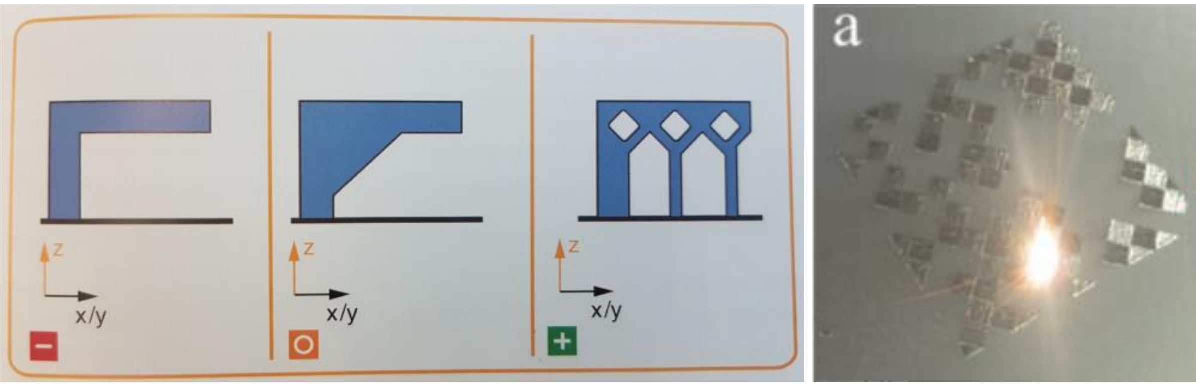

Figure 12: reduction of residual stress induced warpage by 2 solutions - Left: Re-design of component(© Leutenecker-Twelsiek 2018); Right: use of chessboard exposure (©FOTEC)

In most additive manufacturing processes, the raw material (powder, liquid) is applied layer by layer in the entire build space and then material cohesion is selectively created in the intended areas. The non-solidified material is called **residual material**.

Depending on the technology, the residual material can be reused in its entirety or, as with SLS (selective laser sintering for plastics), 50 percent of it must be refreshed.

It must always be ensured in the design that residual material (e.g. metal powder) can be removed from channels or cavities after printing. For this purpose, e.g. cavities are provided with a hole in order to be able to remove material residues.

Determining the component orientation in the build space of the AM machine and thus also determining the assembly direction has a considerable influence on quality, dimensional accuracy and surface finish as well as costs and function due to the layer-by-layer production and the support structures that are slightly necessary as a result.

The procedure of determining the component orientation only after the CAD design is still acceptable for prototype construction, since there the component is usually not designed for additive processes.

In the additive manufacturing of functional components or even series production, this is not effective, as a design iteration often has to be carried out again after the orientation.

Although the components for additive manufacturing are often significantly more complex than those for conventional manufacturing due to the large scope for design, the possibility of subsequent (mechanical) **reworking must be ensured** through design measures. In many cases, the complexity of components makes it difficult to clamp them precisely due to the lack of parallel surfaces for clamping (see Figure 13). It also often happens that the structure of the component is too delicate for the pressure of a machine vice.

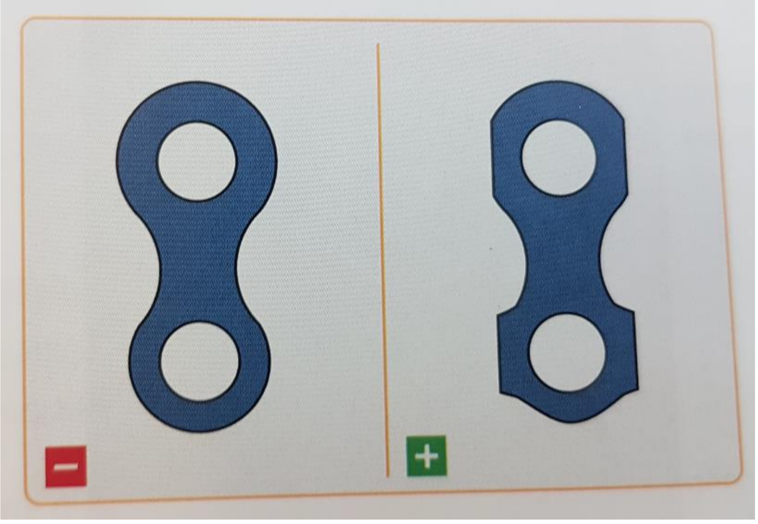

Figure 13: parallel surfaces are necessary for clamping of AM components

2.3 Simulation

The design freedom of the LBM allows to use material only where it is necessary to support the expected load cases. With a more complex design area and mixed load cases, it is often not obvious where how much material is needed and whether the current design can handle the expected loads. For this reason, there are several simulation software vendors that address this problem. The user has to define the connection points to other components as well as the expected forces, moments, temperatures, etc., so that these can be considered in the simulation. The simulation is carried out by the software breaking down the component into many small sections and calculating the forces and stresses acting on each section. Obviously, the smaller the sections, the more accurate the simulation. The only problem is that with smaller sub-pieces the number of sub-pieces increases, which increases the calculation effort and thus also the calculation time. Here it is necessary to achieve a proper balance between accuracy and calculation time.

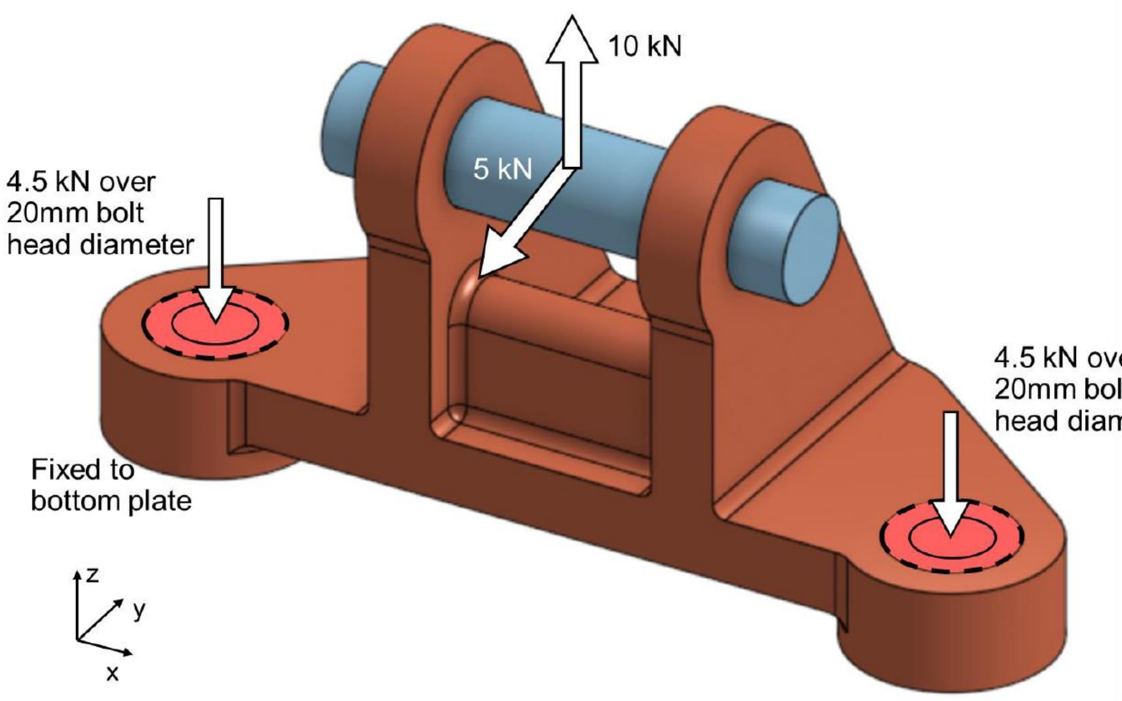

Figure 14: load cases (©MIT)

2.4 Optimization

The results from the simulation is the basis for the optimization. This can aim at one or more of the following goals: Weight reduction, function integration, monolithic design or acceleration of design iterations in product development. The simulation shows in which areas of the design area no or only little stress occurs. In many cases, these areas offer potential for weight reduction, since no material is needed here to meet the mechanical requirements of the part. The optimization result can rarely be used directly. Figure 15 shows the difference between the result of the automated optimization process and the resulting manually optimized part. This part is simulated again to ensure that this version of the part can also handle the load cases without damage. The need for manual remodeling exists because the simulation often does not produce a result that can be manufactured directly, since manufacturing restrictions are often not considered.

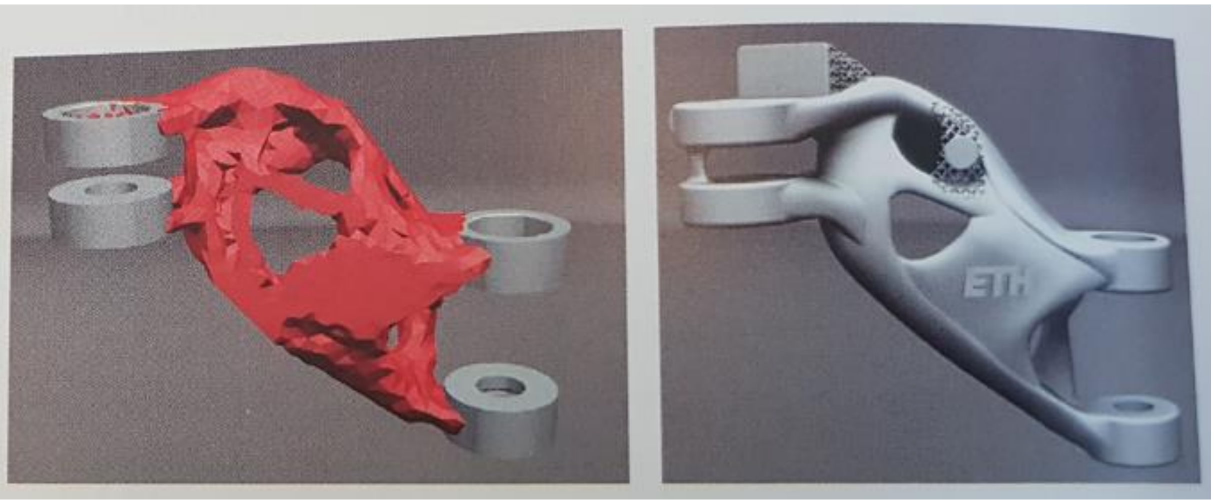

Figure 15: optimization result and finished part (©ETHZ pd|z)

2.5 3D printing

As already described in Chapter 2.2, several design factors must be considered so that the parts can be manufactured efficiently. If the design cannot be modified accordingly, the orientation on the build platform can sometimes save a lot of support structure volume and thus build time. Support structures are necessary in the LBM process for several reasons. The part must be mechanically fixed so that it is not moved from its position during the deposition process. In addition, the high temperature generated during the melting process must be dissipated. This does not work adequately via the loose powder bed, since the powder particles are enclosed by process gas and therefore insulate rather than dissipate the heat. Due to the process principle, in which the top layer is always very strongly heated and then rapidly cools down again, thermal stresses occur in the part. To prevent mechanical deformation caused by the thermal stresses, the support structure is designed to be massive enough to withstand these stresses. Heat treatment, which takes place after the building process, removes the stresses before the parts are separated from the building platform.

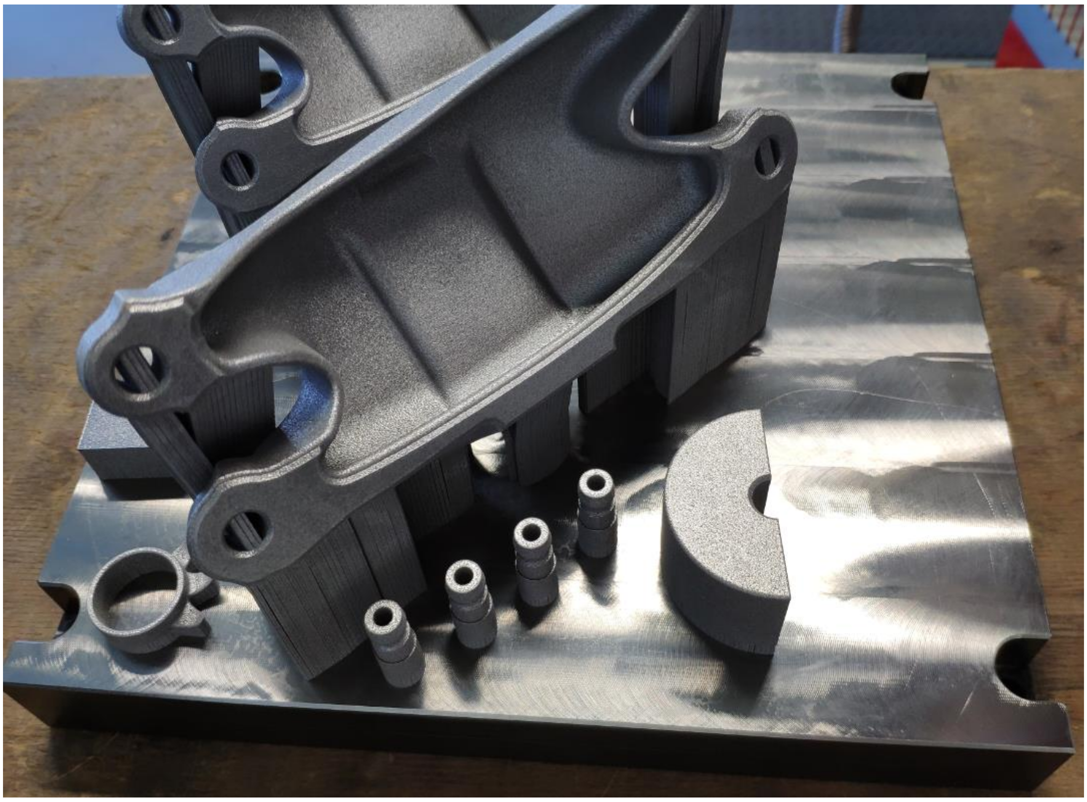

Figure 16: Parts on building platform ©FOTEC

Generally, it can be said that the component expansion in the z-direction on the building platform has the greatest influence on the build time. This circumstance is justified by the fact that the movement of the laser beam within a layer happens very quickly (more than 1m/s). However, the deposition process takes a lot of time proportionally. During the deposition process, the build platform is first lowered to allow the deposition system to pass over the build platform without collision. Metal powder is then fed into the coating system, which is then applied to the build platform in a defined thickness. This process can only be accelerated to a limited extent, as otherwise the quality of the coating decreases.

2.6 Post processing

Post processing includes all the steps necessary to ensure that the part can be used for its intended purpose. This includes heat treatment, support removal, surface finishing and the cleaning process.

2.6.1 Heat treatment

Immediately after the build process, it is necessary for many parts and materials (especially titanium) to reduce the thermal stresses that arise in the part as a result of the process. For this purpose, the parts are heat-treated while still on the building platform. Different heat treatment strategies result in different mechanical properties of the finished parts. It is essential that the temperature ramps and holding times are followed as precisely as possible and without overshooting. Otherwise, small deviations can lead to very different results. Due to the large thermal mass of the build platform, the choice of temperature sensor position is also very important.

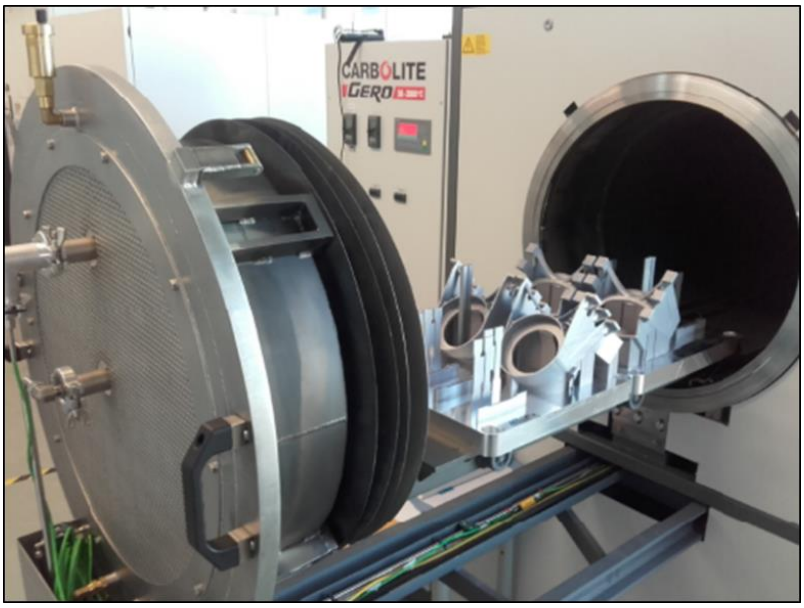

Figure 17: Heat treatment ©FOTEC

In many building jobs there is manufactured a set of in-process samples to verify the compliance with the material data base and to ensure that the manufacturing process was successful. All samples were also heat treated in the same batch as the corresponding parts (see Figure 17).

2.6.2 Support removal

As described in section 2.2 the number of support structures required for the manufacture of parts should be kept as low as possible. Nevertheless, the support structures are necessary to stabilize the manufactured parts due to the following reasons:

- Fixation of part on build platform: The part has a much higher density than the loose powder bed and could sink into it. Moreover, it could be pushed aside by the recoater blade. Support structures keep the part in position.
- Heat dissipation: Loose metal powder is not sufficiently heat conductive to mediate good heat dissipation from the melt pool. This generally leads to an inhomogeneous heat distribution within the manufactured part and causes residual stresses. Support structures improve the heat transfer from the melt pool to the build platform and thereby reduce residual stresses.
- Minimization of warping caused by residual stresses: Residual stresses can cause significant warping of parts in ALM. Unfortunately, they can never be avoided completely. However, such stresses can be partially relieved by heat treatment. Support structures stabilize the part on the built platform and suppress warping until the heat treatment is completed.
- Stabilization of overhanging structures: If a layer is fused on top of loose powder, the powder below the irradiated region is heated too. It partially melts and sticks to the built layer. This phenomenon is called "down-skin" and leads to rough and irregular surfaces. Down-skin effects typically occur at overhangs that form an angle with the build platform of less than ~45°. Such overhangs generally need to be stabilized with support structures.

However, in order to use the built components after manufacturing, they must be freed from the support structures.

After heat treatment, the parts are separated from the build platform. This is usually done with a band saw or by wire EDM. In some cases, it may also be necessary to rework various component surfaces on the building platform by milling or other methods. Before the build platform can be used for a new job, its surface must be smoothed. This is usually done by milling. The removal of support structures can be done by several methods, which are listed below.

Figure 18: Manual Support removal with hammer and chisel (left) or dremel multitool (right) ©FOTEC

2.6.2.1 Manual removal

Manual support removal requires the least preparation time because no additional fixtures need to be made and no milling paths etc. need to be programmed. In addition, there are minimal costs for consumables (see Figure 18). However, the disadvantage is that personnel capacity is tied up and repeatability is not possible. For example, manually overgrinding a surface will always result in a different stock removal. Depending on the subsequent use of the part, this process may be an option.

One method to break off support structures manually are different types of pliers. Needle nose pliers or water pump pliers are some examples for that. To break supports from the part, they should be grabbed as close as possible to the part surface as shown in Figure 19. Occasionally, support structures will not detach completely but will break several millimeters above the part surface. In this cases you can try to break off such residues with water pump pliers as completely as possible before filing and grinding (see Figure 20).

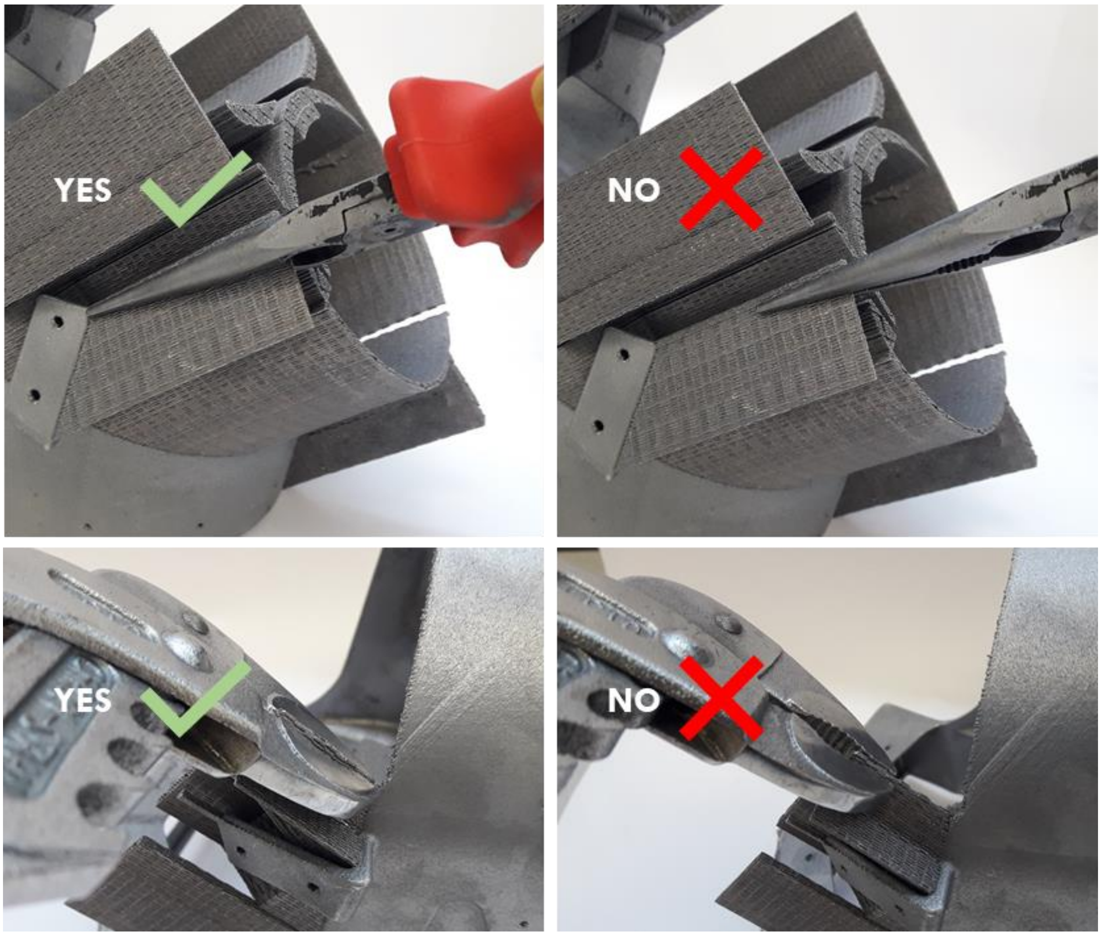

Figure 19: . Support structures should be grabbed with pliers as close as possible to the part surface ©FOTEC

Figure 20: Breaking off support residues with water pump pliers ©FOTEC

2.6.2.2 Mechanical removal

Mechanical support removal has the major advantage of producing repeatable results and requiring significantly fewer human resources. Depending on the available equipment and the complexity of the part, possibilities for clamping must be provided either on the part itself or through additional fixtures. As with manual support removal, all surfaces that are to be post-processed must be accessible and must have been provided with an allowance during the construction.

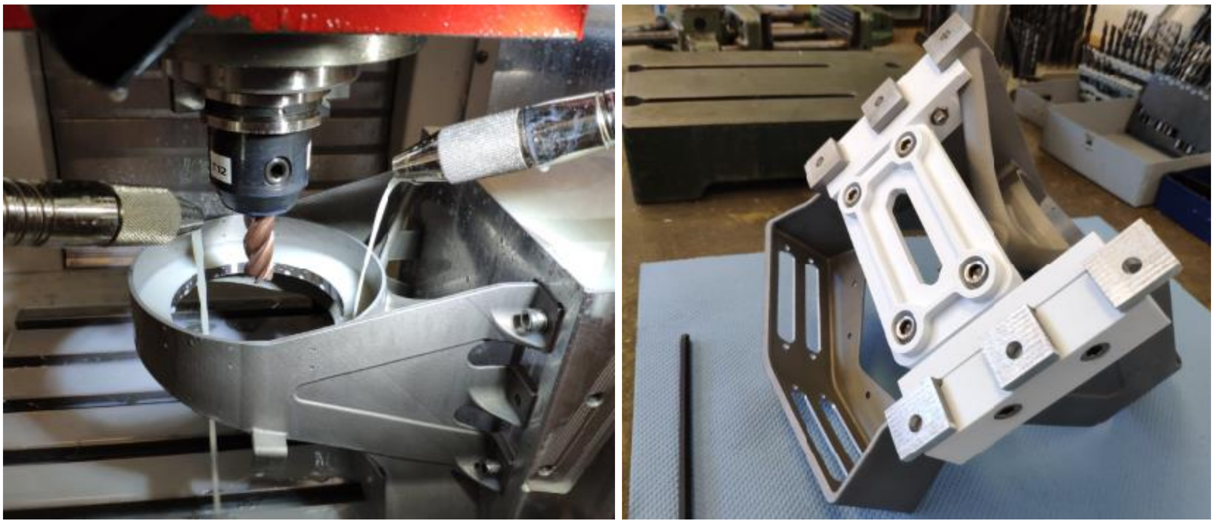

Figure 21: Mechanical Support removal ©FOTEC

2.6.2.3 Electro-chemical removal

Currently, mechanical finishing processes such as milling, and in many cases even hammers and chisels, are used for support removal (see Figure 22 left). Due to the large mechanical forces acting during these processes, there is a high risk that components will be damaged or deformed. This is a major problem for quality assurance, especially in the aerospace sector. In addition, LSS components typically have a rougher surface than subtractive manufactured components. However, this is unfavorable for many technical applications or even partially prevents the use of LSS components in certain areas.

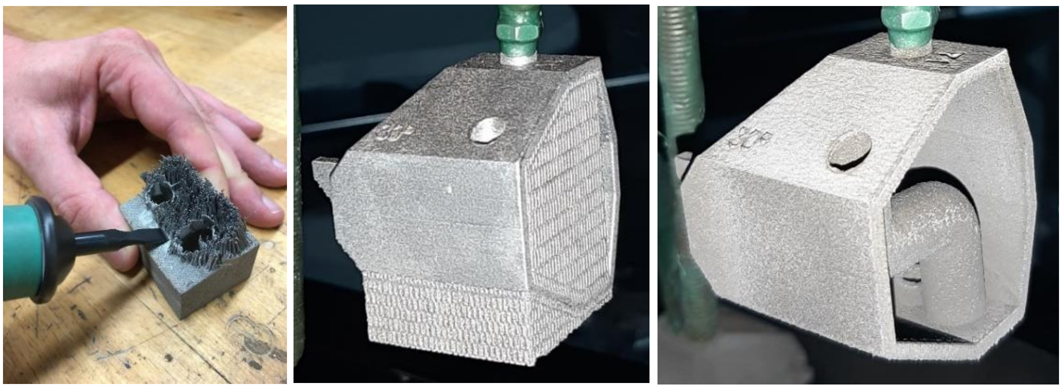

Figure 22: Removal of support with chisel (left, © nc-fertigung.de); part before (middle) and after (right) the hirtisation process ©FOTEC

A very new method of support removal in contrast to the above-mentioned processes is electro-chemical removal of the support structures. In this process, the part is electrically connected to an electrode and immersed in several baths of electrolyte. The combination of applied current and electrolyte breaks down the support structure and smooths the surface of the part, especially interior surfaces (see Figure 22 right). In this process, it must be considered that a surface must be available for electrical contacting and that the electrolyte can drain out of the part so that there is no mixing of the electrolytes (see Figure 23).

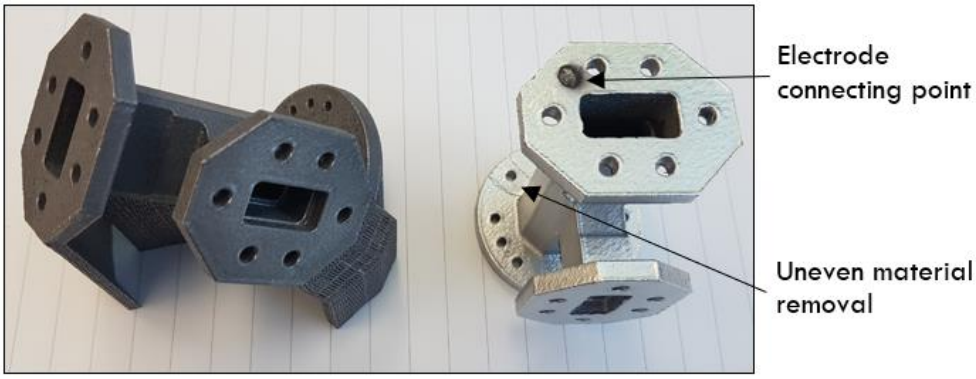

Figure 23: Electro-chemical Support removal ©FOTEC

In contrast to classic electropolishing, the hirtisation process uses sequences of pulses with a special shape, as well as electrolytes matched to the material of the component, which allow the material removal to be controlled in a targeted manner. In this way, the process acts specifically on powder adhesions and superficial roughness and enables fully automatic leveling of surfaces of metallic LSS components, even from mechanically inaccessible inner surfaces and in complex holes, purely chemically-electrochemically without mechanical processing. In contrast to all other electropolishing variants, the hirtisation process also acts on support structures and thus enables fully automatic chemical-electrochemical removal of support structures from metallic LSS components without mechanical machining steps, even from interior spaces and holes with complex geometries.

2.6.3 Surface finishing

Surface finishing serves several purposes. Adhering powder particles are removed and the surface is smoothed and has a homogeneous appearance. This prevents particles from detaching from the surface at a later stage, where they can potentially cause damage. This includes contamination from liquids and gases that flow around the part.

This can be done by blasting chambers (see Figure 24 left) with corundum powder or stainless-steel beads. Another possibility would be the hirtisation process in chapter 2.6.2.3 or by manual work with sandpaper (see Figure 24 right).

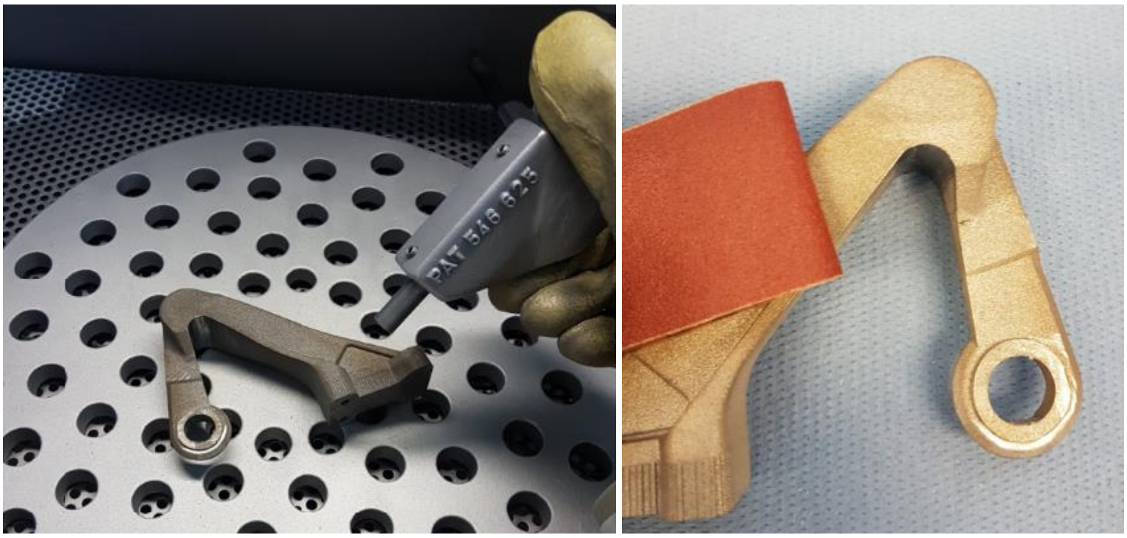

Figure 24: Surface finishing with a blasting chamber (left) or with sandpaper (right) ©FOTEC

2.6.4 Cleaning process

The cleaning process is performed as the last step after all other processing steps have been carried out. Here, all residues from production and rework are removed. This includes, for example, residues of cooling lubricant, adhesions of blasting material, etc. In addition, it is ensured that areas which are not accessible for shot peening are also completely freed from excess powder. Sometimes it is also necessary to remove existing residues of metal powder after separation from the build platform by cleaning to ensure safe finishing.

After the cleaning process, e.g. in an ultrasonic bath (see Figure 25 left) with isopropanol or cleaning fluid, the components are dried in air and packaged. Packaging can be done in simple sample bags or in vacuum-sealed bags (see Figure 25 right).

Figure 25: Cleaning in an ultrasonic bath (left) and packaging in vacuum-sealed bags (right) ©FOTEC

2.7 Testing

Testing of the parts is an elementary stage of the production chain. A distinction can be made here between geometric testing and structural testing.

2.7.1 Geometrical testing

Geometric testing examines whether the geometry of the finished part is within the required tolerances. Any amount of effort can be expended in this process, which often correlates with the complexity of the component. In the simplest case, the main dimensions are checked. In a more complex case, shape and position tolerances can be checked. For this purpose, FOTEC has a FARO 3D scanner with which surfaces can be measured both tactilely and by laser. In this way, a target/actual comparison of the manufactured part with the required 3D model can be carried out in one step. In addition, the part can be measured by means of a CT scan. This method can also be used to measure internal component features that can otherwise only be analyzed destructively. The disadvantages of CT examination are the comparatively high costs and the limited resolution with increasing component dimensions.

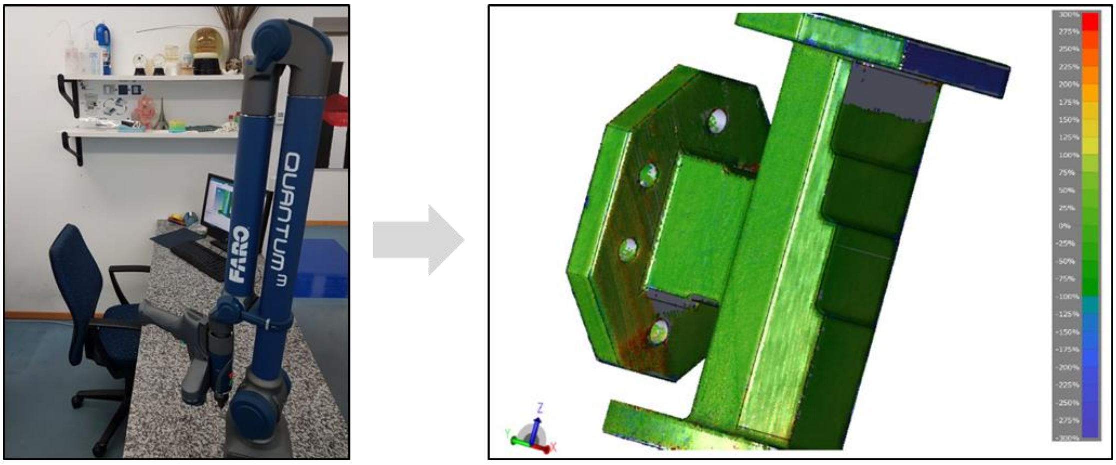

Figure 26: Geometrical testing ©FOTEC

2.7.2 Structural testing

Structural testing checks the mechanical requirements of the parts. This can be done either by transferring the expected stress onto the part. For simple geometries and load cases, this method is quite common. For more complex parts, the mechanical load cases are simulated and the part is designed based on the expected loads. To determine the mechanical parameters for the simulation, standard components (tensile specimens, impact test specimens) are manufactured and tested destructively.

2.8 Quality assurance

From chosen pre-alloyed powder characterized in section 2.1.2 was at different parameters prepared by 3-D printing samples with dimension 5x5x5mm for microstructural analyses.

There where done several process deviations in 20 Layer steps (20x0,03mm/layer=0,6mm each). The modifications where done only one at a time. (e.g. modified Scanspeed means everything else is default)

The following modifications where done from top to bottom:

1. reduced Scanspeed to 1090mm/s --> higher energy density
2. increased Scanspeed to 1520mm/s --> lower energy density
3. reduced distance between laserlines to 0,09mm --> higher energy density
4. increased distance between laserlines to 0,12mm --> lower energy density
5. increased Laser Power to 195W --> higher energy density
6. decreased Laser Power to 140W --> lower energy density

Final density was measured by Archimedes method with weights RADWAG 220 / X were measured the density of samples before sintering and after both sintering. Thus, after the initial soft sintering, the densities were determined samples according to valid standards (MPIF Standard 42) for measuring porous compacts measured by the Archimedean method. Theoretical density from pre-alloyed powder Ti6Al4V is 4,236g/cm^3. For all parameters were measured densities from 4.089 to 4.162 g/cm^3.

2.4.2 SEM-EDS

Sample for porosity and EDS analyses was prepared via standard metallographic process with final steps on OP-S. Images for porosity characterization of sintered samples were obtained via JEOL jsm-7600F Schottky field emission scanning electron microscope (SEM) Porosity was evaluated via Software ImageJ. The chemical composition of sintered samples was determined (SEM) equipped with an energy dispersive spectrometer (EDS) 50 mm^2 from Oxford Instruments with INCA analysis software. EDS measurements were performed at an operating voltage of 15 kV with a 70 nm aperture. The standardized Cobalt reference was used as the calibration element for optimisation of chemical composition measurements.

Via SEM was observed different porous structure into prepared samples on the fig. 24 is possible see the biggest find pores into microstructure 3-D printed samples at the lowest temperature of printing. With increasing of temperature were observed reducing biggest pores

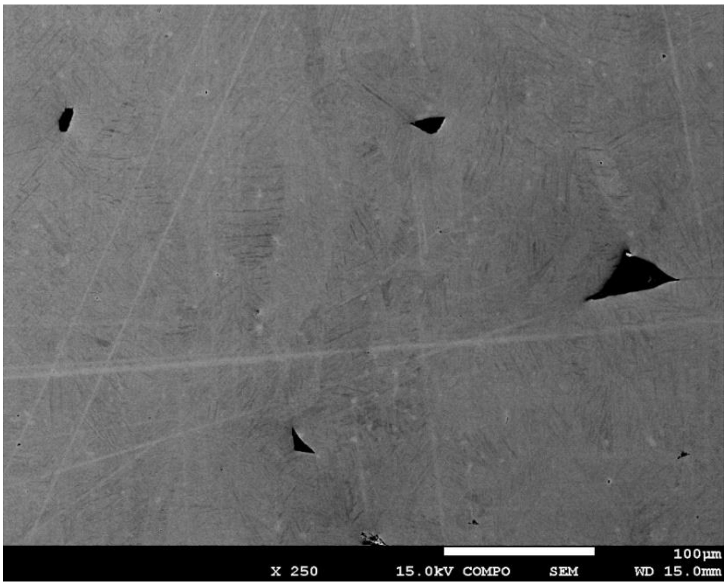

Figure 24: Pores in from cross-section on the prepared 3-D sample (IMMM SAS)

On detailed SEM image in fig.25 is possible observed except small porosity different with orientation of grain structure without strong differences in chemical composition as I possible see on fig.26 observed via EDS elemental mapping.

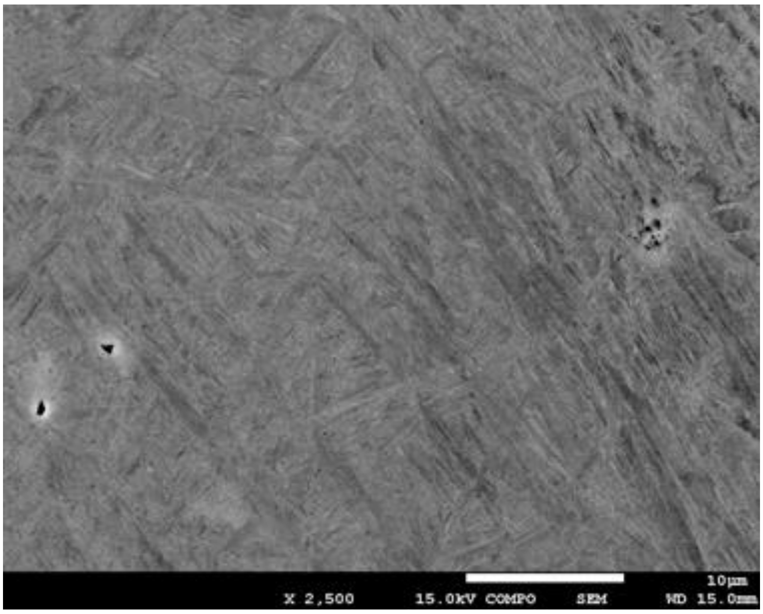

Figure 25: Detailed microstructure (IMMM SAS)

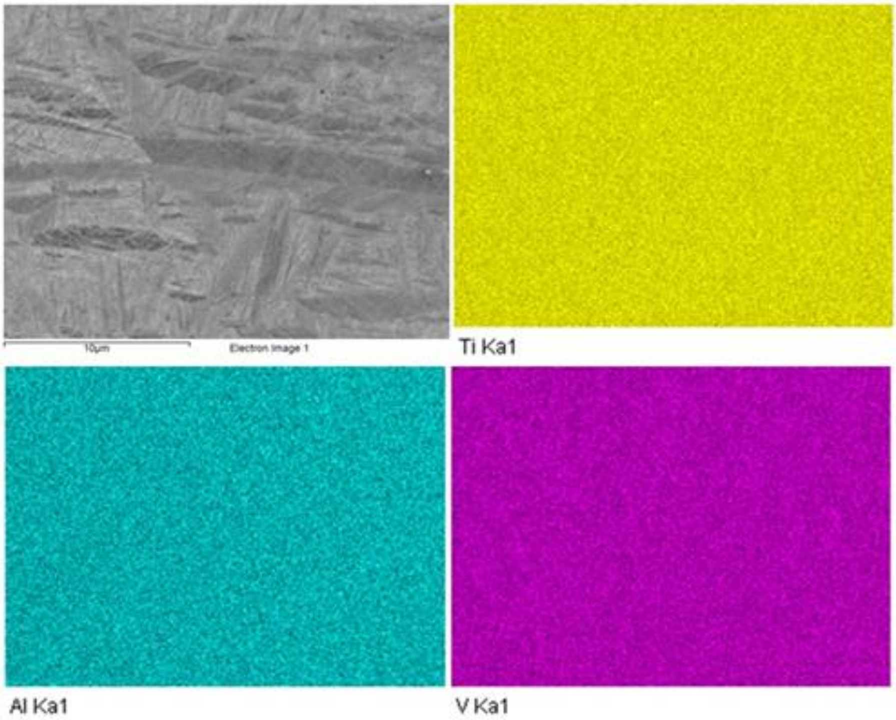

Figure 26: EDS elemental map (IMMM SAS)

Via SEM was also observed roughness of surface 3-D printed samples on the fig.27 this roughness is possible remove by grinding.

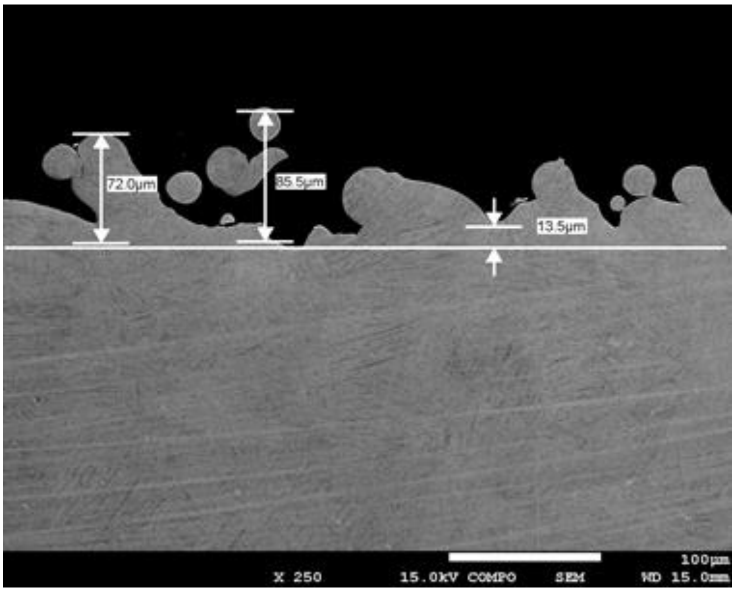

Figure 27: surface of 3-D printed sample (IMMM SAS)

3 Summary of showstopper

In addition to the manufacturing characteristics mentioned in chapter 2.2, design guidelines must also be considered in additive manufacturing. These serve as orientation values for the dimensioning and concrete design of components for additive manufacturing. These are geometry-specific parameters that depend on the additive processes, systems, process parameters and materials that are used. Examples are minimum wall thickness, clearance angles, clearance widths, channel diameters and overhangs. The following section discusses these parameters and provides empirical values for these restrictions in the LBM process.

The **minimum wall thickness** depends on the physical resolution of the system as well as on the planned height of the wall. Due to the mechanical load of the coating system on the wall, the minimal wall thickness of built parts is also limited (typically 300 µm).

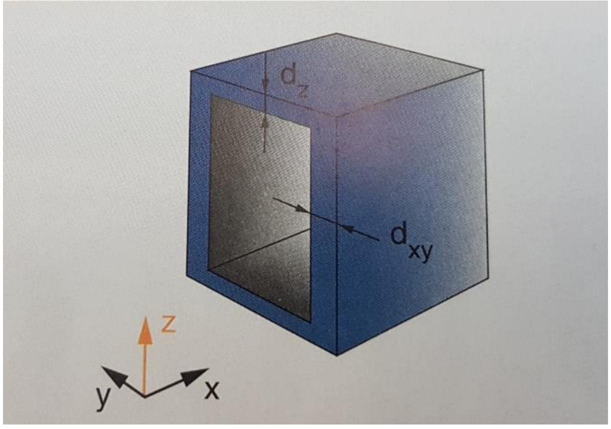

Figure 27: wall thickness (© Leutenecker-Twelsiek 2018)

The **clearance angle** indicates the angle between the build platform and the component from which a geometry can be built without the need for support structures (typically 45 degrees).

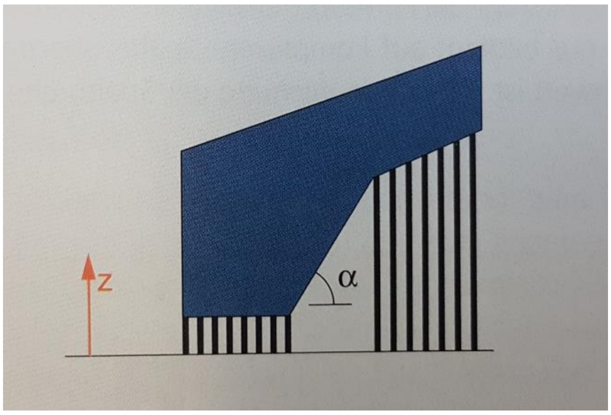

Figure 28: clearance angle (© Leutenecker-Twelsiek 2018)

Clearance widths indicate how narrow a gap between solid geometries can be without melting the residual powder inside the gap and closing the space (typically 100 µm).

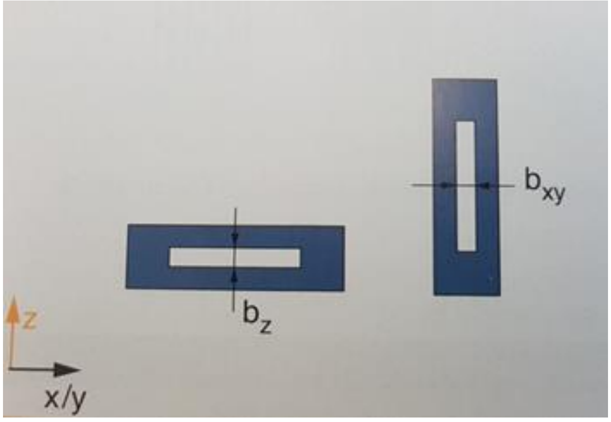

Figure 29: clearance width (© Leutenecker-Twelsiek 2018)

Channel diameter can be interpreted in two ways. One variant is the minimum buildable diameter of a channel without the channel being closed (typically minimum of 1-2 mm horizontally and 0,7 mm vertically). The other variant refers to the maximum duct diameter that can be built horizontally without a support structure is necessary (typically maximum of 12 mm).

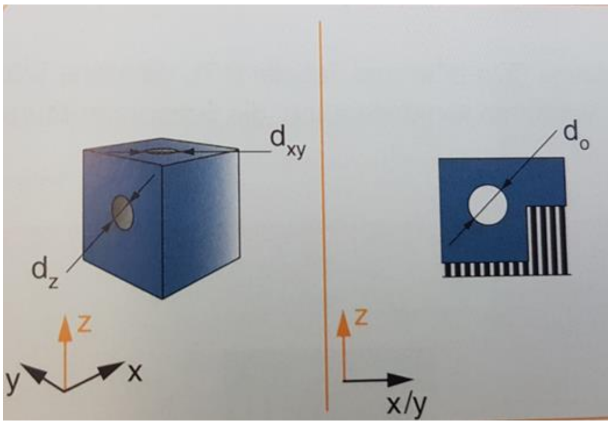

Figure 30: chanel diameter (© Leutenecker-Twelsiek 2018)

Lastly, there is a restriction on **overhangs**. This refers to the maximum overhang length that can be built without support structures below (typically 300 µm).

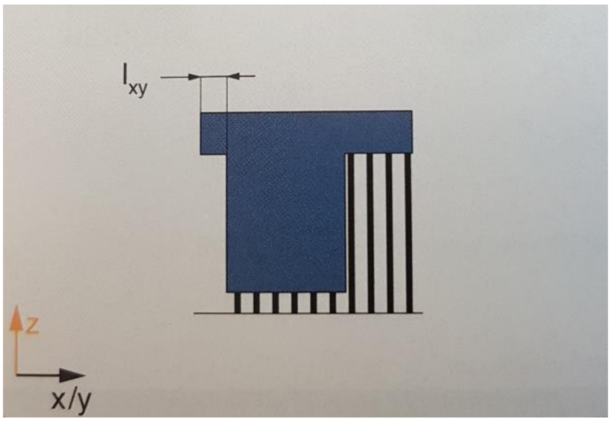

Figure 31: overhang (© Leutenecker-Twelsiek 2018)

There are also obvious factors that need to be considered in the design. Cavities must not be closed, otherwise the unfused powder cannot be removed. In additive manufacturing, it is often necessary to perform post-processing on functional surfaces in order to achieve the necessary surface quality. In this case, it is important to ensure that both accessibility to the surface to be machined and the possibility of clamping the components are available.

Thus, as for other manufacturing technologies, there are some methods that drastically reduce the cost of production of the part. Often it is not necessary for a channel to be round, or a right angle can also be made as a chamfer. Design for manufacturing is also very important in LBM and requires the designers to construct the parts according to the process.

4 State of the art

3D printing is a generative manufacturing process for the layer-by-layer building of three-dimensional workpieces and is known as additive manufacturing (AM). Production takes place directly on the basis of computer-internal data models from formless (liquids, gels/pastes, powders, etc.) or form-neutral (ribbon-, wire-, sheet-shaped) material by means of chemical and/or physical processes (hardening or melting processes). Typical materials for 3D printing are plastics, synthetic resins, ceramics, metals and metal alloys.

With all additive manufacturing systems, the generation of parts is fully automatic from the start of the building process. All additive manufacturing systems have a height-adjustable build platform, material application and selective shaping of the build material in common.

In 3D printing (generative manufacturing, additive manufacturing) of metals, powder bed-based processes dominate, whereby most machines have been and are being sold for laser beam melting (LBM). Currently, there are machines for LBM from different, mainly German, manufacturers on the market, with different machine sizes, configurations and generations.

Laser beam melting (LBM), as the manufacturing process is known according to VDI 3405, is state of the art. It is an additive manufacturing process in which the desired geometry is created by joining volume elements. Additive processes are characterised by the fact that, in addition to the geometry, the material properties are also created simultaneously during the manufacturing process. According to ASTM F2792-12a, laser beam melting is further subdivided into the additive process group "Powder Bed Fusion". This describes an additive manufacturing process in which thermal energy selectively connects areas in a powder bed.

All 3D printing systems have in common that the building process is purely controlled, in other words it works without signal feedback in the sense of a closed-loop control. Although some research groups or machine manufacturers have already succeeded in monitoring parts of the process, such as the residual oxygen concentration in the process chamber, the power of the processing laser, the temperature of the building platform and the powder application, neither research groups nor machine manufacturers have yet succeeded in controlling the entire building process.

The machine manufacturers ***EOS*** and ***Concept Laser*** offer camera-based powder bed monitoring systems for their current machine series, which can be used to verify that a defect-free powder layer is available as a starting point for the latest LBM layer.

In-line process monitoring describes the collection of measurement data already during the building process in order to draw conclusions about the component quality. Some machine manufacturers already offer systems for in-line process monitoring, but these differ greatly. There are differences in the hardware used as well as in the software. For example, the recorded measurement data is only visualised by some suppliers without any form of interpretation or qualification.

SLM Solutions, for example, uses a measuring system that is based only on photodiodes and only allows visualisation of the measured data.

Renishaw combines two photodiodes in the beam path of the laser (700-1040nm & 1090-1700nm). This allows the back reflected radiation from the melt pool to be detected in the near infrared range without being overlaid by the laser wavelength (1064nm). Renishaw also offers an exclusive acoustic monitoring system of the building process. This allows reliable detection of any contacts between the part and the recoater, or if the part breaks away from the building platform.

Concept Laser (part of GE Additive) uses a combination of camera and photodiode data to determine part quality. However, the "QM Meltpool 3D" system requires reference data from an identical build job that is correlated with the measurement data of the current job in order to be able to provide a statement on the component quality.

Trumpf uses only a photodiode-based system. Like the competitors, the photodiodes are positioned in the optical path of the laser, which makes it easy to integrate the system even in multi-laser systems. As with Concept Laser, reference data is needed to analyse the build job.

EOS uses a combination of photodiode and camera, but the measurement systems are not combined, instead they function as independent software solutions. EOS takes an alternative approach to the competition in the quality assurance of its systems and tries to get by without reference data.

It is the complete documentation of the proven part quality that represents the essential component for the further increase of the acceptance of 3D printing among potential interested parties for this technology. The complete documentation of the LBM manufacturing process, including the assessment of the component quality, is essential for the quality assurance of additively manufactured components, especially in the aerospace sector.